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COMPILATION OF AIR POLLUTANT EMISSION FACTORS

VOLUME I: STATIONARY POINT AND AREA SOURCES

FIFTH EDITION

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Office Of Air Quality Planning And Standards
Office Of Air And Radiation
U. S. Environmental Protection Agency
Research Triangle Park, NC 27711

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Volume I

CONTENTS

Page

INTRODUCTION 1

1. EXTERNAL COMBUSTION SOURCES 1.0-1
   - 1.1 Bituminous And Subbituminous Coal Combustion 1.1-1
   - 1.2 Anthracite Coal Combustion 1.2-1
   - 1.3 Fuel Oil Combustion 1.3-1
   - 1.4 Natural Gas Combustion 1.4-1
   - 1.5 Liquefied Petroleum Gas Combustion 1.5-1
   - 1.6 Wood Waste Combustion In Boilers 1.6-1
   - 1.7 Lignite Combustion 1.7-1
   - 1.8 Bagasse Combustion In Sugar Mills 1.8-1
   - 1.9 Residential Fireplaces 1.9-1
   - 1.10 Residential Wood Stoves 1.10-1
   - 1.11 Waste Oil Combustion 1.11-1

2. SOLID WASTE DISPOSAL 2.0-1
   - 2.1 Refuse Combustion 2.1-1
   - 2.2 Sewage Sludge Incineration 2.2-1
   - 2.3 Medical Waste Incineration 2.3-1
   - 2.4 Landfills 2.4-1
   - 2.5 Open Burning 2.5-1
   - 2.6 Automobile Body Incineration 2.6-1
   - 2.7 Conical Burners 2.7-1

3. STATIONARY INTERNAL COMBUSTION SOURCES 3.0-1
   - 3.1 Stationary Gas Turbines For Electricity Generation 3.1-1
   - 3.2 Heavy-duty Natural Gas-fired Pipeline Compressor Engines 3.2-1
   - 3.3 Gasoline And Diesel Industrial Engines 3.3-1
   - 3.4 Large Stationary Diesel And All Stationary Dual-fuel Engines 3.4-1

4. EVAPORATION LOSS SOURCES 4.0-1
   - 4.1 Dry Cleaning 4.1-1
   - 4.2 Surface Coating 4.2-1
   - 4.2.1 Nonindustrial Surface Coating 4.2.1-1
   - 4.2.2 Industrial Surface Coating 4.2.2-1
   - 4.2.2.1 General Industrial Surface Coating 4.2.2.1-1
   - 4.2.2.2 Can Coating 4.2.2.2-1
   - 4.2.2.3 Magnet Wire Coating 4.2.2.3-1
   - 4.2.2.4 Other Metal Coating 4.2.2.4-1
   - 4.2.2.5 Flat Wood Interior Panel Coating 4.2.2.5-1
   - 4.2.2.6 Paper Coating 4.2.2.6-1
   - 4.2.2.7 Polymeric Coating Of Supporting Substrates 4.2.2.7-1
   - 4.2.2.8 Automobile And Light Duty Truck Surface Coating Operations 4.2.2.8-1
   - 4.2.2.9 Pressure Sensitive Tapes And Labels 4.2.2.9-1
   - 4.2.2.10 Metal Coil Surface Coating 4.2.2.10-1

4.2.2.11 Large Appliance Surface Coating 4.2.2.11-1
4.2.2.12 Metal Furniture Surface Coating 4.2.2.12-1
4.2.2.13 Magnetic Tape Manufacturing 4.2.2.13-1
4.2.2.14 Surface Coating Of Plastic Parts For Business Machines 4.2.2.14-1
4.3 Waste Water Collection, Treatment And Storage 4.3-1
4.4 Polyester Resin Plastic Products Fabrication 4.4-1
4.5 Asphalt Paving Operations 4.5-1
4.6 Solvent Degreasing 4.6-1
4.7 Waste Solvent Reclamation 4.7-1
4.8 Tank And Drum Cleaning 4.8-1
4.9 Graphic Arts 4.9-1
4.9.1 General Graphic Printing 4.9.1-1
4.9.2 Publication Gravure Printing 4.9.2-1
4.10 Commercial/Consumer Solvent Use 4.10-1
4.11 Textile Fabric Printing 4.11-1

5. PETROLEUM INDUSTRY 5.0-1
5.1 Petroleum Refining 5.1-1
5.2 Transportation And Marketing Of Petroleum Liquids 5.2-1
5.3 Natural Gas Processing 5.3-1

6. ORGANIC CHEMICAL PROCESS INDUSTRY 6.0-1
6.1 Carbon Black 6.1-1
6.2 Adipic Acid 6.2-1
6.3 Explosives 6.3-1
6.4 Paint And Varnish 6.4-1
6.5 Phthalic Anhydride 6.5-1
6.6 Plastics 6.6-1
6.6.1 Polyvinyl Chloride 6.6.1-1
6.6.2 Poly(ethylene terephthalate) 6.6.2-1
6.6.3 Polystyrene 6.6.3-1
6.6.4 Polypropylene 6.6.4-1
6.7 Printing Ink 6.7-1
6.8 Soap And Detergents 6.8-1
6.9 Synthetic Fibers 6.9-1
6.10 Synthetic Rubber 6.10-1
6.11 Terephthalic Acid 6.11-1
6.12 Lead Alkyl 6.12-1
6.13 Pharmaceuticals Production 6.13-1
6.14 Maleic Anhydride 6.14-1
6.15 Methanol 6.15-1
6.16 Acetone And Phenol 6.16-1
6.17 Propylene 6.17-1
6.18 Benzene, Toluene And Xylenes 6.18-1
6.19 Butadiene 6.19-1
6.20 Cumene 6.20-1
6.21 Ethanol 6.21-1
6.22 Ethyl Benzene 6.22-1
6.23 Ethylene 6.23-1
6.24 Ethylene Dichloride And Vinyl Chloride 6.24-1
6.25 Ethylene Glycol 6.25-1

6.26 Ethylene Oxide 6.26-1
6.27 Formaldehyde 6.27-1
6.28 Glycerine 6.28-1
6.29 Isopropyl Alcohol 6.29-1

7. LIQUID STORAGE TANKS 7.0-1
7.1 Organic Liquid Storage Tanks 7.1-1

8. INORGANIC CHEMICAL INDUSTRY 8.0-1
8.1 Synthetic Ammonia 8.1-1
8.2 Urea 8.2-1
8.3 Ammonium Nitrate 8.3-1
8.4 Ammonium Sulfate 8.4-1
8.5 Phosphate Fertilizers 8.5-1
8.5.1 Normal Superphosphates 8.5.1-1
8.5.2 Triple Superphosphates 8.5.2-1
8.5.3 Ammonium Phosphate 8.5.3-1
8.6 Hydrochloric Acid 8.6-1
8.7 Hydrofluoric Acid 8.7-1
8.8 Nitric Acid 8.8-1
8.9 Phosphoric Acid 8.9-1
8.10 Sulfuric Acid 8.10-1
8.11 Chlor-Alkali 8.11-1
8.12 Sodium Carbonate 8.12-1
8.13 Sulfur Recovery 8.13-1
8.14 Hydrogen Cyanide 8.14-1

9. FOOD AND AGRICULTURAL INDUSTRIES 9.0-1
9.1 Tilling Operations 9.1-1
9.2 Growing Operations 9.2-1
9.2.1 Fertilizer Application 9.2.1-1
9.2.2 Pesticide Application 9.2.2-1
9.2.3 Orchard Heaters 9.2.3-1
9.3 Harvesting Operations 9.3-1
9.3.1 Cotton Harvesting 9.3.1-1
9.3.2 Grain Harvesting 9.3.2-1
9.3.3 Rice Harvesting 9.3.3-1
9.3.4 Cane Sugar Harvesting 9.3.4-1
9.4 Livestock And Poultry Feed Operations 9.4-1
9.4.1 Cattle Feedlots 9.4.1-1
9.4.2 Swine Feedlots 9.4.2-1
9.4.3 Poultry Houses 9.4.3-1
9.4.4 Dairy Farms 9.4.4-1
9.5 Animal And Meat Products Preparation 9.5-1
9.5.1 Meat Packing Plants 9.5.1-1
9.5.2 Meat Smokehouses 9.5.2-1
9.5.3 Meat Rendering Plants 9.5.3-1
9.5.4 Manure Processing 9.5.4-1
9.5.5 Poultry Slaughtering 9.5.5-1
9.6 Dairy Products 9.6-1
9.6.1 Natural And Processed Cheese 9.6.1-1

9.7 Cotton Ginning 9.7-1
9.8 Preserved Fruits And Vegetables 9.8-1
9.8.1 Canned Fruits And Vegetables 9.8.1-1
9.8.2 Dehydrated Fruits And Vegetables 9.8.2-1
9.8.3 Pickles, Sauces And Salad Dressings 9.8.3-1
9.9 Grain Processing 9.9-1
9.9.1 Grain Elevators And Processes 9.9.1-1
9.9.2 Cereal Breakfast Food 9.9.2-1
9.9.3 Pet Food 9.9.3-1
9.9.4 Alfalfa Dehydration 9.9.4-1
9.9.5 Pasta Manufacturing 9.9.5-1
9.9.6 Bread Baking 9.9.6-1
9.9.7 Corn Wet Milling 9.9.7-1
9.10 Confectionery Products 9.10-1
9.10.1 Sugar Processing 9.10.1-1
9.10.1.1 Cane Sugar Processing 9.10.1.1-1
9.10.1.2 Beet Sugar Processing 9.10.1.2-1
9.10.2 Salted And Roasted Nuts And Seeds 9.10.2-1
9.10.2.1 Almond Processing 9.10.2.1-1
9.10.2.2 Peanut Processing 9.10.2.2-1
9.11 Fats And Oils 9.11-1
9.11.1 Vegetable Oil Processing 9.11.1-1
9.12 Beverages 9.12-1
9.12.1 Malt Beverages 9.12.1-1
9.12.2 Wines And Brandy 9.12.2-1
9.12.3 Distilled And Blended Liquors 9.12.3-1
9.13 Miscellaneous Food And Kindred Products 9.13-1
9.13.1 Fish Processing 9.13.1-1
9.13.2 Coffee Roasting 9.13.2-1
9.13.3 Snack Chip Deep Fat Frying 9.13.3-1
9.13.4 Yeast Production 9.13.4-1
9.14 Tobacco Products 9.14-1
9.15 Leather Tanning 9.15-1
9.16 Agricultural Wind Erosion 9.16-1

10. WOOD PRODUCTS INDUSTRY 10.0-1
10.1 Lumber 10.1-1
10.2 Chemical Wood Pulping 10.2-1
10.3 Pulp Bleaching 10.3-1
10.4 Papermaking 10.4-1
10.5 Plywood 10.5-1
10.6 Reconstituted Wood Products 10.6-1
10.6.1 Waferboard And Oriented Strand Board 10.6.1-1
10.6.2 Particleboard 10.6.2-1
10.6.3 Medium Density Fiberboard 10.6.3-1
10.7 Charcoal 10.7-1
10.8 Wood Preserving 10.8-1

11. MINERAL PRODUCTS INDUSTRY 11.0-1
11.1 Hot Mix Asphalt Plants 11.1-1
11.2 Asphalt Roofing 11.2-1

11.3 Bricks And Related Clay Products 11.3-1
11.4 Calcium Carbide Manufacturing 11.4-1
11.5 Refractory Manufacturing 11.5-1
11.6 Portland Cement Manufacturing 11.6-1
11.7 Ceramic Clay Manufacturing 11.7-1
11.8 Clay And Fly Ash Sintering 11.8-1
11.9 Western Surface Coal Mining 11.9-1
11.10 Coal Cleaning 11.10-1
11.11 Coal Conversion 11.11-1
11.12 Concrete Batching 11.12-1
11.13 Glass Fiber Manufacturing 11.13-1
11.14 Frit Manufacturing 11.14-1
11.15 Glass Manufacturing 11.15-1
11.16 Gypsum Manufacturing 11.16-1
11.17 Lime Manufacturing 11.17-1
11.18 Mineral Wool Manufacturing 11.18-1
11.19 Construction Aggregate Processing 11.19-1
11.19.1 Sand And Gravel Processing 11.19.1-1
11.19.2 Crushed Stone Processing 11.19.2-1
11.20 Lightweight Aggregate Manufacturing 11.20-1
11.21 Phosphate Rock Processing 11.21-1
11.22 Diatomite Processing 11.22-1
11.23 Taconite Ore Processing 11.23-1
11.24 Metallic Minerals Processing 11.24-1
11.25 Clay Processing 11.25-1
11.26 Talc Processing 11.26-1
11.27 Feldspar Processing 11.27-1
11.28 Vermiculite Processing 11.28-1
11.29 Alumina Manufacturing 11.29-1
11.30 Perlite Manufacturing 11.30-1
11.31 Abrasives Manufacturing 11.31-1

12. METALLURGICAL INDUSTRY 12.0-1
12.1 Primary Aluminum Production 12.1-1
12.2 Coke Production 12.2-1
12.3 Primary Copper Smelting 12.3-1
12.4 Ferroalloy Production 12.4-1
12.5 Iron And Steel Production 12.5-1
12.6 Primary Lead Smelting 12.6-1
12.7 Zinc Smelting 12.7-1
12.8 Secondary Aluminum Operations 12.8-1
12.9 Secondary Copper Smelting And Alloying 12.9-1
12.10 Gray Iron Foundries 12.10-1
12.11 Secondary Lead Processing 12.11-1
12.12 Secondary Magnesium Smelting 12.12-1
12.13 Steel Foundries 12.13-1
12.14 Secondary Zinc Processing 12.14-1
12.15 Storage Battery Production 12.15-1
12.16 Lead Oxide And Pigment Production 12.16-1
12.17 Miscellaneous Lead Products 12.17-1

12.18 Leadbearing Ore Crushing And Grinding 12.18-1
12.19 Electric Arc Welding 12.19-1

13. MISCELLANEOUS SOURCES 13.0-1
13.1 Wildfires And Prescribed Burning 13.1-1
13.2 Fugitive Dust Sources 13.2-1
13.2.1 Paved Roads 13.2.1-1
13.2.2 Unpaved Roads 13.2.2-1
13.2.3 Heavy Construction Operations 13.2.3-1
13.2.4 Aggregate Handling And Storage Piles 13.2.4-1
13.2.5 Industrial Wind Erosion 13.2.5-1
13.3 Explosives Detonation 13.3-1
13.4 Wet Cooling Towers 13.4-1
13.5 Industrial Flares 13.5-1

APPENDIX A
Miscellaneous Data And Conversion Factors A-1

APPENDIX B.1
Particle Size Distribution Data And Sized Emission Factors For Selected Sources B.1-1

APPENDIX B.2
Generalized Particle Size Distributions B.2-1

APPENDIX C.1
Procedures For Sampling Surface/Bulk Dust Loading C.1-1

APPENDIX C.2
Procedures For Laboratory Analysis Of Surface/Bulk Dust Loading Samples C.2-1

KEY WORD INDEX

Chapter/Section

Abrasives Manufacturing 11.31
Acetone And Phenol 6.16
Acid
  Adipic 6.2
  Hydrochloric 8.6
  Hydrofluoric 8.7
  Nitric 8.8
  Phosphoric 8.9
  Sulfuric 8.10
  Terephthalic 6.11
Adipic Acid 6.2
Aggregate Handling 13.2.4
Aggregate Manufacturing, Lightweight 11.20
Aggregate Processing, Construction 11.19
Aggregate Storage Piles 13.2.4
Agricultural Industries 9.0
Agricultural Wind Erosion 9.16
Alcohol, Isopropyl 6.29
Alfalfa Dehydration 9.9.4
Alkali, Chlor- 8.11
Almond Processing 9.10.2.1
Alumina Manufacturing 11.29
Aluminum
  Operations, Secondary 12.8
  Production, Primary 12.1
Ammonia, Synthetic 8.1
Ammonium Nitrate 8.3
Ammonium Phosphate 8.5.3
Ammonium Sulfate 8.4
Analysis, Surface/Bulk Dust Loading App. C.2
Anhydride, Phthalic 6.5
Animal And Meat Products Preparation 9.5
Anthracite Coal Combustion 1.2
Appliance Surface Coating 4.2.2.11
Ash
  Fly Ash Sintering 11.8
Asphalt
  Hot Mix Plants 11.1
  Paving 4.5
  Roofing 11.2
Automobile Body Incineration 2.6
Automobile Surface Coating 4.2.2.8

- Bagasse Combustion In Sugar Mills . . . 1.8
- Baking, Bread . . . 9.9.6
- Bark
  - Wood Waste Combustion In Boilers . . . 1.6
- Batching, Concrete . . . 11.12
- Battery Production, Storage . . . 12.15
- Beet Sugar Processing . . . 9.10.1.2
- Benzene, Toluene And Xylenes . . . 6.18
- Beverages . . . 9.12
  - Brandy . . . 9.12.2
  - Liquors, Distilled And Blended . . . 9.12.3
  - Malt . . . 9.12.1
  - Wines . . . 9.12.2
- Bituminous Coal Combustion . . . 1.1
- Bleaching, Wood Pulp . . . 10.3
- Brandy . . . 9.12.2
- Bread Baking . . . 9.9.6
- Bricks And Related Clay Products . . . 11.3
- Bulk Material Analysis Procedures . . . App. C.2
- Bulk Material Sampling Procedures . . . App. C.1
- Burners, Conical (Teepee) . . . 2.7
- Burning, Open . . . 2.5
- Burning, Prescribed, And Wildfires . . . 13.1
- Business Machines, Plastic Parts Coating . . . 4.2.2.14
- Butadiene . . . 6.19

- Calcium Carbide Manufacturing . . . 11.4
- Can Coating . . . 4.2.2.2
- Cane Sugar Processing . . . 9.10.1.1
- Canned Fruits And Vegetables . . . 9.8.1
- Carbon Black . . . 6.1
- Carbonate
  - Sodium Carbonate Manufacturing . . . 8.12
- Cattle Feedlots . . . 9.4.1
- Cement
  - Portland Cement Manufacturing . . . 11.6
- Ceramic Clay Manufacturing . . . 11.7
- Cereal Breakfast Food . . . 9.9.2
- Charcoal . . . 10.7
- Cheese, Natural And Processed . . . 9.6.1
- Chemical Wood Pulping . . . 10.2
- Chemicals, Inorganic . . . 8.0
- Chemicals, Organic . . . 6.0
- Chlor-Alkali . . . 8.11
- Clay
  - Bricks And Related Clay Products . . . 11.3
  - Ceramic Clay Manufacturing . . . 11.7
  - Clay And Fly Ash Sintering . . . 11.8
  - Clay Processing . . . 11.25

Cleaning
  Coal 11.10
  Drum 4.8
  Dry Cleaning 4.1
  Tank 4.8
Coal
  Anthracite Combustion 1.2
  Bituminous Combustion 1.1
  Cleaning 11.10
  Conversion 11.11
  Subbituminous Combustion 1.1
  Surface Mining, Western 11.9
Coating, Surface 4.2
  Appliance, Large 4.2.2.11
  Automobile And Light Duty Truck 4.2.2.8
  Can 4.2.2.2
  Fabric 4.2.2.7
  Flat Wood Interior Panel 4.2.2.5
  Labels, Pressure Sensitive 4.2.2.9
  Magnet Wire 4.2.2.3
  Magnetic Tape 4.2.2.13
  Metal Coil 4.2.2.10
  Metal Furniture 4.2.2.12
  Metal, General 4.2.2.4
  Paper 4.2.2.6
  Plastic Parts For Business Machines 4.2.2.14
  Polymeric Coating Of Supporting Substrates 4.2.2.7
  Tapes, Pressure Sensitive 4.2.2.9
Coffee Roasting 9.13.2
Coke Manufacturing 12.2
Collection, Waste Water 4.3
Combustion
  Anthracite Coal 1.2
  Bagasse, In Sugar Mills 1.8
  Bituminous Coal 1.1
  Fuel Oil 1.3
  Internal, Mobile . . . . Vol. II
  Internal, Stationary 3.0
  Lignite 1.7
  Liquefied Petroleum Gas 1.5
  Natural Gas 1.4
  Orchard Heaters 9.2.3
  Refuse 2.1
  Residential Fireplaces 1.9
  Residential Wood Stoves 1.10
  Subbituminous Coal 1.1
  Waste Oil 1.11
  Wood Waste In Boilers 1.6
Compressors, Pipeline, Natural Gas Fired 3.2
Concrete Batching 11.12
Confectionery Products 9.10

. . . 2.7
Conical Burners . . . 11.19
Construction Aggregate Processing . . . 13.2.3
Construction Operations, Heavy . . . App. A
Conversion factors, units, etc. – Miscellaneous . . . 13.4
Cooling Towers, Wet . . .
Copper . . . 12.9
  Alloying . . . 12.3
  Smelting, Primary . . . 12.9
  Smelting, Secondary . . . 9.9.7
Corn Wet Milling . . .
Cotton . . . 9.7
  Ginning . . . 9.3.1
  Harvesting . . . 11.19.2
Crushed Stone Processing . . . 6.20
Cumene . . . 8.14
Cyanide, Hydrogen . . .

. . . 9.4.4
Dairy Farms . . . 9.6
Dairy Products . . . 9.13.3
Deep Fat Frying, Snack Chip . . . 4.6
Degreasing, Solvent . . . 9.8.2
Dehydrated Fruits And Vegetables . . . 9.9.4
Dehydration, Alfalfa . . .
Detergents . . . 6.8
  Soap And Detergents . . . 13.3
Detonation, Explosives . . . 11.22
Diatomite Processing . . . 3.3
Diesel Engines, Industrial . . . 3.4
Diesel Engines, Stationary . . . 9.12.3
Distilled And Blended Liquors . . . 4.8
Drum Cleaning . . . 4.1
Dry Cleaning . . . 3.4
Dual Fuel Engines, Stationary . . . App. C.2
Dust Loading Analysis, Surface/Bulk . . . App. C.1
Dust Loading Sampling Procedures, Surface/Bulk . . . 13.2
Dust Sources, Fugitive . . .

. . . 12.19
Electric Arc Welding . . . 3.1
Electric Utility Power Plants, Gas . . . 3.1
Electricity Generators, Stationary Gas Turbine . . . 13.2.5
Erosion, Wind, Industrial . . . 6.21
Ethanol . . . 6.22
Ethyl Benzene . . . 6.23
Ethylene . . . 6.24
Ethylene Dichloride And Vinyl Chloride . . . 6.25
Ethylene Glycol . . . 6.26
Ethylene Oxide . . . 4.0
Evaporation Loss Sources . . . 6.3
Explosives . . . 13.3
Explosives Detonation . . . 1.0
External Combustion Sources . . .

Fabric Coating 4.2.2.7
Fabric Printing, Textile 4.11
Fats, Cooking 9.11
Feedlots
  Cattle 9.4.1
  Dairy Farms 9.4.4
  Poultry Houses 9.4.3
  Swine 9.4.2
Feldspar Processing 11.27
Ferroalloy Production 12.4
Fertilizer Application 9.2.1
Fertilizers
  Ammonium Phosphate 8.5.3
  Phosphate 8.5
Fiberboard, Medium Density 10.6.3
Fiber Manufacturing, Glass 11.13
Fibers, Synthetic 6.9
Fireplaces, Residential 1.9
Fires
  Forest Wildfires And Prescribed Burning 13.1
Fish Processing 9.13.1
Flares, Industrial 13.5
Flat Wood Interior Panel Coating 4.2.2.5
Fly Ash
  Clay And Fly Ash Sintering 11.8
Food And Agricultural Industries 9.0
Food And Kindred Products, Miscellaneous 9.13
  Coffee Roasting 9.13.2
  Fish Processing 9.13.1
  Snack Chip Deep Fat Frying 9.13.3
  Yeast Production 9.13.4
Formaldehyde 6.27
Foundries
  Gray Iron 12.10
  Steel 12.13
Frit Manufacturing 11.14
Fruits, Preserved 9.8
  Canned 9.8.1
  Dehydrated 9.8.2
Fuel Oil Combustion 1.3
Fugitive Dust Sources 13.2
Furniture Surface Coating, Metal 4.2.2.12

Gas Combustion, Liquefied Petroleum 1.5
Gas, Natural
  Combustion 1.4
  Pipeline Compressors 3.2
  Processing 5.3
  Turbines, Electricity-generating 3.1
Gasoline/Diesel Industrial Engines 3.3
Ginning, Cotton 9.7

Glass Fiber Manufacturing 11.13
Glass Manufacturing 11.15
Graphic Arts 4.9
  General Graphic Printing 4.9.1
  Publication Gravure Printing 4.9.2
Glycerine 6.28
Grain
  Alfalfa Dehydration 9.9.4
  Bread Baking 9.9.6
  Cereal Breakfast Food 9.9.2
  Corn Wet Milling 9.9.7
  Elevators And Processes 9.9.1
  Harvesting 9.3.2
  Pasta Manufacturing 9.9.5
  Pet Food 9.9.3
  Processing 9.9
Gravel Processing 11.19.1
Gray Iron Foundries 12.10
Growing Operations 9.2
Gypsum Manufacturing 11.16

Harvesting Operations 9.3
  Cotton Harvesting 9.3.1
  Grain Harvesting 9.3.2
  Rice Harvesting 9.3.3
  Sugar Cane Harvesting 9.3.4
Heaters, Orchard 9.2.3
Highway Vehicles Vol. II
Hot Mix Asphalt Plants 11.1
Hydrochloric Acid 8.6
Hydrofluoric Acid 8.7
Hydrogen Cyanide 8.14

Incineration
  Automobile Body 2.6
  Medical Waste 2.3
  Open Burning 2.5
  Sewage Sludge 2.2
Industrial Engines, Gasoline And Diesel 3.3
Industrial Flares 13.5
Industrial Surface Coating 4.2.2
Industrial Surface Coating, General 4.2.2.1
Industrial Wind Erosion 13.2.5
Ink, Printing 6.7
Inorganic Chemical Industry 8.0
Interior Panel Coating, Flat Wood 4.2.2.5
Internal Combustion Engines
  Highway Vehicle Vol. II
  Off-highway Mobile Vol. II
  Off-highway Stationary 3.0

Iron
  Gray Iron Foundries . . . 12.10
  Iron Production . . . 12.5
Isopropyl Alcohol . . . 6.29

Labels, Pressure Sensitive . . . 4.2.2.9
Landfills . . . 2.4
Large Bore Engines . . . 3.4
Lead
  Ore Crushing And Grinding . . . 12.18
  Processing, Secondary . . . 12.11
  Products, Miscellaneous . . . 12.17
  Smelting, Primary . . . 12.6
Lead Alkyl . . . 6.12
Lead Oxide Production . . . 12.16
Lead Pigment Production . . . 12.16
Leadbearing Ore Crushing And Grinding . . . 12.18
Leather Tanning . . . 9.15
Light Duty Truck Surface Coating . . . 4.2.2.8
Lightweight Aggregate Manufacturing . . . 11.20
Lignite Combustion . . . 1.7
Lime Manufacturing . . . 11.17
Liquefied Petroleum Gas Combustion . . . 1.5
Liquid Storage Tanks . . . 7.0
Livestock Feed Operations . . . 9.4
Lumber . . . 10.1

Magnesium, Secondary Smelting . . . 12.12
Magnet Wire Coating . . . 4.2.2.3
Magnetic Tape Manufacturing . . . 4.2.2.13
Maleic Anhydride . . . 6.14
Malt Beverages . . . 9.12.1
Manure Processing . . . 9.5.4
Marketing, Petroleum Liquids . . . 5.2
Meat Packing Plants . . . 9.5.1
Meat Products Preparation . . . 9.5
Meat Rendering Plants . . . 9.5.3
Meat Smokehouses . . . 9.5.2
Medical Waste Incineration . . . 2.3
Metal Coating, General . . . 4.2.2.4
Metal Coil Surface Coating . . . 4.2.2.10
Metal Furniture Surface Coating . . . 4.2.2.12
Metallic Minerals Processing . . . 11.24
Metallurgical Industry . . . 12.0
Methanol . . . 6.15
Mineral Products Industry . . . 11.0
Mineral Wool Manufacturing . . . 11.18
Minerals Processing, Metallic . . . 11.24
Mining, Western Surface Coal . . . 11.9
Miscellaneous Sources . . . 13.0

Mobile Sources
  Highway . . . Vol. II
  Off-highway . . . Vol. II

Natural And Processed Cheese . . . 9.6.1
Natural Gas Combustion . . . 1.4
Natural Gas Fired Pipeline Compressors . . . 3.2
Natural Gas Processing . . . 5.3
Nitric Acid Manufacturing . . . 8.8
Nonindustrial Surface Coating . . . 4.2.1
Normal Superphosphates . . . 8.5.1
Nuts And Seeds, Salted And Roasted . . . 9.10.2
  Almond Processing . . . 9.10.2.1
  Peanut Processing . . . 9.10.2.2

Off-highway Mobile Sources . . . Vol. II
Off-highway Stationary Sources . . . 3.0
Oil
  Fuel Oil Combustion . . . 1.3
  Waste Oil Combustion . . . 1.11
Oils, Cooking . . . 9.11
  Vegetable Oil Processing . . . 9.11.1
Open Burning . . . 2.5
Orchard Heaters . . . 9.2.3
Ore Processing
  Leadbearing Ore Crushing And Grinding . . . 12.18
  Taconite . . . 11.23
Organic Chemical Process Industry . . . 6.0
Organic Liquid Storage Tanks . . . 7.1
Oriented Strand Board . . . 10.6.1

Paint And Varnish . . . 6.4
Panel Coating, Flat Wood Interior . . . 4.2.2.5
Paper Coating . . . 4.2.2.6
Papermaking . . . 10.4
Particleboard . . . 10.6.2
Particle size distribution data, factors, generalized . . . App. B.2
Particle size distribution data, factors, selected . . . App. B.1
Pasta Manufacturing . . . 9.9.5
Paved Roads . . . 13.2.1
Paving, Asphalt . . . 4.5
Peanut Processing . . . 9.10.2.2
Perlite Manufacturing . . . 11.30
Pesticide Application . . . 9.2.2
Pet Food . . . 9.9.3
Petroleum
  Liquefied Petroleum Gas Combustion . . . 1.5
  Liquids, Transportation And Marketing . . . 5.2
  Refining . . . 5.1
  Storage Of Organic Liquids . . . 7.1
Petroleum Industry . . . 5.0

Pharmaceuticals Production 6.13
Phenol 6.16
Phosphate, Ammonium 8.5.3
Phosphate Fertilizers 8.5
Phosphate Rock Processing 11.21
Phosphoric Acid 8.9
Phthalic Anhydride 6.5
Pickles 9.8.3
Pigment
  Lead Oxide And Pigment Production 12.16
Pipeline Compressors, Natural Gas Fired 3.2
Plastic Part Surface Coating, Business Machine 4.2.2.14
Plastics 6.6
Plywood 10.5
Polyester Resin Plastic Products Fabrication 4.4
Poly(ethylene terephthalate) 6.6.2
Polymeric Coating Of Supporting Substrates 4.2.2.7
Polypropylene 6.6.4
Polystyrene 6.6.3
Polyvinyl Chloride 6.6.1
Portland Cement Manufacturing 11.6
Poultry Feed Operations 9.4
Poultry Houses 9.4.3
Poultry Slaughtering 9.5.5
Prescribed Burning, Wildfires And 13.1
Preserved Fruits And Vegetables 9.8
Preserving, Wood 10.8
Printing, General Graphic 4.9.1
Printing, Publication Gravure 4.9.2
Printing, Textile Fabric 4.11
Printing Ink 6.7
Processed Cheese 9.6.1
Propylene 6.17
Pulp Bleaching, Wood 10.3
Pulping, Chemical Wood 10.2

Reclamation, Waste Solvent 4.7
Reconstituted Wood Products 10.6
Recovery, Sulfur 8.13
Refining, Petroleum 5.1
Refractory Manufacturing 11.5
Refuse Combustion 2.1
Rendering Plants, Meat 9.5.3
Residential Fireplaces 1.9
Resin, Polyester, Plastic Product Fabrication 4.4
Rice Harvesting 9.3.3
Roads
  Paved 13.2.1
  Unpaved 13.2.2
Roasted Nuts And Seeds 9.10.2
Roasting, Coffee 9.13.2

Rock Processing, Phosphate 11.21
Roofing, Asphalt 11.2
Rubber, Synthetic 6.10

Salad Dressings 9.8.3
Salted And Roasted Nuts And Seeds 9.10.2
  Almond Processing 9.10.2.1
  Peanut Processing 9.10.2.2
Sampling, Surface/Bulk Loading App. C.1
Sand And Gravel Processing 11.19.1
Sauces 9.8.3
Seeds, Salted And Roasted 9.10.2
Sewage Sludge Incineration 2.2
Sized emission factors, generalized App. B.2
Sized emission factors, selected App. B.1
Smelting
  Primary Copper 12.3
  Primary Lead 12.6
  Secondary Copper Smelting And Alloying 12.9
  Secondary Magnesium 12.12
  Zinc 12.7
Smokehouses, Meat 9.5.2
Snack Chip Deep Fat Frying 9.13.3
Soap And Detergent Manufacturing 6.8
Sodium Carbonate Manufacturing 8.12
Solid Waste Disposal 2.0
Solvent
  Commercial/Consumer Use 4.10
  Degreasing 4.6
  Waste, Reclamation 4.7
Stationary Gas Turbines 3.1
Stationary Internal Combustion Sources, Off-highway 3.0
Steel
  Foundries 12.13
  Production 12.5
Stone Processing, Crushed 11.19.2
Storage, Waste Water 4.3
Storage Battery Production 12.15
Storage Piles, Aggregate 13.2.4
Storage Tanks, Liquid 7.0
  Organic Liquid Storage Tanks 7.1
Subbituminous Coal Combustion 1.1
Substrates, Supporting, Polymeric Coating Of 4.2.2.7
Sugar Harvesting, Cane 9.3.4
Sugar Mills, Bagasse Combustion In 1.8
Sugar Processing 9.10.1
Sugar Processing, Beet 9.10.1.2
Sugar Processing, Cane 9.10.1.1
Sulfur Recovery 8.13
Sulfuric Acid 8.10
Surface/Bulk Dust Loading Analysis App. C.2

Surface/Bulk Dust Loading Sampling Procedures . . . . App. C.1
Surface Coal Mining, Western 11.9
Surface Coating 4.2
Surface Coating, Industrial 4.2.2
Surface Coating, Nonindustrial 4.2.1
Surface Material Analysis Procedures . . . . App. C.2
Surface Material Sampling Procedures . . . . App. C.1
Swine Feedlots 9.4.2
Synthetic Ammonia 8.1
Synthetic Fibers 6.9
Synthetic Rubber 6.10

Taconite Ore Processing 11.23
Talc Processing 11.26
Tank And Drum Cleaning 4.8
Tape, Magnetic, Manufacturing 4.2.2.13
Tapes And Labels, Pressure Sensitive 4.2.2.9
Teepee (Conical) Burners 2.7
Terephthalic Acid 6.11
Textile Fabric Printing 4.11
Tilling Operations 9.1
Tobacco Products 9.14
Toluene 6.18
Transportation And Marketing Of Petroleum Liquids 5.2
Treatment, Waste Water 4.3
Triple Superphosphates 8.5.2
Truck, Light Duty, Surface Coating, ... 4.2.2.8
Turbines, Natural Gas Fired 3.1

Unpaved Roads 13.2.2
Urea 8.2

Varnish
  Paint And Varnish Manufacturing 6.4
Vegetable Oil Processing 9.11.1
Vegetables, Canned 9.8.1
Vegetables, Dehydrated 9.8.2
Vegetables, Preserved 9.8
Vehicles, Highway And Off-highway . . . . Vol. II
Vermiculite Processing 11.28
Vinyl Chloride 6.24

Waferboard 10.6.1
Waste Disposal, Solid 2.0
Waste Oil Combustion 1.11
Waste Solvent Reclamation 4.7
Waste Water Collection, Treatment and Storage 4.3
Welding, Electric Arc 12.19
Wet Cooling Towers 13.4
Wet Milling, Corn 9.9.7
Wildfires 13.1

Wind Erosion
  Agricultural 9.16
  Industrial 13.2.5
Wines 9.12.2
Wire Coating, Magnet 4.2.2.3
Wood
  Charcoal 10.7
  Flat Interior Panel Coating 4.2.2.5
  Lumber 10.1
  Medium Density Fiberboard 10.6.3
  Oriented Strand Board 10.6.1
  Papermaking 10.4
  Particleboard 10.6.2
  Plywood 10.5
  Pulp Bleaching 10.3
  Pulping, Chemical 10.2
  Reconstituted Wood Products 10.6
  Stoves 1.10
  Waferboard 10.6.1
  Waste Combustion In Boilers 1.6
  Wood Preserving 10.8
Wood Products Industry 10.0

Xylenes 6.18

Yeast Production 9.13.4

Zinc
  Processing, Secondary 12.14
  Smelting 12.7

INTRODUCTION

Emission factors and emission inventories have long been fundamental tools for air quality management. Emission estimates are important for developing emission control strategies, determining applicability of permitting and control programs, ascertaining the effects of sources and appropriate mitigation strategies, and a number of other related applications by an array of users, including federal, state, and local agencies, consultants, and industry. Data from source-specific emission tests or continuous emission monitors are usually preferred for estimating a source's emissions because those data provide the best representation of the tested source's emissions. However, test data from individual sources are not always available and, even then, they may not reflect the variability of actual emissions over time. Thus, emission factors are frequently the best or only method available for estimating emissions, in spite of their limitations.

The passage of the *Clean Air Act Amendments Of 1990* (*CAAA*) and the *Emergency Planning And Community Right-To-Know Act* (*EPCRA*) of 1986 has increased the need for both criteria and Hazardous air pollutant (HAP) emission factors and inventories. The Emission Factor And Inventory Group (EFIG), in the U. S. Environmental Protection Agency's (EPA) Office Of Air Quality Planning And Standards (OAQPS), develops and maintains emission estimating tools to support the many activities mentioned above. The AP-42 series is the principal means by which EFIG can document its emission factors. These factors are cited in numerous other EPA publications and electronic data bases, but without the process details and supporting reference material provided in AP-42.

What Is An AP-42 Emission Factor?

An emission factor is a <u>representative value</u> that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e. g., kilograms of particulate emitted per megagram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i. e., a population average).

The general equation for emission estimation is:

$$E = A \times EF \times (1 - ER/100)$$

where:

E = emissions,
A = activity rate,
EF = emission factor, and
ER = overall emission reduction efficiency, %.

ER is further defined as the product of the control device destruction or removal efficiency and the capture efficiency of the control system. When estimating emissions for a long time period

(e. g., one year), both the device and the capture efficiency terms should account for upset periods as well as routine operations.

Emission factor ratings in AP-42 (discussed below) provide indications of the robustness, or appropriateness, of emission factors for estimating average emissions for a source activity. Usually, data are insufficient to indicate the influence of various process parameters such as temperature and reactant concentrations. For a few cases, however, such as in estimating emissions from petroleum storage tanks, this document contains empirical formulae (or emission models) that relate emissions to variables such as tank diameter, liquid temperature, and wind velocity. Emission factor formulae that account for the influence of such variables tend to yield more realistic estimates than would factors that do not consider those parameters.

The extent of completeness and detail of the emissions information in AP-42 is determined by the information available from published references. Emissions from some processes are better documented than others. For example, several emission factors may be listed for the production of one substance: one factor for each of a number of steps in the production process such as neutralization, drying, distillation, and other operations. However, because of less extensive information, only one emission factor may be given for production facility releases for another substance, though emissions are probably produced during several intermediate steps. There may be more than one emission factor for the production of a certain substance because differing production processes may exist, or because different control devices may be used. Therefore, it is necessary to look at more than just the emission factor for a particular application and to observe details in the text and in table footnotes.

The fact that an emission factor for a pollutant or process is not available from EPA does not imply that the Agency believes the source does not emit that pollutant or that the source should not be inventoried, but it is only that EPA does not have enough data to provide any advice.

Uses Of Emission Factors

Emission factors may be appropriate to use in a number of situations such as making source-specific emission estimates for areawide inventories. These inventories have many purposes including ambient dispersion modeling and analysis, control strategy development, and in screening sources for compliance investigations. Emission factor use may also be appropriate in some permitting applications, such as in applicability determinations and in establishing operating permit fees.

Emission factors in AP-42 are neither EPA-recommended emission limits (e. g., best available control technology or BACT, or lowest achievable emission rate or LAER) nor standards (e. g., National Emission Standard for Hazardous Air Pollutants or NESHAP, or New Source Performance Standards or NSPS). Use of these factors as source-specific permit limits and/or as emission regulation compliance determinations is not recommended by EPA. Because emission factors essentially represent an average of a range of emission rates, approximately half of the subject sources will have emission rates greater than the emission factor and the other half will have emission rates less than the factor. As such, a permit limit using an AP-42 emission factor would result in half of the sources being in noncompliance.

Also, for some sources, emission factors may be presented for facilities having air pollution control equipment in place. Factors noted as being influenced by control technology do not necessarily reflect the best available or state-of-the-art controls, but rather reflect the level of (typical) control for which data were available at the time the information was published. Sources often are tested more frequently when they are new and when they are believed to be operating properly, and either situation may bias the results.

As stated, source-specific tests or continuous emission monitors can determine the actual pollutant contribution from an existing source better than can emission factors. Even then, the results will be applicable only to the conditions existing at the time of the testing or monitoring. To provide the best estimate of longer-term (e. g., yearly or typical day) emissions, these conditions should be representative of the source's routine operations.

A material balance approach also may provide reliable average emission estimates for specific sources. For some sources, a material balance may provide a better estimate of emissions than emission tests would. In general, material balances are appropriate for use in situations where a high percentage of material is lost to the atmosphere (e. g., sulfur in fuel, or solvent loss in an uncontrolled coating process.) In contrast, material balances may be inappropriate where material is consumed or chemically combined in the process, or where losses to the atmosphere are a small portion of the total process throughput. As the term implies, one needs to account for all the materials going into and coming out of the process for such an emission estimation to be credible.

If representative source-specific data cannot be obtained, emissions information from equipment vendors, particularly emission performance guarantees or actual test data from similar equipment, is a better source of information for permitting decisions than an AP-42 emission factor. When such information is not available, use of emission factors may be necessary as a last resort. Whenever factors are used, one should be aware of their limitations in accurately representing a particular facility, and the risks of using emission factors in such situations should be evaluated against the costs of further testing or analyses.

Figure 1 depicts various approaches to emission estimation, in a hierarchy of requirements and levels of sophistication, that one should consider when analyzing the tradeoffs between cost of the estimates and the quality of the resulting estimates. Where risks of either adverse environmental effects or adverse regulatory outcomes are high, more sophisticated and more costly emission determination methods may be necessary. Where the risks of using a poor estimate are low, and the costs of more extensive methods are unattractive, then less expensive estimation methods such as emission factors and emission models may be both satisfactory and appropriate. In cases where no emission factors are available but adverse risk is low, it may even be acceptable to apply factors from similar source categories using engineering judgment. Selecting the method to be used to estimate source-specific emissions may warrant a case-by-case analysis considering the costs and risks in the specific situation. All sources and regulatory agencies should be aware of these risks and costs and should assess them accordingly.

Variability Of Emissions

Average emissions differ significantly from source to source and, therefore, emission factors frequently may not provide adequate estimates of the average emissions for a specific source. The extent of between-source variability that exists, even among similar individual sources, can be large depending on process, control system, and pollutant. Although the causes of this variability are considered in emission factor development, this type of information is seldom included in emission test reports used to develop AP-42 factors. As a result, some emission factors are derived from tests that may vary by an order of magnitude or more. Even when the major process variables are accounted for, the emission factors developed may be the result of averaging source tests that differ by factors of five or more.

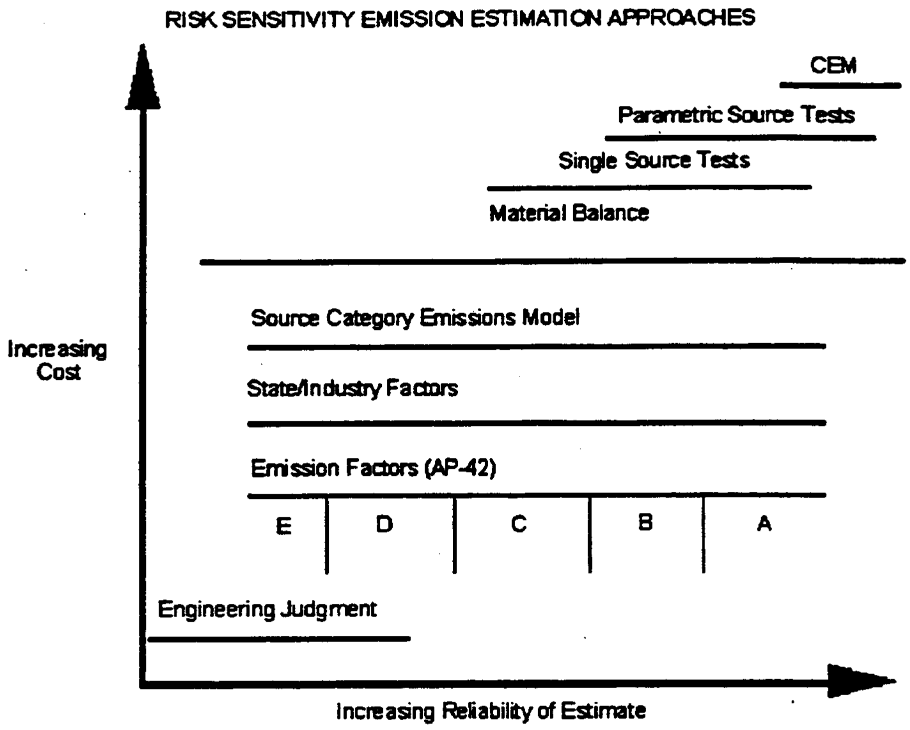

Figure 1. Approach to emission estimation.

Air pollution control devices also may cause differing emission characteristics. The design criteria of air pollution control equipment affect the resulting emissions. Design criteria include such items as the type of wet scrubber used, the pressure drop across a scrubber, the plate area of an electrostatic precipitator, and the alkali feed rate to an acid gas scrubber. Often, design criteria are not included in emission test reports (at least not in a form conducive to detailed analysis of how varying process parameters can affect emissions) and therefore may not be accounted for in the resulting factors.

Before simply applying AP-42 emission factors to predict emissions from new or proposed sources, or to make other source-specific emission assessments, the user should review the latest literature and technology to be aware of circumstances that might cause such sources to exhibit emission characteristics different from those of other, typical existing sources. Care should be taken to assure that the subject source type and design, controls, and raw material input are those of the source(s) analyzed to produce the emission factor. This fact should be considered, as well as the age of the information and the user's knowledge of technology advances.

Estimates of short-term or peak (e. g., daily or hourly) emissions for specific sources are often needed for regulatory purposes. Using emission factors to estimate short-term emissions will add further uncertainty to the emission estimate. Short-term emissions from a single specific source often vary significantly with time (i. e., within-source variability) because of fluctuations in process operating conditions, control device operating conditions, raw materials, ambient conditions, and other such factors. Emission factors generally are developed to represent long-term average emissions, so testing is usually conducted at normal operating conditions. Parameters that can cause short-term fluctuations in emissions are generally avoided in testing and are not taken into account in test evaluation. Thus, using emission factors to estimate short-term emissions will cause even greater uncertainty. The AP-42 user should be aware of this limitation and should evaluate the possible effects on the particular application.

To assess within-source variability and the range of short-term emissions from a source, one needs either a number of tests performed over an extended period of time or continuous monitoring data from an individual source. Generally, material balance data are not likely to be sufficient for assessing short-term emission variability because the accuracy of a material balance is greatly reduced for shorter time intervals. In fact, one of the advantages of a material balance approach is that it averages out all of the short-term fluctuations to provide a good long-term average.

Pollutant Terminology And Conventions

The need for clearly and precisely defined terms in AP-42 should be evident to all. The factors in this document represent units of pollutants (or for ozone, precursors) for which there are National Ambient Air Quality Standards (NAAQS). These are often referred to as "criteria" pollutants. Factors may be presented also for HAPs ("hazardous" air pollutants designated in the *Clean Air Act*) and for other "regulated" and unregulated air pollutants. If the pollutants are organic compounds or particulate matter, additional species or analytical information may be needed for specific applications. It is often the case that the ideal measure of a pollutant for a specific application may not be available, or even possible, because of test method or data limitations, costs, or other problems. When such qualifications exist in AP-42, they will be noted in the document. If a pollutant is not mentioned in AP-42, that does not necessarily mean that the pollutant is not emitted.

Many pollutants are defined by their chemical names, which often may have synonyms and trade names. Trade names are often given to mixtures to obscure proprietary information, and the same components may have several trade names. For assurance of the use of the proper chemical identification, the Chemical Abstract Service (CAS) number for the chemical should be consulted along with the list of synonyms. Some pollutants, however, follow particular conventions when used in air quality management practices. The pollutant terminology and conventions currently used in AP-42 are discussed below.

Particulate Matter -

Terms commonly associated with the general pollutant, "particulate matter" (PM), include PM-10, PM-X, total particulate, total suspended particulate (TSP), primary particulate, secondary particulate, filterable particulate, and condensable particulate. TSP consists of matter emitted from sources as solid, liquid, and vapor forms, but existing in the ambient air as particulate solids or liquids. Primary particulate matter includes that solid, liquid, or gaseous material at the pressure and temperature in the process or stack that would be expected to become a particulate at ambient temperature and pressure. AP-42 contains emission factors for pollutants that are expected to be primary particulate matter. Primary particulate matter includes matter that may eventually revert to a gaseous condition in the ambient air, but it does not include secondary particulate matter. Secondary particulate matter is gaseous matter that may eventually convert to particulate matter through atmospheric chemical reactions. The term "total particulate" is used in AP-42 only to describe the emissions that are primary particulate matter. The term "Total PM-X" is used in AP-42 to describe those emissions expected to become primary particulate matter smaller than "X" micrometers (μm) in aerodynamic diameter. For example, "PM-10" is emitted particulate matter less than 10 μm in diameter. In AP-42, "Total Particulate" and "Total PM-X" may be divided into "Filterable Particulate", "Filterable PM-X", "Condensable Organic Particulate", and "Condensable Inorganic Particulate". The filterable portions include that material that is smaller than the stated size and is collected on the filter of the particulate sampling train.

Unless noted, it is reasonable to assume that the emission factors in AP-42 for processes that operate above ambient temperatures are for filterable particulate, as defined by EPA Method 5 or its equivalent (a filter temperature of 121°C (250°F). The condensable portions of the particulate matter consist of vaporous matter at the filter temperature that is collected in the sampling train impingers and is analyzed by EPA Method 202 or its equivalent. AP-42 follows conventions in attempts to define Total Particulate and its subcomponents, filterable particulate, condensable particulate, and PM-10 and their interrelationships. Because of test method and data limitations, this attempt may not always be successful, and some sources may not generate such components.

Because emission factors in AP-42 are usually based upon the results of emission test reports, and because Method 202 was only recently developed, AP-42 emission factors often may adequately characterize only in-stack filterable PM-10. Recent parts of the AP-42 series have used a clearer nomenclature for the various particulate fractions. It is reasonable to assume that, where AP-42 does not define the components of particulate clearly and specifically, the PM-10 factor includes only the filterable portion of the total PM-10. Therefore, an evaluation of potential condensable particulate emissions should be based upon additional data or engineering judgment.

As an additional convention, users should note that many hazardous or toxic compounds may be emitted in particulate form. In such cases, AP-42 factors for particulate matter represent the total, and factors for such compounds or elements are reported as mass of that material.

Organic Compounds -

Precursors of the criteria pollutant "ozone" include organic compounds. "Volatile organic compounds" (VOC) are required in a State Implementation Plan (SIP) emission inventory. VOCs have been defined by EPA (40 CFR 51.100, February 3, 1992) as "any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric chemical reactions". There are a number of compounds deemed to have "negligible photochemical reactivity", and these are therefore exempt from the definition of VOC. These exempt compounds include methane, ethane, methylene chloride, methyl chloroform, many chlorofluorocarbons, and certain classes of perfluorocarbons. Additional compounds may be added to the exempt list in the future.

Though the regulatory definition of VOC is followed in ozone control programs, the exempt organic compounds are of concern when developing the complete emission inventory that is needed for broader applications. Therefore, this document strives to report the total organic emissions and component species, so that the user may choose those that are necessary for a particular application. In many cases, data are not available to identify and quantify either all the components (such as some oxygenated compounds that are not completely measured by many common test methods), the total organics, or other variations of the quantities desired. In such cases, the available information is annotated in an effort to provide the data to the user in a clear and unambiguous manner. It is not always possible to present a complete picture with the data that are available.

The term "total organic compounds" (TOC) is used in AP-42 to indicate all VOCs and all exempted organic compounds including methane, ethane, chlorofluorocarbons, toxics and HAPs, aldehydes, and semivolatile compounds. Component species are separately identified and quantified, if data are available, and these component species are included in TOCs. Often, a test method will produce a data set that excludes methane. In such cases, the term total nonmethane organic compound (TNMOC) may be used. Here, methane will be separately quantified if the data are available. Factors are nominally given in terms of actual weight of the emitted substance. However, in some cases where data do not allow calculation of the result in this form, factors may be given "as methane", "as propane", etc. Once the species distribution is determined, actual mass can be calculated based on molecular weight of each compound represented. In an AP-42 table giving organic emission factors, the ideal table headings would be:

TOC	Methane	Ethane	VOC	Other Species

Many organic compounds are also HAPs. Where such species can be quantified, an emission factor representing their individual mass will be presented. This quantity will also be included in the total VOC and/or TOC factors, as appropriate. To avoid double counting regarding permit fees, etc., this fact should be taken into consideration.

Sulfur Dioxide -

The primary product from combustion of sulfur is sulfur dioxide, SO_2. However, other oxidation states are usually formed. When reported in this document, these compounds are jointly referred to as SO_x, or oxides of sulfur. SO_2 means sulfur dioxide, and SO_x means the combination of all such emissions reported on the basis of the molecular weight of SO_2.

Oxides Of Nitrogen -

The primary combustion product of nitrogen is nitrogen dioxide, NO_2. However, several other nitrogen compounds are usually emitted at the same time (nitric oxide or NO, nitrous oxide or N_2O, etc.), and these may or may not be distinguishable in available test data. They are usually in a rapid state of flux, with NO_2 being, in the short term, the ultimate product emitted or formed shortly downstream of the stack. The convention followed in AP-42 is to report the distinctions wherever possible, but to report total NO_x on the basis of the molecular weight of NO_2.

Lead -

Lead is emitted and measured as particulate and often will be reported for a process both separately and as a component of the particulate matter emission factor. The lead may exist as pure metal or as compounds. The convention followed in AP-42 is that all emissions of lead are expressed as the weight of the elemental lead. Lead compounds will also be reported on the basis of the weight of those compounds if the information is available.

Toxic, Hazardous, And Other Noncriteria Pollutants -

Hazardous Air Pollutants are defined for EPA regulatory purposes in Title III of the *CAAA*. However, many states and other authorities designate additional toxic or hazardous compounds, organic or inorganic, that can exist in gaseous or particulate form. Also, as mentioned, compounds emitted as VOCs may be of interest for their participation in photochemical reactivity. Few EPA Reference Test Methods exist for these compounds, which may come from the myriad sources covered in this document. However, test methods are available to allow reasonably reliable quantification of many compounds, and adequate test results are available to yield estimates of sufficient quality to be included in this document. Where such compounds are quantified herein with emission factors, they represent the actual mass of that compound emitted. Totals for PM or VOC, as appropriate, are inclusive of the component species unless otherwise noted. There are a limited number of gaseous hazardous or toxic compounds that may not be VOCs, and whenever they occur they will be identified separately.

The Emission Factor And Inventory Group produces a separate series of reports that focus on a number of the more significant HAPs and related sources. Titles of these documents generally follow the format of *Locating And Estimating Emissions From Sources Of . . . (Substance)*.

Examples Of Emission Factor Application -

Calculating carbon monoxide (CO) emissions from distillate oil combustion serves as an example of the simplest use of emission factors. Consider an industrial boiler that burns 90,000 liters of distillate oil per day. In Section 1.3 of AP-42, "Fuel Oil Combustion", the CO emission factor for industrial boilers burning distillate oil is 0.6 kilograms (kg) CO per 10^3 liters of oil burned.

Then CO emissions

= CO emission factor x distillate oil burned/day
= 0.6 x 90
= <u>54 kg/day</u>

In a more complex case, suppose a sulfuric acid (H_2SO_4) plant produces 200 Mg of 100 percent H_2SO_4 per day by converting sulfur dioxide (SO_2) into sulfur trioxide (SO_3) at 97.5 percent efficiency. In Section 8.10, "Sulfuric Acid", the SO_2 emission factors are listed according to SO_2-to-SO_3 conversion efficiencies in whole numbers. The reader is directed by footnote to an interpolation formula that may be used to obtain the emission factor for 97.5 percent SO_2-to-SO_3 conversion.

The emission factor for kg SO_2/Mg 100% H_2SO_4

= 682 - [(6.82)(% SO_2-to-SO_3 conversion)]
= 682 - [6.82)(97.5)]
= 682 - 665
= <u>17 kg</u>

In the production of 200 Mg of 100 percent H_2SO_4 per day, SO_2 emissions are calculated thus:

SO_2 emissions
= 17 kg SO_2 emissions/Mg 100 percent H_2SO_4 x 200 Mg 100 percent H_2SO_4/day
= <u>3400 kg/day</u>

Emission Factor Ratings

Each AP-42 emission factor is given a rating from A through E, with A being the best. A factor's rating is a general indication of the reliability, or robustness, of that factor. This rating is assigned based on the estimated reliability of the tests used to develop the factor and on both the amount and the representative characteristics of those data. In general, factors based on many observations, or on more widely accepted test procedures, are assigned higher rankings. Conversely, a factor based on a single observation of questionable quality, or one extrapolated from another factor for a similar process, would probably be rated much lower. Because ratings are subjective and only indirectly consider the inherent scatter among the data used to calculate factors, the ratings should be seen only as approximations. AP-42 factor ratings do not imply statistical error bounds or confidence intervals about each emission factor. At most, a rating should be considered an <u>indicator</u> of the accuracy and precision of a given factor being used to estimate emissions from a large number of sources. This indicator is largely a reflection of the professional judgment of AP-42 authors and reviewers concerning the reliability of any estimates derived with these factors.

Because emission factors can be based on source tests, modeling, mass balance, or other information, factor ratings can vary greatly. Some factors have been through more rigorous quality assurance than others.

Two steps are involved in factor rating determination. The first step is an appraisal of data quality, the reliability of the basic emission data that will be used to develop the factor. The second step is an appraisal of the ability of the factor to stand as a national annual average emission factor for that source activity.

Test data quality is rated A through D, and ratings are thus assigned:

A = Tests are performed by a sound methodology and are reported in enough detail for adequate validation.
B = Tests are performed by a generally sound methodology, but lacking enough detail for adequate validation.
C = Tests are based on an unproven or new methodology, or are lacking a significant amount of background information.
D = Tests are based on a generally unacceptable method, but the method may provide an order-of-magnitude value for the source.

The quality rating of AP-42 data helps identify good data, even when it is not possible to extract a factor representative of a typical source in the category from those data. For example, the data from a given test may be good enough for a data quality rating of "A", but the test may be for a unique feed material, or the production specifications may be either more or less stringent than at the typical facility.

The AP-42 emission factor rating is an overall assessment of how good a factor is, based on both the quality of the test(s) or information that is the source of the factor and on how well the factor represents the emission source. Higher ratings are for factors based on many unbiased observations, or on widely accepted test procedures. For example, ten or more source tests on different randomly selected plants would likely be assigned an "A" rating if all tests are conducted using a single valid reference measurement method. Likewise, a single observation based on questionable methods of testing would be assigned an "E", and a factor extrapolated from higher-rated factors for similar processes would be assigned a "D" or an "E".

AP-42 emission factor quality ratings are thus assigned:

A — Excellent. Factor is developed from A- and B-rated source test data taken from many randomly chosen facilities in the industry population. The source category population is sufficiently specific to minimize variability.

B — Above average. Factor is developed from A- or B-rated test data from a "reasonable number" of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with an A rating, the source category population is sufficiently specific to minimize variability.

C — Average. Factor is developed from A-, B-, and/or C-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. As with the A rating, the source category population is sufficiently specific to minimize variability.

D — Below average. Factor is developed from A-, B- and/or C-rated test data from a small number of facilities, and there may be reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source population.

E — Poor. Factor is developed from C- and D-rated test data, and there may be reason to suspect that the facilities tested do not represent a random sample of the industry. There also may be evidence of variability within the source category population.

Public Review Of Emission Factors

Since AP-42 emission factors may have effects on most aspects of air pollution control and air quality management including operating permit fees, compliance assessments, and SIP attainment emission inventories, these factors are always made available for public review and comment before publication. The Emission Factor And Inventory Group panel of public and peer reviewers includes representatives of affected industries, state and local air pollution agencies, and environmental groups. More information on AP-42 review procedures is available in the document, *Public Participation Procedures For EPA's Emission Estimation Guidance Materials*, EPA-454/R-94-022, July 1994. This publication is available on EFIG's *CHIEF* (Clearinghouse For Inventories And Emission Factors) electronic bulletin board (BB) and its *Fax CHIEF*, an automated facsimile machine. It is also available in conventional paper copy from the National Technical Information Service (NTIS). The Agency encourages all interested parties to take every opportunity to review factors and to provide information for factor quality improvement. Toward this objective, EFIG invites comments and questions about AP-42, and users are invited to submit any data or other information in accordance with this procedures document.

Other Ways To Obtain AP-42 Information And Updates

All or part of AP-42 can be downloaded either from the *CHIEF* BB or *Fax CHIEF*, and it is available on the *Air CHIEF* CD-ROM (Compact Disc - Read Only Memory). AP-42 is available in conventional paper copy from the Government Printing Office and NTIS, as well as through the *Fax CHIEF*.

The emission factors contained in AP-42 are available in the *Factor Information Retrieval System (FIRE)*. Also, software has been developed for emission models such as *TANKS*, *WATER7*, the *Surface Impoundment Modeling System (SIMS)*, and fugitive dust models. This software and the *FIRE* data base are available through the *CHIEF* BB. *FIRE* is also on the *Air CHIEF* compact disc. The *Fax CHIEF* and the *CHIEF* BB will always contain the latest factor information, as they are updated frequently, whereas *Air CHIEF*, the *FIRE* program, and printed AP-42 portions are routinely updated only once per year.

For information or assistance regarding the availability or use of any of these tools and services, an AP-42 telephone help desk, *Info CHIEF*, is available at (919) 541-5285.

1. EXTERNAL COMBUSTION SOURCES

External combustion sources include steam/electric generating plants, industrial boilers, and commercial and domestic combustion units. Coal, fuel oil, and natural gas are the major fossil fuels used by these sources. Liquefied petroleum fuels are also used in relatively small quantities. Coal, oil, and natural gas currently supply about 95 percent of the total thermal energy consumed in the United States. Nationwide consumption in 1980 was over 530 x 10^6 megagrams (585 million tons) of bituminous coal, nearly 3.6 x 10^6 megagrams (4 million tons) of anthracite coal, 91 x 10 liters (24 billion gallons) of distillate oil, 114 x 10^9 liters (37 billion gallons) of residual oil, and 57 x 10^{12} cubic meters (20 trillion cubic feet) of natural gas.

Power generation, process heating, and space heating are some of the largest fuel combustion sources of sulfur oxides, nitrogen oxides, and particulate emissions. The following sections present emission factor data on the major fossil fuels and others.

1.1 Bituminous And Subbituminous Coal Combustion

1.1.1 General

Coal is a complex combination of organic matter and inorganic ash formed over eons from successive layers of fallen vegetation. Coal types are broadly classified as anthracite, bituminous, subbituminous, or lignite. These classifications are based on coal heating value together with relative amounts of fixed carbon, volatile matter, ash, sulfur, and moisture. Formulae and tables for classifying coals are given in Reference 1. See AP-42 Section 1.2 and Section 1.7 for discussions of anthracite and lignite combustion, respectively.

There are three major coal combustion techniques: suspension firing, grate firing, and fluidized bed combustion. Suspension firing is the primary combustion mechanism in pulverized coal and cyclone systems. Grate firing is the primary mechanism in underfeed and overfeed stokers. Both mechanisms are employed in spreader stokers. Fluidized bed combustion, while not constituting a significant percentage of the total boiler population, has nonetheless gained popularity in the last decade and today generates steam for industries, cogenerators, independent power producers, and utilities.

Pulverized coal furnaces are used primarily in utility and large industrial boilers. In these systems, the coal is pulverized in a mill to the consistency of talcum powder (i. e., at least 70 percent of the particles will pass through a 200-mesh sieve). The pulverized coal is generally entrained in primary air before being fed through burners to the furnace, where it is fired in suspension. Pulverized coal furnaces are classified as either dry or wet bottom, depending on the ash removal technique. Dry bottom furnaces fire coals with high ash fusion temperatures and use dry ash removal techniques. In wet bottom (or slag tap) furnaces, coals with low ash fusion temperatures are combusted and molten ash is drained from the bottom of the furnace. Pulverized coal furnaces are further classified by the firing position of the burners, i. e., single (front or rear) wall, horizontally opposed, vertical, tangential (or corner-fired). Wall-fired boilers can be either single wall-fired (with burners on only 1 wall of the furnace firing horizontally) or opposed wall-fired (with burners mounted on two opposing walls). Tangentially fired boilers have burners mounted in the corners of the furnace. The fuel and air are injected toward the center of the furnace to create a vortex that enhances air and fuel mixing.

Cyclone furnaces burn low ash fusion temperature coal which has been crushed to below 4-mesh particle size. The coal is fed tangentially in a stream of primary air to a horizontal cylindrical furnace. Within the furnace, small coal particles are burned in suspension while larger particles are forced against the outer wall. Because of the high temperatures developed in the relatively small furnace volume, and because of the low fusion temperature of the coal ash, much of the ash forms a liquid slag on the furnace walls. The slag drains from the walls to the bottom of the furnace where it is removed through a slag tap opening. Cyclone furnaces are used mostly in utility and large industrial applications.

In spreader stokers, a flipping mechanism throws the coal into the furnace and onto a moving fuel bed. Combustion occurs partly in suspension and partly on the grate. Because of significant carbon content in the particulate, fly ash reinjection from mechanical collectors is commonly employed to improve boiler efficiency. Ash residue from the fuel bed is deposited in a receiving pit at the end of the grate.

In overfeed stokers, coal is fed onto a traveling or vibrating grate and burns on the fuel bed as it progresses through the furnace. Ash particles fall into an ash pit at the rear of the stoker. The term "overfeed" applies because the coal is fed onto the moving grate under an adjustable gate. Conversely, in "underfeed" stokers, coal is fed into the firing zone from below by mechanical rams or screw conveyors. The coal moves in a channel, known as a retort, from which it is forced upward, spilling over the top of each side to form and to feed the fuel bed. Combustion is completed by the time the bed reaches the side dump grates, from which the ash is discharged into shallow pits. Underfeed stokers include single retort units and multiple retort units, the latter having several retorts side by side.

Small hand-fired boilers and furnaces are sometimes found in small industrial, commercial, institutional, or residential applications. In most hand-fired units, the fuel is primarily burned in layers on the bottom of the furnace or on a grate. From an emissions standpoint, hand-fired units generally have higher carbon monoxide (CO) and volatile organic compounds (VOC) emissions than larger boilers because of their lower combustion efficiencies.

In a fluidized bed combustor (FBC), the coal is introduced to a bed of either sorbent (limestone or dolomite) or inert material (usually sand) which is fluidized by an upward flow of air. Most of the combustion occurs within the bed, but some smaller particles burn above the bed in the "freeboard" space. The two principal types of atmospheric FBC boilers are bubbling bed and circulating bed.[12] The fundamental distinguishing feature between these types is the fluidization velocity. In the bubbling bed design, the fluidization velocity is relatively low, ranging between 1.5 and 4 m/sec (5 and 12 ft/sec), in order to minimize solids carryover or elutriation from the combustor. Circulating FBCs, however, employ fluidization velocities as high as 9 m/sec (30 ft/sec) to promote the carryover or circulation of solids. High-temperature cyclones are used in circulating FBCs and in some bubbling FBCs to capture the solid fuel and bed material for return to the primary combustion chamber. The circulating FBC maintains a continuous, high-volume recycle rate which increases the fuel residence time compared to the bubbling bed design. Because of this feature, circulating FBCs often achieve higher combustion efficiency and better sorbent utilization than bubbling bed units.[2]

1.1.2 Emissions And Controls

The major pollutants of concern from bituminous and subbituminous coal combustion are particulate matter (PM), sulfur oxides (SO_x), and nitrogen oxides (NO_x). Emissions from coal combustion depend on the rank and composition of the fuel, the type and size of the boiler, firing conditions, load, type of control technologies, and the level of equipment maintenance. Some unburnt combustibles, including numerous organic compounds and CO, are generally emitted even under proper boiler operating conditions. Emission factors for major and minor pollutants are given in Tables 1.1-1, 1.1-2, 1.1-3, 1.1-4, 1.1-5, 1.1-6, 1.1-7, 1.1-8, 1.1-9, 1.1-10, 1.1-11, 1.1-12, 1.1-13, and 1.1-14.

Particulate Matter -

Particulate matter composition and emission levels are a complex function of firing configuration, boiler operation, and coal properties.[2,4-5] In pulverized coal systems, combustion is almost complete, and thus emitted particulate is largely comprised of inorganic ash residues. In wet bottom pulverized coal units and cyclones, the quantity of ash leaving the boiler is lower than in dry bottom units, because some of the ash liquifies, collects on the furnace walls, and drains from the furnace bottom as molten slag. Particulate emission limits specified in applicable New Source Performance Standards (NSPS) are summarized in Table 1.1-15.

Table 1.1-1 (English Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	SO_x[b]		NO_x[c]		CO[d,e]	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	38S (35S)	A	21.7	A	0.5	A
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	38S (35S)	A	14.4	A	0.5	A
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	38S (35S)	D	34.0	C	0.5	A
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	38S (35S)	D	33.8	C	0.5	A
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	38S (35S)	B	13.7	A	5	A
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	38S (35S)	B	13.7	A	5	A
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	38S (35S)	A	13.7	A	5	A
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	38S (35S)	B	7.5	A	6	B

Table 1.1-1 (cont.).

Firing Configuration	SCC	SO_x[b]		NO_x[c]		CO[d,e]	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Feed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	38S (35S)	B	7.5	A	6	B
Underfeed stoker	1-02-002-06 1-03-002-08	31S	B	9.5	A	11	B
Underfeed stoker, with multiple cyclones	1-02-002-06 1-03-002-08	31S	B	9.5	A	11	B
Hand-fed units	1-03-002-14	31S	D	9.1	E	275	E
Fluidized bed combustor, circulating bed	1-01-002-17 1-02-002-17 1-03-002-17	—[g]	E	3.9	E	18	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	—[g]	E	15.2	D	18	D

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

[b] Expressed as SO_2, including SO_2, SO_3, and gaseous sulfates. Factors in parentheses should be used to estimate gaseous SO_x emissions for subbituminous coal. In all cases, S is weight percent sulfur content of coal as fired. Emission factor would be calculated by multiplying the weight percent sulfur in the coal by the numerical value preceding S. On average for bituminous coal, 95% of fuel sulfur is emitted as SO_2, and only about 0.7% of fuel sulfur is emitted as SO_3 and gaseous sulfate. An equally small percent of fuel sulfur is emitted as particulate sulfate (References 9, 13). Small quantities of sulfur are also retained in bottom ash. With subbituminous coal, about 10% more fuel sulfur is retained in the bottom ash and particulate because of the more alkaline nature of the coal ash. Conversion to gaseous sulfate appears about the same as for bituminous coal.

[c] Expressed as NO_2. Generally, 95+ volume % of nitrogen oxides present in combustion exhaust will be in the form of NO, the rest NO_2 (Reference 11). To express factors as NO, multiply factors by 0.66. All factors represent emission at baseline operation (i. e., 60 to 110% load and no NO_x control measures).

Table 1.1-1 (cont.).

[d] Nominal values achievable under normal operating conditions. Values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

[e] Emission factors for CO_2 emissions from coal combustion should be calculated using CO_2/ton coal = 73.3C, where C is the weight percent carbon content of the coal.

[f] Includes traveling grate, vibrating grate, and chain grate stokers.

[g] Sulfur dioxide emission factors for fluidized bed combustion are a function of fuel sulfur content and calcium-to-sulfur ratio. For both bubbling bed and circulating bed design, use: lb SO_2/ton coal = $39.6(S)(Ca/S)^{-1.9}$. In this equation, S is the weight percent sulfur in the fuel and Ca/S is the molar calcium-to-sulfur ratio in the bed. This equation may be used when the Ca/S is between 1.5 and 7. When no calcium-based sorbents are used and the bed material is inert with respect to sulfur capture, the emission factor for underfeed stokers should be used to estimate the FBC SO_2 emissions. In this case, the emission factor ratings are E for both bubbling and circulating units.

Table 1.1-2 (Metric Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

		SO_x[b]		NO_x[c]		CO[d,e]	
Firing Configuration	SCC	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	19S (17.5S)	A	10.85	A	0.25	A
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	19S (17.5S)	A	7.2	A	0.25	A
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	19S (17.5S)	D	17	C	0.25	A
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	19S (17.5S)	D	16.9	C	0.25	A
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	19S (17.5S)	B	6.85	A	2.5	A
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	19S (17.5S)	B	6.85	A	2.5	A
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	19S (17.5S)	A	6.85	A	2.5	A
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	19S (17.5S)	B	3.75	A	3	B

Table 1.1-2 (cont.).

Firing Configuration	SCC	SO_x[b]		NO_x[c]		CO[d,e]	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Overfeed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	19S (17.5S)	B	3.75	A	3	B
Underfeed stoker	1-02-002-06 1-03-002-08	15.5S	B	4.75	A	5.5	B
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	15.5S	B	4.75	A	5.5	B
Hand-fed units	1-03-002-14	15.5S	D	4.55	E	137.5	E
Fluidized bed combustor, circulating bed	1-01-002-17 1-02-002-17 1-03-002-17	—[g]	E	1.95	E	9	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	—[g]	E	7.6	D	9	D

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

[b] Expressed as SO_2, including SO_2, SO_3, and gaseous sulfates. Factors in parentheses should be used to estimate gaseous SO_x emissions for subbituminous coal. In all cases, S is weight percent sulfur content of coal as fired. Emission factor would be calculated by multiplying the weight percent sulfur in the coal by the numerical value preceding S. On average for bituminous coal, 95% of fuel sulfur is emitted as SO_2, and only about 0.7% of fuel sulfur is emitted as SO_3 and gaseous sulfate. An equally small percent of fuel sulfur is emitted as particulate sulfate (References 9, 13). Small quantities of sulfur are also retained in bottom ash. With subbituminous coal, about 10% more fuel sulfur is retained in the bottom ash and particulate because of the more alkaline nature of the coal ash. Conversion to gaseous sulfate appears about the same as for bituminous coal.

[c] Expressed as NO_2. Generally, 95+ volume % of nitrogen oxides present in combustion exhaust will be in the form of NO, the rest NO_2 (Reference 11). To express factors as NO, multiply factors by 0.66. All factors represent emission at baseline operation (i. e., 60 to 110% load and no NO_x control measures).

Table 1.1-2 (cont.).

[d] Nominal values achievable under normal operating conditions. Values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

[e] Emission factors for CO_2 emissions from coal combustion should be calculated using CO_2/Mg coal = 36.7C, where C is the weight percent carbon content of the coal.

[f] Includes traveling grate, vibrating grate, and chain grate stokers.

[g] Sulfur dioxide emission factors for fluidized bed combustion are a function of fuel sulfur content and calcium-to-sulfur ratio. For both bubbling bed and circulating bed design, use: kg SO_2/Mg coal = $19.8(S)(Ca/S)^{-1.9}$. In this equation, S is the weight percent sulfur in the fuel and Ca/S is the molar calcium-to-sulfur ratio in the bed. This equation may be used when the Ca/S is between 1.5 and 7. When no calcium-based sorbents are used and the bed material is inert with respect to sulfur capture, the emission factor for underfeed stokers should be used to estimate the FBC SO_2 emissions. In this case, the emission factor ratings are E for both bubbling and circulating units.

Table 1.1-3 (English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND PM LESS THAN 10 MICROMETERS (PM-10) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	Filterable PM[b]		PM-10	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	10A	A	2.3A	E
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	10A	B	2.3A[c]	E
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	7A[d]	D	2.6A	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	2A[d]	E	0.26A	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	66[e]	B	13.2	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	17	B	12.4	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	12	A	7.8	E
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	16[g]	C	6.0	E

Table 1.1-3 (cont.).

Firing Configuration	SCC	Filterable PM[b]		PM-10	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Overfeed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	9[h]	C	5.0	E
Underfeed stoker	1-02-002-06 1-03-002-08	15[j]	D	6.2	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	11[h]	D	6.2[j]	E
Hand-fed units	1-03-002-14	15	E	6.2[k]	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	12	E	13.2[m]	E
Fluidized bed combustor, circulating bed	1-01-002-17 1-02-002-17 1-03-002-17	17	E	13.2	E

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

[b] Based on EPA Method 5 (front half catch) as described in Reference 28. Where particulate is expressed in terms of coal ash content, A, factor is determined by multiplying weight % ash content of coal (as fired) by the numerical value preceding the A. For example, if coal with 8% ash is fired in a pulverized coal fired, dry bottom unit, the PM emission factor would be 10 x 8, or 80 lb/ton. The "condensable" matter collected in back half catch of EPA Method 5 averages $<5\%$ of front half, or "filterable", catch for pulverized coal and cyclone furnaces; 10% for spreader stokers; 15% for other stokers; and 50% for handfired units (References 6, 29, 30).

[c] No data found; emission factor for pulverized coal-fired dry bottom boilers used.

[d] Uncontrolled particulate emissions, when no fly ash reinjection is employed. When control device is installed, and collected fly ash is reinjected to boiler, particulate from boiler reaching control equipment can increase up to a factor of two.

[e] Accounts for fly ash settling in an economizer, air heater, or breaching upstream of control device or stack. (Particulate directly at boiler outlet typically will be twice this level.) Factor should be applied even when fly ash is reinjected to boiler from air heater or economizer dust hoppers.

Table 1.1-3 (cont.).

[f] Includes traveling grate, vibrating grate, and chain grate stokers.
[g] Accounts for fly ash settling in breaching or stack base. Particulate loadings directly at boiler outlet typically can be 50% higher.
[h] See Reference 34 for discussion of apparently low multiple cyclone control efficiencies, regarding uncontrolled emissions.
[j] Accounts for fly ash settling in breaching downstream of boiler outlet.
[k] No data found; emission factor for underfeed stoker used.
[m] No data found; emission factor for spreader stoker used.

Table 1.1-4 (Metric Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND PM LESS THAN 10 MICROMETERS (PM-10) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	Fitlerable PM[b]		PM-10	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	5A	A	1.15A	E
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	5A	B	1.15A[c]	E
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	3.5A[d]	D	1.3A	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	1A[d]	E	0.13A	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	33[e]	B	6.6	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	8.5	B	6.6	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	6	A	3.9	E
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	8[g]	C	3.0	E

Table 1.1-4 (cont.).

Firing Configuration	SCC	Fitlerable PM[b]		PM-10	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Overfeed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	4.5[h]	C	2.5	E
Underfeed stoker	1-02-002-06 1-03-002-08	7.5[j]	D	3.1	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	5.5[h]	D	3.1[j]	E
Hand-fed units	1-03-002-14	7.5	E	3.1[k]	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	6	E	6.6[m]	E
Fluidized bed combustor, circulating bed	1-01-002-17 1-02-002-17 1-03-002-17	8.5	E	6.6	E

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

[b] Based on EPA Method 5 (front half catch) as described in Reference 28. Where particulate is expressed in terms of coal ash content, A, factor is determined by multiplying weight % ash content of coal (as fired) by the numerical value preceding the A. For example, if coal with 8% ash is fired in a pulverized coal fired, dry bottom unit, the PM emission factor would be 5 x 8, or 40 kg/Mg. The "condensable" matter collected in back half catch of EPA Method 5 averages <5% of front half, or "filterable", catch for pulverized coal and cyclone furnaces; 10% for spreader stokers; 15% for other stokers; and 50% for handfired units (References 6,29,30).

[c] No data found; use assumed emission factor for pulverized coal-fired dry bottom boilers.

[d] Uncontrolled particulate emissions, when no fly ash reinjection is employed. When control device is installed, and collected fly ash is reinjected to boiler, particulate from boiler reaching control equipment can increase up to a factor of two.

[e] Accounts for fly ash settling in an economizer, air heater, or breaching upstream of control device or stack. (Particulate directly at boiler outlet typically will be twice this level.) Factor should be applied even when fly ash is reinjected to boiler from air heater or economizer dust hoppers.

Table 1.1-4 (cont.).

[f] Includes traveling grate, vibrating grate, and chain grate stokers.

[g] Accounts for fly ash settling in breaching or stack base. Particulate loadings directly at boiler outlet typically can be 50% higher.

[h] See Reference 34 for discussion of apparently low multiple cyclone control efficiencies, regarding uncontrolled emissions.

[j] Accounts for fly ash settling in breaching downstream of boiler outlet.

[k] No data found; use emission factor for underfeed stoker.

[m] No data found; use emission factor for spreader stoker.

Table 1.1-5 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR DRY BOTTOM BOILERS BURNING PULVERIZED BITUMINOUS COAL[a]

Particle Size[b] (µm)	Cumulative Mass % ≤ Stated Size					Cumulative Emission Factor[c] (kg/Mg [lb/ton] Coal, As Fired)				
	Uncontrolled	Controlled				Uncontrolled[d]	Controlled[e]			
		Multiple Cyclones	Scrubber	ESP	Baghouse		Multiple Cyclones[f]	Scrubber[g]	ESP[g]	Baghouse[f]
15	32	54	81	79	97	1.6A (3.2A)	0.54A (1.08A)	0.24A (0.48A)	0.032A (0.064A)	0.010A (0.02A)
10	23	29	71	67	92	1.15A (2.3A)	0.29A (0.58A)	0.21A (0.42A)	0.027A (0.054A)	0.009A (0.02A)
6	17	14	62	50	77	0.85A (1.7A)	0.14A (0.28A)	0.19A (0.38A)	0.020A (0.024A)	0.008A (0.02A)
2.5	6	3	51	29	53	0.3A (0.6A)	0.03A (0.06A)	0.15A (0.3A)	0.012A (0.024A)	0.005A (0.01A)
1.25	2	1	35	17	31	0.10A (0.2A)	0.01A (0.02A)	0.11A (0.22A)	0.007A (0.01A)	0.003A (0.006A)
1.00	2	1	31	14	25	0.10A (0.2A)	0.01A (0.02A)	0.09A (0.18A)	0.006A (0.01A)	0.003A (0.006A)
0.625	1	1	20	12	14	0.05A (0.10A)	0.01A (0.02A)	0.06A (0.12A)	0.005A (0.01A)	0.001A (0.002A)
TOTAL	100	100	100	100	100	5A (10A)	1A (2A)	0.3A (0.6A)	0.04A (0.08A)	0.01A (0.02A)

[a] Reference 32. Applicable Source Classification Codes are 1-01-002-02, 1-02-002-02, 1-03-002-06, 1-01-002-12, 1-02-002-12, and 1-03-002-16. ESP = electrostatic precipitator.

[b] Expressed as aerodynamic equivalent diameter.

[c] A = coal ash weight percent, as fired.

[d] EMISSION FACTOR RATING = C.

[e] Estimated control efficiency for multiple cyclones is 80%; for scrubber, 94%; for ESP, 99.2%; and for baghouse, 99.8%.

[f] EMISSION FACTOR RATING = E.

[g] EMISSION FACTOR RATING = D.

Table 1.1-6 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR WET BOTTOM BOILERS BURNING PULVERIZED BITUMINOUS COAL[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size			Cumulative Emission Factor[c] (kg/Mg [lb/ton] Coal, As Fired)		
		Controlled			Controlled[d]	
	Uncontrolled	Multiple Cyclones	ESP	Uncontrolled	Multiple Cyclones	ESP
15	40	99	83	1.4A (2.8A)	0.69A (1.38A)	0.023A (0.046A)
10	37	93	75	1.30A (2.6A)	0.65A (1.3A)	0.021A (0.042A)
6	33	84	63	1.16A (2.32A)	0.59A (1.18A)	0.018A (0.036A)
2.5	21	61	40	0.74A (1.48A)	0.43A (0.86A)	0.011A (0.022A)
1.25	6	31	17	0.21A (0.42A)	0.22A (0.44A)	0.005A (0.01A)
1.00	4	19	8	0.14A (0.28A)	0.13A (0.26A)	0.002A (0.004A)
0.625	2	—[e]	—[e]	0.07A (0.14A)	—[e]	—[e]
TOTAL	100	100	100	3.5A (7.0A)	0.7A (1.4A)	0.028A (0.056A)

[a] Reference 32. Applicable Source Classification Codes are 1-01-002-01, 1-02-002-01, and 1-03-002-05. ESP = electrostatic precipitator.

[b] Expressed as aerodynamic equivalent diameter.

[c] A = coal ash weight %, as fired.

[d] Estimated control efficiency for multiple cyclones is 94%; and for ESP, 99.2%.

[e] Insufficient data.

Table 1.1-7 (Metric And English Units). CUMULATIVE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR CYCLONE FURNACES BURNING BITUMINOUS COAL[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size			Cumulative Emission Factor[c] (kg/Mg [lb/ton] Coal, As Fired)		
	Uncontrolled	Controlled		Uncontrolled	Controlled[e]	
		Multiple Cyclones	ESP		Multiple Cyclones	ESP
15	33	95	90	0.33A (0.66A)	0.057A (0.114A)	0.0064A (0.013A)
10	13	94	68	0.13A (0.26A)	0.056A (0.112A)	0.0054A (0.011A)
6	8	93	56	0.08A (0.16A)	0.056A (0.112A)	0.0045A (0.009A)
2.5	0	92	36	0	0.055A (0.11A)	0.0029A (0.006A)
1.25	0	85	22	0	0.051A (0.10A)	0.0018A (0.004A)
1.00	0	82	17	0	0.049A (0.10A)	0.0014A (0.003A)
0.625	0	—[d]	—[d]	0	—[d]	—[d]
TOTAL	100	100	100	1A (2A)	0.06A (0.12A)	0.008A (0.016A)

[a] Reference 32. Applicable Source Classification Codes are 1-01-002-03, 1-02-002-03, and 1-03-002-03. ESP = electrostatic precipitator.

[b] Expressed as aerodynamic equivalent diameter.

[c] A = coal ash weight percent, as fired.

[d] Insufficient data.

[e] Estimated control efficiency for multiple cyclones is 94%; and for ESP, 99.2%.

Table 1.1-8 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR SPREADER STOKERS BURNING BITUMINOUS COAL[a]

Particle Size[b] (µm)	Cumulative Mass % ≤ Stated Size					Cumulative Emission Factor[c] (kg/Mg [lb/ton]) Coal, As Fired)				
	Uncontrolled	Controlled				Uncontrolled[e]	Controlled[d]			
		Multiple Cyclones[c]	Multiple Cyclones[d]	ESP	Baghouse		Multiple Cyclones[c,f]	Multiple Cyclones[d,e]	ESP[f,g]	Baghouse[e,g]
15	28	86	74	97	72	8.4 (17)	4.4 (8.8)	0.23 (0.46)	0.043 (0.086)	0.010A (0.02A)
10	20	73	65	90	60	6.2 (12)	3.9 (7.8)	0.22 (0.44)	0.036 (0.072)	0.009A (0.02A)
6	14	51	52	82	46	4.3 (8.6)	3.1 (6.2)	0.20 (0.60)	0.028 (0.056)	0.008A (0.02A)
2.5	7	8	27	61	26	0.7 (1.4)	1.6 (3.2)	0.15 (0.30)	0.016 (0.032)	0.005A (0.01A)
1.25	5	2	16	46	18	0.2 (0.4)	1.0 (2.0)	0.11 (0.22)	0.011 (0.022)	0.003A (0.006A)
1.00	5	2	14	41	15	0.2 (0.4)	0.8 (1.6)	0.10 (0.20)	0.009 (0.018)	0.003A (0.006A)
0.625	4	1	9	—[h]	7	0.1 (0.2)	0.5 (1.0)	—[h]	0.004 (0.006)	0.001A (0.002A)
TOTAL	100	100	100	100	100	8.5 (17.0)	6.0 (12.0)	0.24 (0.48)	0.06 (0.12)	0.01A (0.02A)

[a] Reference 32. Applicable Source Classification Codes are 1-01-002-04, 1-02-002-04, 1-03-002-09. ESP = electrostatic precipitator.

[b] Expressed as aerodynamic equivalent diameter.

[c] With flyash reinjection.

[d] Without flyash reinjection.

[e] EMISSION FACTOR RATING = C.

[f] EMISSION FACTOR RATING = E.

[g] Estimated control efficiency for ESP is 99.22%; and for baghouse, 99.8%.

[h] Insufficient data.

Table 1.1-9 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR OVERFEED STOKERS BURNING BITUMINOUS COAL[a]

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor[c] (kg/Mg [lb/ton] Coal, As Fired)			
			Uncontrolled		Multiple Cyclones Controlled[d]	
	Uncontrolled	Multiple Cyclones Controlled	Factor	RATING	Factor	RATING
15	49	60	3.9 (7.8)	C	2.7 (5.4)	E
10	37	55	3.0 (6.0)	C	2.5 (5.0)	E
6	24	49	1.9 (3.8)	C	2.2 (4.4)	E
2.5	14	43	1.1 (2.2)	C	1.9 (3.8)	E
1.25	13	39	1.0 (2.0)	C	1.8 (3.6)	E
1.00	12	39	1.0 (2.0)	C	1.8 (3.6)	E
0.625	—[c]	16	—[c]	C	0.7 (1.4)	E
TOTAL	100	100	8.0 (16.0)	C	4.5 (9.0)	E

[a] Reference 32. Applicable Source Classification Codes are 1-01-002-05, 1-02-002-05, and 1-03-002-07.

[b] Expressed as aerodynamic equivalent diameter.

[c] Insufficient data.

[d] Estimated control efficiency for multiple cyclones is 80%.

Table 1.1-10 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNDERFEED STOKERS BURNING BITUMINOUS COAL[a]

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Uncontrolled Cumulative Emission Factor[c] (kg/Mg [lb/ton] Coal, As Fired)	
		Factor	RATING
15	50	3.8 (7.6)	C
10	41	3.1 (6.2)	C
6	32	2.4 (4.8)	C
2.5	25	1.9 (3.8)	C
1.25	22	1.7 (3.4)	C
1.00	21	1.6 (3.2)	C
0.625	18	1.4 (2.7)	C
TOTAL	100	7.5 (15.0)	C

[a] Reference 32. Applicable Source Classification Codes are 1-02-002-06 and 1-03-002-08.

[b] Expressed as aerodynamic equivalent diameter.

[c] May also be used for uncontrolled hand-fired units.

Table 1.1-11 (English Units). EMISSION FACTORS FOR METHANE (CH_4), NONMETHANE TOTAL ORGANIC COMPOUNDS (NMTOC), AND NITROUS OXIDE (N_2O) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	CH_4[b]		NMTOC[b,c]		N_2O[d]	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	0.04	B	0.06	B	0.09	D
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	0.04	B	0.06	B	0.03	D
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	0.05	B	0.04	B	0.09[e]	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	0.01	B	0.11	B	0.09[e]	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.06	B	0.05	B	0.09[e]	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.06	B	0.05	B	0.09[e]	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.06	B	0.05	B	0.09[e]	E

Table 1.1-11 (cont.).

Firing Configuration	SCC	CH_4[b]		NMTOC[b,c]		N_2O[d]	
		lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.06	B	0.05	B	0.09[e]	E
Overfeed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.06	B	0.05	B	0.09[e]	E
Underfeed stoker	1-02-002-06 1-03-002-08	0.8	B	1.3	B	0.09[e]	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	0.8	B	1.3	B	0.09[e]	E
Hand-fed units	1-03-002-14	5	E	10	E	0.09[e]	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	0.06	E	0.05	E	5.9[g]	E
Fluidized bed combustor, circulating bed	1-01-002-17 1-02-002-17 1-03-002-17	0.06	E	0.05	E	5.5	E

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

[b] Reference 35. Nominal values achievable under normal operating conditions; values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

[c] Nonmethane total organic compounds are expressed as C2 to C16 alkane equivalents (Reference 31). Because of limited data, the effects of firing configuration on NMTOC emission factors could not be distinguished. As a result, all data were averaged collectively to develop a single average emission factor for pulverized coal units, cyclones, spreaders, and overfeed stokers.

[d] References 36-38.

[e] No data found; emission factor for pulverized coal-fired dry bottom boilers used.

[f] Includes traveling grate, vibrating grate, and chain grate stokers.

[g] No data found; emission factor for circulating fluidized bed used.

Table 1.1-12 (Metric Units). EMISSION FACTORS FOR METHANE (CH_4), NONMETHANE TOTAL ORGANIC COMPOUNDS (NMTOC), AND NITROUS OXIDE (N_2O) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

Firing Configuration	SCC	CH_4[b]		NMTOC[b,c]		N_2O[d]	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Pulverized coal fired, dry bottom, wall fired	1-01-002-02/22 1-02-002-02/22 1-03-002-06/22	0.02	B	0.04	B	0.045	D
Pulverized coal fired, dry bottom, tangentially fired	1-01-002-12/26 1-02-002-12/26 1-03-002-16/26	0.02	B	0.04	B	0.015	D
Pulverized coal fired, wet bottom	1-01-002-01/21 1-02-002-01/21 1-03-002-05/21	0.025	B	0.02	B	0.045[e]	E
Cyclone furnace	1-01-002-03/23 1-02-002-03/23 1-03-002-03/23	0.005	B	0.055	B	0.045[e]	E
Spreader stoker	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.03	B	0.025	B	0.045[e]	E
Spreader stoker, with multiple cyclones, and reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.03	B	0.025	B	0.045[e]	E
Spreader stoker, with multiple cyclones, no reinjection	1-01-002-04/24 1-02-002-04/24 1-03-002-09/24	0.03	B	0.025	B	0.045[e]	E

Table 1.1-12 (cont.).

Firing Configuration	SCC	CH_4[b]		NMTOC[b,c]		N_2O[d]	
		kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
Overfeed stoker[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.03	B	0.025	B	0.045[e]	E
Overfeed stoker, with multiple cyclones[f]	1-01-002-05/25 1-02-002-05/25 1-03-002-07/25	0.03	B	0.025	B	0.045[e]	E
Underfeed stoker	1-02-002-06 1-03-002-08	0.4	B	0.65	B	0.045[e]	E
Underfeed stoker, with multiple cyclone	1-02-002-06 1-03-002-08	0.4	B	0.65	B	0.045[e]	E
Hand-fed units	1-03-002-14	2.5	E	5	E	0.045[e]	E
Fluidized bed combustor, bubbling bed	1-01-002-17 1-02-002-17 1-03-002-17	0.03	E	0.025	E	2.75[g]	E
Fluidized bed combustor, circulating bed	1-01-002-17 1-02-002-17 1-03-002-17	0.03	E	0.025	E	2.75	E

[a] Factors represent uncontrolled emissions unless otherwise specified and should be applied to coal feed, as fired. SCC = Source Classification Code.

[b] Reference 35. Nominal values achievable under normal operating conditions; values 1 or 2 orders of magnitude higher can occur when combustion is not complete.

[c] Nonmethane total organic compounds are expressed as C2 to C16 alkane equivalents (Reference 31). Because of limited data, the effects of firing configuration on NMTOC emission factors could not be distinguished. As a result, all data were averaged collectively to develop a single average emission factor for pulverized coal units, cyclones, spreaders, and overfeed stokers.

[d] References 36-38.

[e] No data found; use emission factor for pulverized coal-fired dry bottom boilers.

[f] Includes traveling grate, vibrating grate, and chain grate stokers.

[g] No data found; use emission factor for circulating fluidized bed.

Table 1.1-13 (English Units). EMISSION FACTORS FOR TRACE ELEMENTS, POLYCYCLIC ORGANIC MATTER (POM), AND FORMALDEHYDE (HCOH) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	Emission Factor, lb/10^{12} Btu									
	As	Be	Cd	Cr	Pb	Mn	Hg	Ni	POM	HCOH
Pulverized coal, configuration unknown (no SCC)	ND	ND	ND	1922	ND	ND	ND	ND	ND	112[b]
Pulverized coal, wet bottom (1-01-002-01/21, 1-02-002-01/21, 1-03-002-05/21)	538	81	44-70	1020-1570	507[c]	808-2980	16	840-1290	ND	ND
Pulverized coal, dry bottom (1-01-002-02/22, 1-02-002-06/22, 1-03-002-06/22)	684	81	44.4	1250-1570	507[c]	228-2980	16	1030-1290	2.08	ND
Pulverized coal, dry bottom, tangential (1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26)	ND	ND	ND	ND	ND	ND	ND	ND	2.4	ND
Cyclone furnace (1-01-002-03/23, 1-02-002-03/23, 1-03-002-03/23)	115	<81	28	212-1502	507[c]	228-1300	16	174-1290	ND	ND
Stoker, configuration unknown (no SCC)	ND	73	ND	19-300	ND	2170	16	775-1290	ND	ND
Spreader stoker (1-01-002-04/24, 1-02-002-04/24, 1-03-002-09/24)	264-542	ND	21-43	942-1570	507[c]	ND	ND	ND	ND	221[d]
Overfeed stoker, traveling grate (1-01-002-05/25, 1-02-002-05/25, 1-03-002-07/25)	542-1030	ND	43-82	ND	507[c]	ND	ND	ND	ND	140[e]

[a] References 39-44. The emission factors in this table represent the ranges of factors reported in the literature. If only 1 data point was found, it is still reported in this table. SCC = Source Classification Code. ND = no data.

[b] Based on 2 units; 456 MWe and 133 million Btu/hr.

[c] Lead emission factors were taken directly from an EPA background document for support of the NAAQS.

[d] Based on 1 unit; 59 million Btu/hr.

[e] Based on 1 unit; 52 million Btu/hr.

Table 1.1-14 (Metric Units). EMISSION FACTORS FOR TRACE ELEMENTS, POLYCYCLIC ORGANIC MATTER (POM), AND FORMALDEHYDE (HCOH) FROM BITUMINOUS AND SUBBITUMINOUS COAL COMBUSTION[a]

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	Emission Factor, pg/J									
	As	Be	Cd	Cr	Pb	Mn	Hg	Ni	POM	HCOH
Pulverized coal, configuration unknown (no SCC)	ND	ND	ND	825	ND	ND	ND	ND	ND	48[b]
Pulverized coal, wet bottom (1-01-002-01/21, 1-02-002-01/21, 1-03-002-05/21)	231	35	18-30	439-676	218[c]	348-1282	7	361-555	ND	ND
Pulverized coal, dry bottom (1-01-002-02/22, 1-02-002-02/22, 1-03-002-06/22)	294	35	19	538-676	218[c]	98-1282	7	443-555	0.894	ND
Pulverized coal, dry bottom, tangential (1-01-002-12/26, 1-02-002-12/26, 1-03-002-16/26)	ND	ND	ND	ND	ND	ND	ND	ND	1.03	ND
Cyclone furnace (1-01-002-03/23, 1-02-002-03/23, 1-03-002-03/23)	49.5-133	<34.9	12	91.2-676	218[c]	98-5590	6.9	74.9-555	ND	ND
Stoker, configuration unknown (no SCC)	ND	31.4	ND	8.1-675	ND	934	6.9	334-555	ND	ND
Spreader stoker (1-01-002-04/24, 1-02-002-04/24, 1-03-002-09/24)	114-233	ND	9.0-18.5	404-674	218[c]	ND	ND	ND	ND	95[d]
Overfeed stoker, traveling grate (1-01-002-05/25, 1-02-002-05/25, 1-03-002-07/25)	233-443	ND	19-35	ND	218[c]	ND	ND	ND	ND	60[e]

[a] References 39-44. The emission factors in this table represent the ranges of factors reported in the literature. If only 1 data point was found, it is still reported in this table. SCC = Source Classification Code. ND = no data.

[b] Based on 2 units; 456 MWe and 39 MW.

[c] Lead emission factors were taken directly from an EPA background document for support of the NAAQS.

[d] Based on 1 unit; 17 MW.

[e] Based on 1 unit; 15 MW.

Table 1.1-15 (Metric And English Units). NEW SOURCE PERFORMANCE STANDARDS FOR FOSSIL FUEL-FIRED BOILERS

Standard/ Boiler Types/ Applicability Criteria	Boiler Size MW (Million Btu/hr)	Fuel Or Boiler Type	PM ng/J (lb/MMBtu) [% reduction]	SO_2 ng/J (lb/MMBtu) [% reduction]	NO_x ng/J (lb/MMBtu) [% reduction]
Subpart D	>73 (>250)	Gas	43 (0.10)	NA[d]	86 (0.20)
Industrial-Utility		Oil	43 (0.10)	340 (0.80)	129 (0.30)
Commence construction after 8/17/71		Bit./Subbit. Coal	43 (0.10)	520 (1.20)	300 (0.70)
Subpart Da	>73 (>250)	Gas	13 (0.03) [NA]	340 (0.80) [90][a]	86 (0.20) [25]
Utility Commence construction after 9/18/78		Oil	13 (0.03) [70]	340 (0.80) [90][a]	130 (0.30) [30]
		Bit./Subbit. Coal	13 (0.03) [99]	520 (1.20) [90][a]	260/210[c] (0.60/0.50) [65/65]
Subpart Db	>29 (>100)	Gas	NA[d]	NA[d]	43[f] (0.10)
Industrial-Commercial Institution		Distillate Oil	43 (0.10)	340[n] (0.80) [90]	43[f] (0.10)
Commence construction after 6/19/84[m]		Residual Oil	(Same as for distillate oil)	(Same as for distillate oil)	130[g] (0.30)
		Pulverized Bit./Subbit. Coal	22[e] (0.05)	520[e] (1.20) [90]	300 (0.70)
		Spreader Stoker & FBC	22[e] (0.05)	520[e] (1.20) [90]	260 (0.60)
		Mass-Feed Stoker	22[e] (0.05)	520[e] (1.20) [90]	210 (0.50)

Table 1.1-15 (cont.).

Standard/ Boiler Types/ Applicability Criteria	Boiler Size MW (Million Btu/hr)	Fuel Or Boiler Type	PM ng/J (lb/MMBtu) [% reduction]	SO_2 ng/J (lb/MMBtu) [% reduction]	NO_x ng/J (lb/MMBtu) [% reduction]
Subpart Dc	2.9 - 29 (10 -100)	Gas	—[h]	—	—
Small Industrial Commercial-Institutional		Oil	—[h,j]	215 (0.50)	—
Commence construction after 6/9/89		Bit./Subbit. Coal	22[j,k] (0.05)	520[k] (1.20) [90]	—

[a] Zero percent reduction when emissions are less than 86 ng/J (0.20 lb/MMBtu). FBC = fluidized bed combustion. NA = not applicable.

[b] 70% reduction when emissions are less than 260 ng/J (0.60 lb/MMBtu).

[c] The first number applies to bituminous coal and the second to subbituminous coal.

[d] Standard applies when gas is fired in combination with coal, see 40 CFR 60, Subpart Db.

[e] Standard is adjusted for fuel combinations and capacity factor limits, see 40 CFR 60, Subpart Db.

[f] For furnace heat release rates greater than 730,000 J/s-m^3 (70,000 Btu/hr-ft^3), the standard is 86 ng/J (0.20 lb/MMBtu).

[g] For furnace heat release rates greater than 730,000 J/s-m^3 (70,000 Btu/hr-ft^3), the standard is 170 ng/J (0.40 lb/MMBtu).

[h] Standard applies when gas or oil is fired in combination with coal, see 40 CFR 60, Subpart Dc.

[j] 20 percent capacity limit applies for heat input capacities of 8.7 Mwt (30 MMBtu/hr) or greater.

[k] Standard is adjusted for fuel combinations and capacity factor limits, see 40 CFR 60, Subpart Dc.

[m] Additional requirements apply to facilities which commenced construction, modification, or reconstruction after 6/19/84 but on or before 6/19/86 (see 40 Code of Federal Regulations Part 60, Subpart Db).

[n] 215 ng/J (0.50 lb/million Btu) limit (but no percent reduction requirement) applies if facilities combust only very low sulfur oil (< 0.5 wt. % sulfur).

Because a mixture of fine and coarse coal particles is fired in spreader stokers, significant unburnt carbon can be present in the particulate. To improve boiler efficiency, fly ash from collection devices (typically multiple cyclones) is sometimes reinjected into spreader stoker furnaces. This practice can dramatically increase the particulate loading at the boiler outlet and, to a lesser extent, at the mechanical collector outlet. Fly ash can also be reinjected from the boiler, air heater, and economizer dust hoppers. Fly ash reinjection from these hoppers increases particulate loadings less than from multiple cyclones.

Uncontrolled overfeed and underfeed stokers emit considerably less particulate than do pulverized coal units and spreader stokers, since combustion takes place in a relatively quiescent fuel bed. Fly ash reinjection is not practiced in these kinds of stokers.

Variables other than firing configuration and fly ash reinjection can affect PM emissions from stokers. Particulate loadings will often increase as load increases (especially as full load is approached) and with sudden load changes. Similarly, particulate can increase as the coal ash and "fines" contents increase. Fines, in this context, are coal particles smaller than about 1.6 millimeters (1/16 inch) in diameter. Conversely, particulate can be reduced significantly when overfire air pressures are increased.

FBCs may tax conventional particulate control systems. The particulate mass concentration exiting FBCs is typically 2 to 4 times higher than that from pulverized coal boilers.[13] Fluidized bed combustor particles are also, on average, smaller in size, irregularly shaped, and have higher surface area and porosity relative to pulverized coal ashes. Fluidized bed combustion ash is more difficult to collect in electrostatic precipitators (ESPs) than pulverized coal ash because FBC ash has a higher electrical resistivity. In addition, the use of multiclones for fly ash recycling, inherent with FBC processes, tends to reduce flue gas stream particulate size.[13]

The primary kinds of PM control devices used for coal combustion include multiple cyclones, ESPs, fabric filters (or baghouses), and scrubbers. Some measure of control will even result from fly ash settling in boiler/air heater/economizer dust hoppers, large breeching, and chimney bases. The effects of such settling are reflected in current emission factors.

ESPs are the most common high-efficiency PM control device used on pulverized coal and cyclone units; they are also being used increasingly on stokers. Generally, ESP collection efficiencies are a function of collection plate area per unit volumetric flow rate of flue gas through the device. Particulate control efficiencies of 99.9 percent or above are obtainable with ESPs. ESPs located downstream of air preheaters (i. e., cold side precipitators) operate at significantly reduced efficiencies when low sulfur coal is fired. Fabric filters have recently seen increased use in both utility and industrial applications, generally achieving at least 99.8 percent efficiency. An advantage of fabric filters is that they are unaffected by the high fly ash resistivities associated with low sulfur coals. Scrubbers are also used to control particulate, although their primary use is to control sulfur oxides. One drawback of scrubbers is the high energy usage required to achieve control efficiencies comparable to those for ESPs and baghouses.[3]

Mechanical collectors, generally multiple cyclones, are the primary means of PM control on many stokers. They are sometimes installed upstream of high-efficiency control devices in order to reduce the ash collection burden on these devices. Cyclones are also an integral part of most FBC designs. Depending on application and design, multiple cyclone efficiencies can vary widely. Where cyclone design flow rates are not attained (which is common with underfeed and overfeed stokers), these devices may be only marginally effective and may prove little better in reducing particulate than a large breeching. Conversely, well-designed multiple cyclones, operating at the required flow rates, can achieve collection efficiencies on spreader stokers and overfeed stokers of 90 to 95 percent. Even higher collection efficiencies are obtainable on spreader stokers with reinjected fly ash because of the larger particle sizes and increased particulate loading reaching the controls.[5-6]

Sulfur Oxides -

Gaseous SO_x from coal combustion are primarily sulfur dioxide (SO_2), with a much lower quantity of sulfur trioxide (SO_3) and gaseous sulfates.[7-9] These compounds form as the organic and pyritic sulfur in the coal is oxidized during the combustion process. On average, about 95 percent of the sulfur present in bituminous coal will be emitted as gaseous SO_x, whereas somewhat less will be emitted when subbituminous coal is fired. The more alkaline nature of the ash in some subbituminous coals causes some of the sulfur to react in the furnace to form various sulfate salts that are retained in the boiler or in the flyash. In general, boiler size, firing configuration and boiler operations have little effect on the percent conversion of fuel sulfur to SO_x.[14] Sulfur dioxide emission limits specified in applicable NSPS are summarized in Table 1.1-15.

Several techniques are used to reduce SO_x emissions from coal combustion.[15] One way is to switch to lower sulfur coals, since SO_x emissions are proportional to the sulfur content of the coal. This alternative may not be possible where lower sulfur coal is not readily available or where a different grade of coal cannot be satisfactorily fired. In some cases, various coal cleaning processes may be employed to reduce the fuel sulfur content. Physical coal cleaning removes mineral sulfur such as pyrite but is not effective in removing organic sulfur. Chemical cleaning and solvent refining processes are being developed to remove organic sulfur.

Many flue gas desulfurization (FGD) techniques can remove SO_2 formed during combustion.[16] Flue gases can be treated using wet, dry, or semi-dry desulfurization processes of either the throwaway type (in which all waste streams are discarded) or the recovery/regenerable type (in which the SO_2 absorbent is regenerated and reused). To date, wet systems are the most commonly applied. Wet systems generally use alkali slurries as the SO_2 absorbent medium and can be designed to remove greater than 90 percent of the incoming SO_2. Particulate reduction of up to 99 percent is also possible with wet scrubbers, but fly ash is often collected by upstream ESPs or baghouses, to avoid erosion of the desulfurization equipment and possible interference with FGD process reactions.[7] Also, the volume of scrubber sludge is reduced with separate fly ash removal and contamination of the reagents and byproducts is prevented. Lime/limestone scrubbers, sodium scrubbers, and dual alkali scrubbing are among the commercially proven wet FGD systems. The effectiveness of these devices depends not only on control device design but also operating variables. A summary table of commercial post-combustion SO_2 controls is provided in Table 1.1-16.

A number of dry and wet sorbent injection technologies are under development to capture SO_2 in the furnace, the heat transfer sections, or ductwork downstream of the boiler. These technologies are generally designed for retrofit applications and are well-suited for coal combustion sources requiring moderate SO_2 reduction and which have a short remaining life.

Nitrogen Oxides -

Nitrogen oxides (NO_x) emissions from coal combustion are primarily nitrogen oxide (NO), with only a few volume percent as nitrogen dioxide (NO_2).[10-11] Nitrous oxide (N_2O) is also emitted at ppm levels. Nitrogen oxides formation results from thermal fixation of atmospheric nitrogen (thermal NO_x) in the combustion flame and from oxidation of nitrogen bound in the coal. Experimental measurements of thermal NO_x formation have shown that the NO_x concentration is exponentially dependent on temperature and is proportional to N_2 concentration in the flame, the square root of oxygen (O_2) concentration in the flame, and the gas residence time.[22] Typically, only 20 to 60 percent of the fuel nitrogen is converted to NO_x. Bituminous and subbituminous coals usually contain from 0.5 to 2 weight percent nitrogen, mainly present in aromatic ring structures. Fuel nitrogen can account for up to 80 percent of total NO_x from coal combustion. Nitrogen oxide emission limits in applicable NSPS are summarized in Table 1.1-15.

A number of combustion modifications have been used to reduce NO_x emissions from boilers. A summary of currently utilized NO_x control technology for stokers is given in Table 1.1-17. Low excess air (LEA) firing is the most widespread combustion modification, because it can be practiced in both old and new units and in all sizes of boilers. Low excess air firing is easy to implement and has the added advantage of increasing fuel use efficiency. Low excess air firing is generally effective only above 20 percent excess air for pulverized coal units and above 30 percent excess air for stokers. Below these levels, the NO_x reduction from decreased O_2 availability is offset by increased NO_x production due to higher flame temperatures. Another NO_x reduction technique is simply to switch to a coal having a lower nitrogen content, although many boilers may not properly fire coals with different properties.

Table 1.1-16. POST-COMBUSTION SO_2 CONTROLS FOR COAL COMBUSTION SOURCES

Control Technology	Process	Typical Control Efficiencies	Remarks
Wet scrubber	Lime/limestone	80 - 95+%	Applicable to high sulfur fuels, Wet sludge product
	Sodium carbonate	80 - 98%	1-125 MW (5-430 million Btu/hr) typical application range, High reagent costs
	Magnesium oxide/ hydroxide	80 - 95+%	Can be regenerated
	Dual alkali	90 - 96%	Uses lime to regenerate sodium-based scrubbing liquor
Spray drying	Calcium hydroxide slurry, vaporizes in spray vessel	70 - 90%	Applicable to low and medium sulfur fuels, Produces dry product
Furnace injection	Dry calcium carbonate/hydrate injection in upper furnace cavity	25 - 50%	Commercialized in Europe, Several U. S. demonstration projects underway
Duct injection	Dry sorbent injection into duct, sometimes combined with water spray	25 - 50+%	Several R&D and demonstration projects underway, Not yet commercially available in the U. S.

Off-stoichiometric (or staged) combustion is also an effective means of controlling NO_x emissions from coal-fired equipment. This can be achieved by using overfire air or low-NO_x burners designed to stage combustion in the flame zone. Other NO_x reduction techniques include flue gas recirculation, load reduction, and steam or water injection. However, these techniques are not very effective for use on coal-fired equipment because of the fuel nitrogen effect. Ammonia injection is a post-combustion technique which can also be used, but it is costly relative to other methods. For cyclone boilers, the use of natural gas reburning for NO_x emission control is under investigation on a

Table 1.1-17. COMBUSTION MODIFICATION NO_x CONTROLS FOR STOKER COAL-FIRED INDUSTRIAL BOILERS

Control Technique	Description Of Technique	Effectiveness Of Control (% NO_x Reduction)	Range Of Application	Commercial Availability/R&D Status	Comments
Low Excess Air (LEA)	Reduction of air flow under stoker bed	5-25	Excess oxygen limited to 5-6% minimum	Available now but need R&D on lower limit of excess air	Danger of overheating grate, clinker formation, corrosion, and high CO emissions
Staged combustion (LEA + overfire air [OFA])	Reduction of undergrate air flow and increase of overfire air flow	5-25	Excess oxygen limited to 5% minimum	Most stokers have OFA ports as smoke control devices but may need better sir flow control devices	Need research to determine optimum location and orientation of OFA ports for NO_x emission control. Overheating grate, corrosion, and high CO emission can occur if undergrate airflow is reduced below acceptable level as in LEA
Load Reduction (LR)	Reduction of coal and air feed to the stoker	Varies from 49% decrease to 25% increase in NO_x (average 15% decrease)	Has been used down to 25% load	Available	Only stokers that can reduce load without increasing excess air. Not a desirable technique because of loss in boiler efficiency
Reduced air preheat (RAP)	Reduction of combustion air temperature	8	Combustion air temperature reduced from 473K to 453K	Available now if boiler has combustion air heater	Not a desirable technique because of loss in boiler efficiency
Ammonia injection	Injection of NH_3 in convective section of boiler	40-40 (from gas- and oil-fired boiler experience)	Limited by furnace geometry. Feasible NH_3 injection rate limited to 1.5 NH_3/NO	Commercially offered but not yet demonstrated	Elaborate NH_3 injection, monitoring, and control system required. Possible load restrictions on boiler and air preheater fouling by ammonium bisulfate

full-scale utility boiler.[33] The net reduction of NO_x from any of these techniques or combinations thereof varies considerably with boiler type, coal properties, and boiler operating practices. Typical reductions will range from 10 to 60 percent. References 10 and 27 may be consulted for detailed discussion of each of these NO_x reduction techniques. To date, flue gas treatment has not been used commercially to reduce NO_x emissions from coal-fired boilers because of its higher relative cost.

Carbon Monoxide -

The rate of CO emissions from combustion sources depends on the fuel oxidation efficiency of the source. By controlling the combustion process carefully, CO emissions can be minimized. Thus, if a unit is operated improperly or not well maintained, the resulting concentrations of CO (as well as organic compounds) may increase by several orders of magnitude. Smaller boilers, heaters, and furnaces tend to emit more CO and organics than larger combustors. This is because smaller units usually have less high-temperature residence time and, therefore, less time to achieve complete combustion than larger combustors. Various combustion modification techniques used to reduce NO_x can produce increased CO emissions.

Organic Compounds -

Small amounts of organic compounds are emitted from coal combustion. As with CO emissions, the rate at which organic compounds are emitted depends on the combustion efficiency of the boiler. Therefore, any combustion modification which reduces the combustion efficiency will most likely increase the concentrations of organic compounds in the flue gases.

Total organic compounds (TOC) include volatile organic compounds (VOCs), semivolatile organic compounds, and condensable organic compounds. Emissions of VOCs are primarily characterized by the criteria pollutant class of unburned vapor-phase hydrocarbons. Unburned hydrocarbon emissions can include essentially all vapor phase organic compounds emitted from a combustion source. These are primarily emissions of aliphatic, oxygenated, and low molecular weight aromatic compounds which exist in the vapor phase at flue gas temperatures. These emissions include alkanes, alkenes, aldehydes, carboxylic acids, and substituted benzenes (e. g., benzene, toluene, xylene, and ethyl benzene).[17,18]

The remaining organic emissions are composed largely of compounds emitted from combustion sources in a condensed phase. These compounds can almost exclusively be classed into a group known as polycyclic organic matter (POM), and a subset of compounds called polynuclear aromatic hydrocarbons (PNA or PAH). There are also PAH-nitrogen analogs. Polycyclic organic matter can be especially prevalent in the emissions from coal combustion, because a large fraction of the volatile matter in coal exits as POM.[19]

Formaldehyde is formed and emitted during combustion of hydrocarbon-based fuels such as coal. Formaldehyde is present in the vapor phase of the flue gas. Formaldehyde is subject to oxidation and decomposition at the high temperatures encountered during combustion. Thus, larger units with efficient combustion (resulting from closely regulated air-fuel ratios, uniformly high combustion chamber temperatures, and relatively long gas residence times) have lower formaldehyde emission rates than do smaller, less efficient combustion units.[20,21]

Trace Elements -

Trace elements are also emitted from the combustion of coal. For this update of AP-42, trace metals included in the list of 189 hazardous air pollutants under Title III of the 1990 Clean Air Act Amendments[23] were considered. The quantity of trace metals depends on combustion temperature, fuel feed mechanism, and the composition of the fuel. The temperature determines the degree of volatilization of specific trace elements contained in the fuel. The fuel feed mechanism affects the partitioning of elements between bottom ash and fly ash. The quantity of any given metal emitted, in general, depends on:

- the physical and chemical properties of the element itself;
- its concentration in the fuel;
- the combustion conditions; and
- the type of particulate control device used, and its collection efficiency as a function of particle size.

It has become widely recognized that some trace metals become concentrated in certain waste particle streams from a combustor (e. g., bottom ash, collector ash, and flue gas particulate) while others do not.[19] Various classification schemes have been developed to describe this partitioning behavior.[24-26] The classification scheme used by Baig et al.[26] is as follows:

- Class 1: Elements which are approximately equally distributed between fly ash and bottom ash, or show little or no small particle enrichment.
- Class 2: Elements which are enriched in fly ash relative to bottom ash, or show increasing enrichment with decreasing particle size.
- Class 3: Elements which are intermediate between Class 1 and 2.
- Class 4: Elements which are emitted in the gas phase.

Fugitive Emissions -

Fugitive emissions are defined as pollutants which escape from an industrial process due to leakage, materials handling, inadequate operational control, transfer, or storage. The fly ash handling operations in most modern utility and industrial combustion sources consist of pneumatic systems or enclosed and hooded systems which are vented through small fabric filters or other dust control devices. The fugitive PM emissions from these systems are therefore minimal. Fugitive particulate emissions can sometimes occur during fly ash transfer operations from silos to trucks or rail cars.

Emission factors for SO_x, NO_x, and CO are presented in Tables 1.1-1 and 1.1-2, along with emission factor ratings. Particulate matter and PM-10 emission factors and ratings are given in Tables 1.1-3 and 1.1-4. Cumulative particle size distribution and particulate size-specific emission factors are given in Figure 1.1-1, Figure 1.1-2, Figure 1.1-3, Figure 1.1-4, Figure 1.1-5, and Figure 1.1-6 and Tables 1.1-5, 1.1-6, 1.1-7, 1.1-8, 1.1-9, and 1.1-10, respectively. Emission factors and ratings for speciated organics and N_2O are given in Tables 1.1-11 and 1.1-12. Emission factors and ratings for other noncriteria pollutants and lead are listed in Tables 1.1-13 and 1.1-14.

In general, the baseline emissions of criteria and noncriteria pollutants are those from uncontrolled combustion sources. Uncontrolled sources are those without add-on pollution control (APC) equipment, low-NO_x burners, or other modifications designed for emission control. Baseline emission for SO_2 and PM can also be obtained from measurements taken upstream of APC equipment.

Because of the inherently low NO_x emission characteristics of FBCs and the potential for in-bed SO_2 capture by calcium-based sorbents, uncontrolled emission factors for this source category were not developed in the same sense as with the other source categories. For NO_x emissions, the data collected from test reports were considered to be baseline if no additional add-on NO_x control system (such as ammonia injection) was operated. For SO_2 emissions, a correlation was developed from reported data on FBCs to relate SO_2 emissions to the coal sulfur content and the calcium-to-sulfur ratio in the bed.

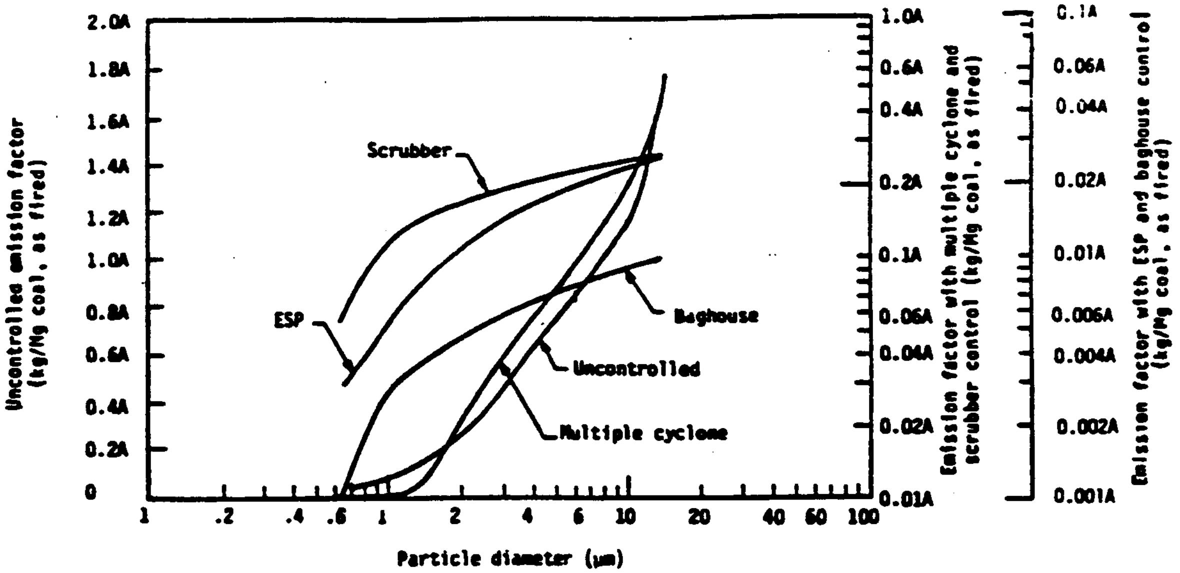

Figure 1.1-1. Cumulative size-specific emission factors for dry bottom boilers burning pulverized bituminous coal.

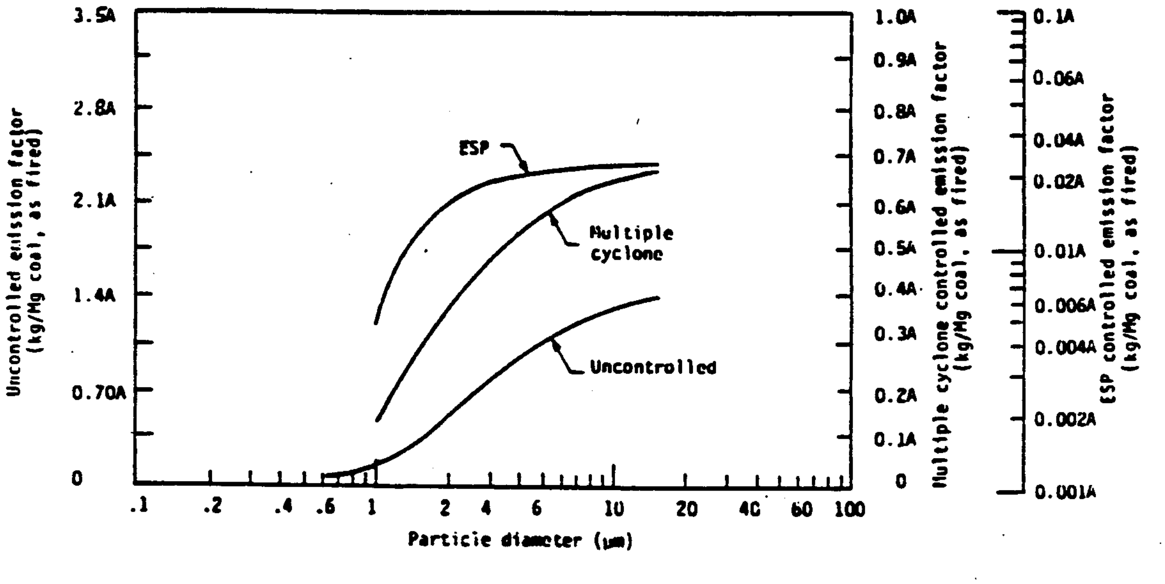

Figure 1.1-2. Cumulative size-specific emission factors for wet bottom boilers burning pulverized bituminous coal.

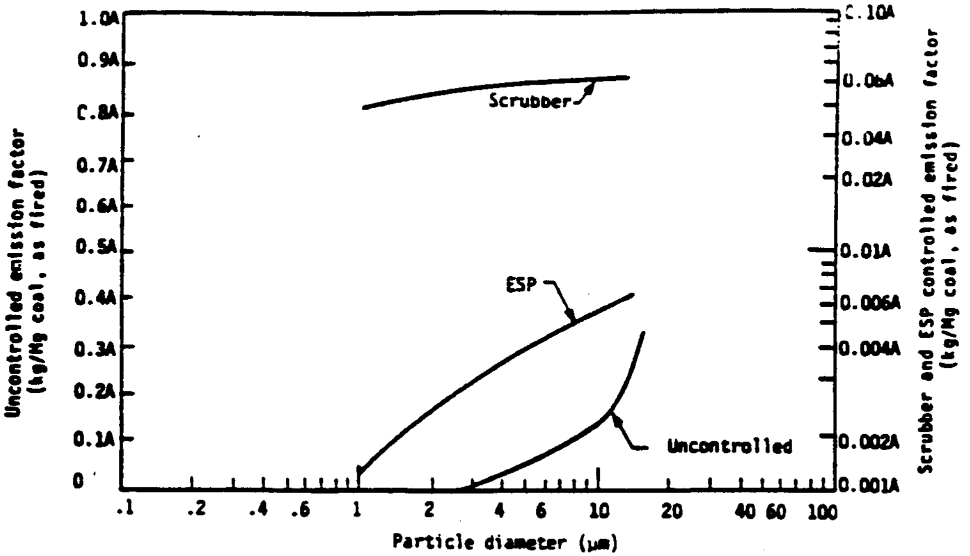

Figure 1.1-3. Cumulative size-specific emission factors for cyclone furnaces burning bituminous coal.

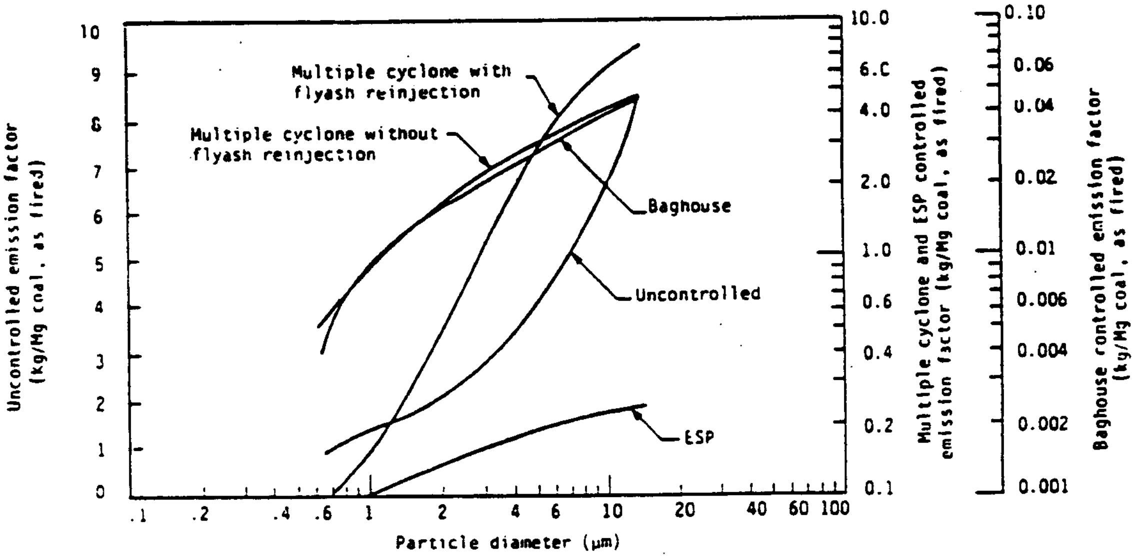

Figure 1.1-4. Cumulative size-specific emission factors for spreader stokers burning bituminous coal.

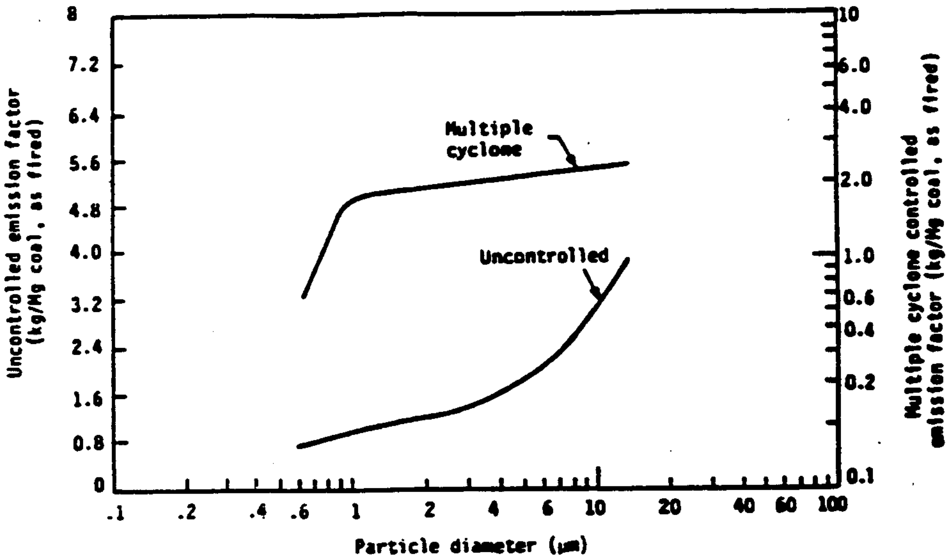

Figure 1.1-5. Cumulative size-specific emission factors for overfeed stokers burning bituminous coal.

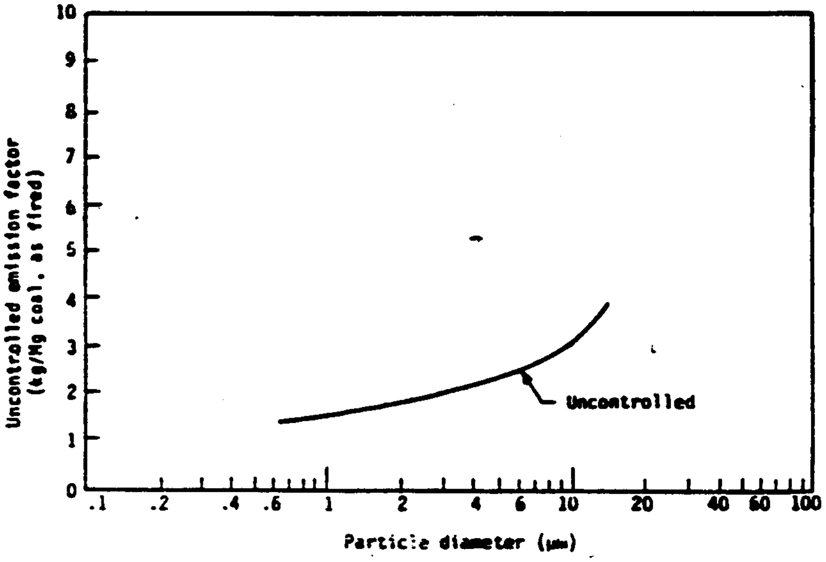

Figure 1.1-6. Cumulative size-specific emission factors for underfeed stokers burning bituminous coal.

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1.2 Anthracite Coal Combustion

1.2.1 General[1-4]

Anthracite coal is a high-rank coal with more fixed carbon and less volatile matter than either bituminous coal or lignite; anthracite also has higher ignition and ash fusion temperatures. In the United States, nearly all anthracite is mined in northeastern Pennsylvania and consumed in Pennsylvania and its surrounding states. The largest use of anthracite is for space heating. Lesser amounts are employed for steam/electric production; coke manufacturing, sintering, and pelletizing; and other industrial uses. Anthracite currently is only a small fraction of the total quantity of coal combusted in the United States.

Another form of anthracite coal burned in boilers is anthracite refuse, commonly known as culm. Culm was produced as breaker reject material from the mining/sizing of anthracite coal and was typically dumped by miners on the ground near operating mines. It is estimated that there are over 15 million Mg (16 million tons) of culm scattered in piles throughout northeastern Pennsylvania. The heating value of culm is typically in the 1,400 to 2,800 kcal/kg (2,500 to 5,000 Btu/lb) range, compared to 6,700 to 7,800 kcal/kg (12,000 to 14,000 Btu/lb) for anthracite coal.

1.2.2 Firing Practices[5-7]

Due to its low volatile matter content, and non-clinkering characteristics, anthracite coal is largely used in medium-sized industrial and institutional stoker boilers equipped with stationary or traveling grates. Anthracite coal is not used in spreader stokers because of its low volatile matter content and relatively high ignition temperature. This fuel may also be burned in pulverized coal-fired (PC-fired) units, but, due to ignition difficulties, this practice is limited to only a few plants in eastern Pennsylvania. Anthracite coal has also been widely used in hand-fired furnaces. Culm has been combusted primarily in fluidized bed combustion (FBC) boilers because of its high ash content and low heating value.

Combustion of anthracite coal on a traveling grate is characterized by a coal bed of 8 to 13 cm (3 to 5 inches) in depth and a high blast of underfire air at the rear or dumping end of the grate. This high blast of air lifts incandescent fuel particles and combustion gases from the grate and reflects the particles against a long rear arch over the grate towards the front of the fuel bed where fresh or "green" fuel enters. This special furnace arch design is required to assist in the ignition of the green fuel.

A second type of stoker boiler used to burn anthracite coal is the underfeed stoker. Various types of underfeed stokers are used in industrial boiler applications but the most common for anthracite coal firing is the single-retort side-dump stoker with stationary grates. In this unit, coal is fed intermittently to the fuel bed by a ram. In very small units the coal is fed continuously by a screw. Feed coal is pushed through the retort and upward towards the tuyere blocks. Air is supplied through the tuyere blocks on each side of the retort and through openings in the side grates. Overfire air is commonly used with underfeed stokers to provide combustion air and turbulence in the flame zone directly above the active fuel bed.

In PC-fired boilers, the fuel is pulverized to the consistency of powder and pneumatically injected through burners into the furnace. Injected coal particles burn in suspension within the furnace region of the boiler. Hot flue gases rise from the furnace and provide heat exchange with boiler tubes in the walls and upper regions of the boiler. In general, PC-fired boilers operate either in a wet-bottom or dry-bottom mode; because of its high ash fusion temperature, anthracite coal is burned in dry-bottom furnaces.

For anthracite culm, combustion in conventional boiler systems is difficult due to the fuel's high ash content, high moisture content, and low heating value. However, the burning of culm in a fluidized bed system was demonstrated at a steam generation plant in Pennsylvania. A fluidized bed consists of inert particles (e. g., rock and ash) through which air is blown so that the bed behaves as a fluid. Anthracite coal enters in the space above the bed and burns in the bed. Fluidized beds can handle fuels with moisture contents up to near 70 percent (total basis) because of the large thermal mass represented by the hot inert bed particles. Fluidized beds can also handle fuels with ash contents as high as 75 percent. Heat released by combustion is transferred to in-bed steam-generating tubes. Limestone may be added to the bed to capture sulfur dioxide formed by combustion of fuel sulfur.

1.2.3 Emissions And Controls[4-6]

Particulate matter (PM) emissions from anthracite coal combustion are a function of furnace firing configuration, firing practices (boiler load, quantity and location of underfire air, soot blowing, flyash reinjection, etc.), and the ash content of the coal. Pulverized coal-fired boilers emit the highest quantity of PM per unit of fuel because they fire the anthracite in suspension, which results in a high percentage of ash carryover into exhaust gases. Traveling grate stokers and hand-fired units produce less PM per unit of fuel fired, and coarser particulates, because combustion takes place in a quiescent fuel bed without significant ash carryover into the exhaust gases. In general, PM emissions from traveling grate stokers will increase during soot blowing and flyash reinjection and with higher fuel bed underfeed air flowrates. Smoke production during combustion is rarely a problem, because of anthracite's low volatile matter content.

Limited data are available on the emission of gaseous pollutants from anthracite combustion. It is assumed, based on bituminous coal combustion data, that a large fraction of the fuel sulfur is emitted as sulfur oxides. Also, because combustion equipment, excess air rates, combustion temperatures, etc., are similar between anthracite and bituminous coal combustion, nitrogen oxide emissions are also assumed to be similar. Nitrogen oxide emissions from FBC units burning culm are typically lower than from other anthracite coal-burning boilers due to the lower operating temperatures which characterize FBC beds.

Carbon monoxide and total organic compound emissions are dependent on combustion efficiency. Generally their emission rates, defined as mass of emissions per unit of heat input, decrease with increasing boiler size. Organic compound emissions are expected to be lower for pulverized coal units and higher for underfeed and overfeed stokers due to relative combustion efficiency levels.

Controls on anthracite emissions mainly have been applied to PM. The most efficient particulate controls, fabric filters, scrubbers, and electrostatic precipitators have been installed on large pulverized anthracite-fired boilers. Fabric filters can achieve collection efficiencies exceeding 99 percent. Electrostatic precipitators typically are only 90 to 97 percent efficient, because of the characteristic high resistivity of low sulfur anthracite fly ash. It is reported that higher efficiencies can be achieved using larger precipitators and flue gas conditioning. Mechanical collectors are frequently employed upstream from these devices for large particle removal.

Older traveling grate stokers are often uncontrolled. Indeed, particulate control has often been considered unnecessary because of anthracite's low smoking tendencies and the fact that a significant fraction of large size flyash from stokers is readily collected in flyash hoppers as well as in the breeching and base of the stack. Cyclone collectors have been employed on traveling grate stokers, and limited information suggests these devices may be up to 75 percent efficient on particulate. Flyash reinjection, frequently used in traveling grate stokers to enhance fuel use efficiency, tends to increase PM emissions per unit of fuel combusted. High-energy venturi scrubbers can generally achieve PM collection efficiencies of 90 percent or greater.

Emission factors and ratings for pollutants from anthracite coal combustion and anthracite culm combustion are given in Tables 1.2-1, 1.2-2, 1.2-3, 1.2-4, 1.2-5, 1.2-6, and 1.2-7. Cumulative size distribution data and size-specific emission factors and ratings for particulate emissions are summarized in Table 1.2-8. Uncontrolled and controlled size-specific emission factors are presented in Figure 1.2-1. Particle size distribution data for bituminous coal combustion may be used for uncontrolled emissions from pulverized anthracite-fired furnaces, and data for anthracite-fired traveling grate stokers may be used for hand-fired units (Figure 1.2-2).[10-13]

Table 1.2-1 (Metric And English Units). EMISSION FACTORS FOR SPECIATED METALS FROM ANTHRACITE COAL COMBUSTION IN STOKER FIRED BOILERS[a]

EMISSION FACTOR RATING: E

Pollutant	Emission Factor Range		Average Emission Factor	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Mercury	4.4 E-05 - 6.5 E-05	8.7 E-05 - 1.3 E-04	6.5 E-05	1.3 E-04
Arsenic	BDL - 1.2 E-04	BDL - 2.4 E-04	9.3 E-05	1.9 E-04
Antimony	BDL	BDL	BDL	BDL
Beryllium	1.5 E-05 - 2.7 E-04	3.0 E-05 - 5.4 E-04	1.5 E-04	3.1 E-04
Cadmium	2.3 E-05 - 5.5 E-03	4.5 E-05 - 1.1 E-04	3.6 E-05	7.1 E-05
Chromium	3.0 E-03 - 2.5 E-02	5.9 E-03 - 4.9 E-02	1.4 E-02	2.8 E-02
Manganese	4.9 E-04 - 2.7 E-03	9.8 E-04 - 5.3 E-03	1.8 E-03	3.6 E-03
Nickel	3.9 E-03 - 1.8 E-02	7.8 E-03 - 3.5 E-02	1.3 E-02	2.6 E-02
Selenium	2.4 E-04 - 1.1 E-03	4.7 E-04 - 2.1 E-03	6.3 E-04	1.3 E-03

[a] Reference 9. Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. Source Classification Codes are 1-01-001-02, 1-02-001-04, and 1-03-001-02. BDL = below detection limit.

Table 1.2-2 (Metric And English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC) AND METHANE (CH_4) FROM ANTHRACITE COAL COMBUSTORS[a]

Source Category	TOC Emission Factor			CH_4 Emission Factor		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Stoker fired boilers[b] (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	0.10	0.20	E	ND	ND	NA
Residential space heaters[c]	ND	ND	NA	4	8	E

[a] Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 9.

[c] Reference 14.

Table 1.2-3 (Metric Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM ANTHRACITE COAL COMBUSTORS[a]

EMISSION FACTOR RATING: E

Pollutant	Stoker Fired Boilers[b] (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	Residential Space Heaters[c] (No SCC)	
	Emission Factor	Emission Factor Range	Emission Factor
Biphenyl	1.25 E-02	ND	ND
Phenanthrene	3.4 E-03	4.6 E-02 - 2.1 E-02	1.6 E-01
Naphthalene	0.65 E-01	4.5 E-03 - 2.4 E-02	1.5 E-01
Acenaphthene	ND	7.0 E-03 - 3.4 E-01	3.5 E-01
Acenaphthalene	ND	7.0 E-03 - 2.0 E-02	2.5 E-01
Fluorene	ND	4.5 E-03 - 2.9 E-02	1.7 E-02
Anthracene	ND	4.5 E-03 - 2.3 E-02	1.6 E-02
Fluoranthrene	ND	4.8 E-02 - 1.7 E-01	1.1 E-01
Pyrene	ND	2.7 E-02 - 1.2 E-01	7.9 E-02
Benzo(a)anthracene	ND	7.0 E-03 - 1.0 E-01	2.8 E-01
Chrysene	ND	1.2 E-02 - 1.1 E-01	5.3 E-02
Benzo(k)fluoranthrene	ND	7.0 E-03 - 3.1 E-02	2.5 E-01
Benzo(e)pyrene	ND	2.3 E-03 - 7.3 E-03	4.2 E-03
Benzo(a)pyrene	ND	1.9 E-03 - 4.5 E-03	3.5 E-03
Perylene	ND	3.8 E-04 - 1.2 E-03	8.5 E-04
Indeno(123-cd) perylene	ND	2.3 E-03 - 7.0 E-03	2.4 E-01
Benzo(g,h,i,) perylene	ND	2.2 E-03 - 6.0 E-03	2.1 E-01
Anthanthrene	ND	9.5 E-05 - 5.5 E-04	3.5 E-03
Coronene	ND	5.5 E-04 - 4.0 E-03	1.2 E-02

[a] Units are kg of pollutant/Mg of anthracite coal burned. SCC = Source Classification Code. ND = no data.

[b] Reference 9.

[c] Reference 14.

Table 1.2-4 (English Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM ANTHRACITE COAL COMBUSTORS[a]

EMISSION FACTOR RATING: E

	Stoker Fired Boilers[b] (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	Residential Space Heaters[c] (No SCC)	
Pollutant	Emission Factor	Emission Factor Range	Emission Factor
Biphenyl	2.5 E-02	ND	ND
Phenanthrene	6.8 E-03	9.1 E-02 - 4.3 E-02	3.2 E-01
Naphthalene	1.3 E-01	9.0 E-03 - 4.8 E-02	3.0 E-01
Acenaphthene	ND	1.4 E-02 - 6.7 E-01	7.0 E-01
Acenaphthalene	ND	1.4 E-02 - 3.0 E-01	4.9 E-01
Fluorene	ND	9.0 E-03 - 5.8 E-02	3.4 E-02
Anthracene	ND	9.0 E-03 - 4.5 E-02	3.3 E-02
Fluoranthrene	ND	9.6 E-02 - 3.3 E-01	2.2 E-01
Pyrene	ND	5.4 E-02 - 2.4 E-01	1.6 E-01
Benzo(a)anthracene	ND	1.4 E-02 - 2.0 E-01	5.5 E-01
Chrysene	ND	2.3 E-02 - 2.2 E-01	1.1 E-01
Benzo(k)fluoranthrene	ND	1.4 E-02 - 6.3 E-02	5.0 E-01
Benzo(e)pyrene	ND	4.5 E-03 - 1.5 E-02	8.4 E-03
Benzo(a)pyrene	ND	3.8 E-03 - 9.0 E-03	7.0 E-03
Perylene	ND	7.6 E-04 - 2.3 E-03	1.7 E-03
Indeno(123-cd) perylene	ND	4.5 E-03 - 1.4 E-02	4.7 E-01
Benzo(g,h,i,) perylene	ND	4.3 E-03 - 1.2 E-02	4.2 E-01
Anthanthrene	ND	1.9 E-04 - 1.1 E-03	7.0 E-03
Coronene	ND	1.1 E-03 - 8.0 E-03	2.4 E-02

[a] Units are lbs. of pollutant/ton of anthracite coal burned. SCC = Source Classification Code. ND = no data.

[b] Reference 9.

[c] Reference 14.

Table 1.2-5 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND LEAD (Pb) FROM ANTHRACITE COAL COMBUSTORS[a]

Source Category	Filterable PM Emission Factor			Condensable PM Emission Factor			Pb Emission Factor		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Stoker fired boilers[b] (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	0.4A[c]	0.8A	C	0.04A	0.08A	C	4.5 E-03	8.9 E-03	E
Hand fired units[d] (SCC 1-02-002-07, 1-03-001-03)	5	10	B	ND	ND	NA	ND	ND	NA

[a] Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] References 9-12.

[c] A = ash content of fuel, weight percent.

[d] Reference 16.

Table 1.2-6 (Metric And English Units). EMISSION FACTORS FOR NITROGEN OXIDE COMPOUNDS (NO_x) AND SULFUR DIOXIDE (SO_2) FROM ANTHRACITE COAL COMBUSTORS[a]

Source Category	NO_x Emission Factor[b]			SO_2 Emission Factor[c]		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Stoker fired boilers[d] (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	4.6	9.0	C	19.5S[e]	39S	B
FBC boilers[f] (no SCC)	0.9	1.8	E	1.5	2.9	E
Pulverized coal boilers (SCC 1-01-001-01, 1-02-001-01, 1-03-001-01)	9	18	B	19.5S	39S	B
Residential space heaters (no SCC)	1.5	3	B	19.5S	39S	B

[a] Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. SCC = Source Classification Code. FBC = fluidized bed combustion.

[b] References 17-18.

[c] Reference 19.

[d] References 10-11.

[e] S = weight percent sulfur.

[f] Reference 15. FBC boilers burning culm fuel; all other sources burning anthracite coal.

Table 1.2-7 (Metric And English Units). EMISSION FACTORS FOR CARBON MONOXIDE (CO) AND CARBON DIOXIDE (CO_2) FROM ANTHRACITE COAL COMBUSTORS[a]

Source Category	CO Emission Factor			CO_2 Emission Factor		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Stoker fired boilers[b] (SCC 1-01-001-02, 1-02-001-04, 1-03-001-02)	0.3	0.6	B	2840	5680	C
FBC boilers[c] (no SCC)	0.15	0.3	E	ND	ND	NA

[a] Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned. SCC = Source Classification Code. FBC = fluidized bed combustion. ND = no data. NA = not applicable.

[b] References 10,13.

[c] Reference 15. FBC boilers burning culm fuel; all other sources burning anthracite coal.

Table 1.2-8 (Metric And English Units). CUMULATIVE PARTICLE SIZE-DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR DRY BOTTOM BOILERS BURNING PULVERIZED ANTHRACITE COAL[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size			Cumulative Emission Factor[d] kg/Mg (lb/ton) Coal, As Fired		
	Uncontrolled	Controlled[c]		Uncontrolled	Controlled[c]	
		Multiple Cyclone	Baghouse		Multiple Cyclone	Baghouse
15	32	63	79	1.6A (3.2A)[e]	0.63A (1.26A)	0.0079A (0.016A)
10	23	55	67	1.2A (2.3A)	0.55A (1.10A)	0.0067A (0.013A)
6	17	46	51	0.9A (1.7A)	0.46A (0.92A)	0.0051A (0.010A)
2.5	6	24	32	0.3A (0.6A)	0.24A (0.48A)	0.0032A (0.006A)
1.25	2	13	21	0.1A (0.2A)	0.13A (0.26A)	0.0021A (0.004A)
1.00	2	10	18	0.1A (0.2A)	0.10A (0.20A)	0.0018A (0.004A)
0.625	1	7	ND	0.05A (0.1A)	0.07A (0.14A)	—[f]
TOTAL	100	100	100	5A (10A)	1A (2A)	0.01A (0.02A)

Table 1.2-8 (cont.).

[a] Reference 8. Source Classification Codes are 1-01-001-01, 1-02-001-01, and 1-03-001-01.
[b] Expressed as aerodynamic equivalent diameter.
[c] Estimated control efficiency for multiple cyclone is 80%; for baghouse, 99.8%.
[d] Units are kg of pollutant/Mg of coal burned and lb of pollutant/ton of coal burned.
[e] A = coal ash weight %, as fired.
[f] Insufficient data.

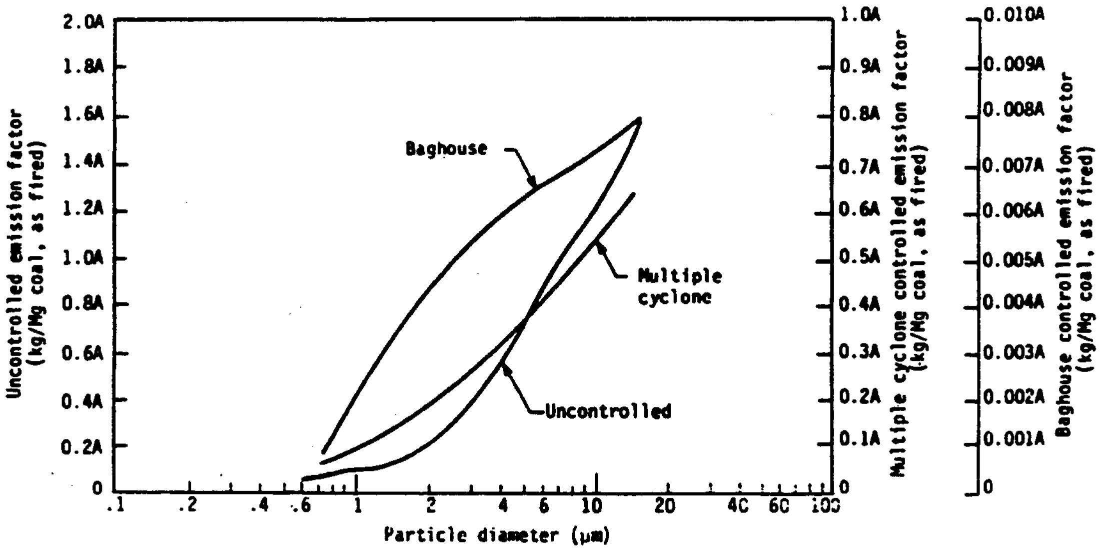

Figure 1.2-1. Cumulative size-specific emission factors for dry bottom boilers burning pulverized anthracite coal.

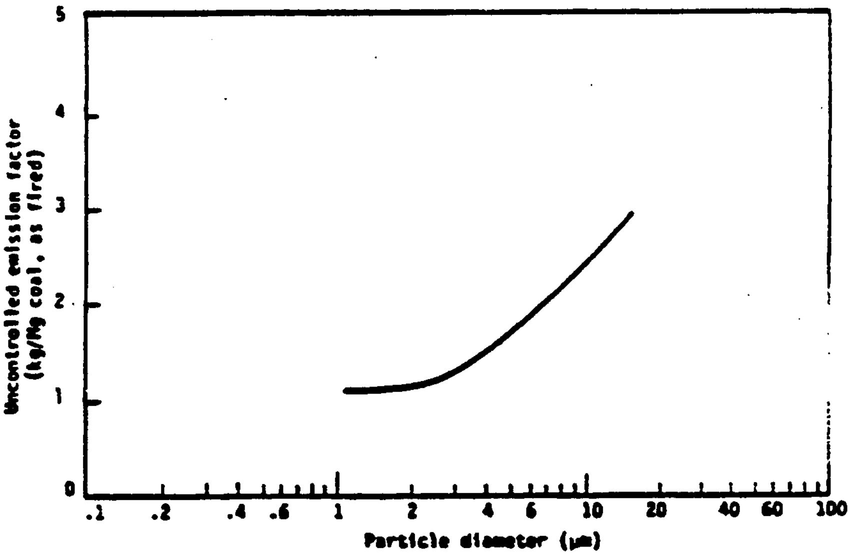

Figure 1.2-2. Cumulative size-specific emission factors for traveling grate stokers burning anthracite coal.

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12. *Source Sampling of Anthracite Coal Fired Boilers, Pennhurst Center, Spring City, PA, Final Report*, TRC Environmental Consultants, Inc., Wethersfield, CT, January 23, 1980.

13. *Source Sampling of Anthracite Coal Fired Boilers, West Chester State College, West Chester, PA*, Pennsylvania Department of Environmental Resources, Harrisburg, PA 1980.

14. *Characterization of Emissions of PAHs From Residential Coal Fired Space Heaters*, Vermont Agency of Environmental Conservation, 1983.

15. *Design, Construction, Operation, and Evaluation of a Prototype Culm Combustion Boiler/Heater Unit*, Contract No. AC21-78ET12307, U. S. Dept. of Energy, Morgantown Energy Technology Center, Morgantown, WV, October 1983.

16. *Air Pollutant Emission Factors*, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

17. *Source Test Data on Anthracite Fired Traveling Grate Stokers*, Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1975.

18. N. F. Suprenant, *et al.*, *Emissions Assessment of Conventional Stationary Combustion Systems, Volume IV: Commercial/Institutional Combustion Sources*, EPA Contract No. 68-02-2197, GCA Corporation, Bedford, MA, October 1980.

19. R. W. Cass and R. W. Bradway, *Fractional Efficiency of a Utility Boiler Baghouse: Sunbury Steam Electric Station*, EPA-600/2-76-077a, U. S. Environmental Protection Agency, Washington, DC, March 1976.

1.3 Fuel Oil Combustion

1.3.1 General[1-2, 26]

Two major categories of fuel oil are burned by combustion sources: distillate oils and residual oils. These oils are further distinguished by grade numbers, with Nos. 1 and 2 being distillate oils; Nos. 5 and 6 being residual oils; and No. 4 either distillate oil or a mixture of distillate and residual oils. No. 6 fuel oil is sometimes referred to as Bunker C. Distillate oils are more volatile and less viscous than residual oils. They have negligible nitrogen and ash contents and usually contain less than 0.3 percent sulfur (by weight). Distillate oils are used mainly in domestic and small commercial applications. Being more viscous and less volatile than distillate oils, the heavier residual oils (Nos. 5 and 6) must be heated for ease of handling and to facilitate proper atomization. Because residual oils are produced from the residue remaining after the lighter fractions (gasoline, kerosene, and distillate oils) have been removed from the crude oil, they contain significant quantities of ash, nitrogen, and sulfur. Residual oils are used mainly in utility, industrial, and large commercial applications.

1.3.2 Emissions[27]

Emissions from fuel oil combustion depend on the grade and composition of the fuel, the type and size of the boiler, the firing and loading practices used, and the level of equipment maintenance. Because the combustion characteristics of distillate and residual oils are different, their combustion can produce significantly different emissions. In general, the baseline emissions of criteria and noncriteria pollutants are those from uncontrolled combustion sources. Uncontrolled sources are those without add-on air pollution control (APC) equipment or other combustion modifications designed for emission control. Baseline emissions for sulfur dioxide (SO_2) and particulate matter (PM) can also be obtained from measurements taken upstream of APC equipment.

In this section, point source emissions of nitrogen oxides (NO_x), SO_2, PM, and carbon monoxide (CO) are being evaluated as criteria pollutants (those emissions for which National Primary and Secondary Ambient Air Quality Standards have been established. Particulate matter emissions are sometimes reported as total suspended particulate (TSP). More recent data generally quantify the portion of inhalable PM that is considered to be less than 10 micrometers in aerodynamic diameter (PM-10). In addition to the criteria pollutants, this section includes point source emissions of some noncriteria pollutants, nitrous oxide (N_2O), volatile organic compounds (VOCs), and hazardous air pollutants (HAPs), as well as data on particle size distribution to support PM-10 emission inventory efforts. Emissions of carbon dioxide (CO_2) are also being considered because of its possible participation in global climatic change and the corresponding interest in including this gas in emission inventories. Most of the carbon in fossil fuels is emitted as CO_2 during combustion. Minor amounts of carbon are emitted as CO, much of which ultimately oxidizes to CO_2 or as carbon in the ash. Finally, fugitive emissions associated with the use of oil at the combustion source are being included in this section.

Tables 1.3-1, 1.3-2, 1.3-3, and 1.3-4 present emission factors for uncontrolled emissions of criteria pollutants from fuel oil combustion. A general discussion of emissions of criteria and noncriteria pollutants from coal combustion is given in the following paragraphs. Tables 1.3-5, 1.3-6, 1.3-7, and 1.3-8 present cumulative size distribution data and size-specific emission factors for

Table 1.3-1 (Metric Units). CRITERIA POLLUTANT EMISSION FACTORS FOR UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC)[a]	SO_2[b]		SO_3[c]		NO_x[d]		CO[e,f]		Filterable PM[g]	
	kg/10^3 L	EMISSION FACTOR RATING	kg/10^3 L	EMISSION FACTOR RATING	kg/10^3 L	EMISSION FACTOR RATING	kg/10^3 L	EMISSION FACTOR RATING	kg/10^3 L	EMISSION FACTOR RATING
Utility boilers										
No. 6 oil fired, normal firing (1-01-004-01)	19S	A	0.69S	C	8	A	0.6	A	—[h]	A
No. 6 oil fired, tangential firing (1-01-004-04)	19S	A	0.69S	C	5	A	0.6	A	—[h]	A
No. 5 oil fired, normal firing (1-01-004-05)	19S	A	0.69S	C	8	A	0.6	A	—[h]	B
No. 5 oil fired, tangential firing (1-01-004-06)	19S	A	0.69S	C	5	A	0.6	A	—[h]	B
No. 4 oil fired, normal firing (1-01-005-04)	18S	A	0.69S	C	8	A	0.6	A	—[h]	B
No. 4 oil fired, tangential firing (1-01-005-05)	18S	A	0.69S	C	5	A	0.6	A	—[h]	B
Industrial boilers										
No. 6 oil fired (1-02-004-01/02/03)	19S	A	0.24S	A	6.6	A	0.6	A	—[h]	A
No. 5 oil fired (1-02-004-04)	19S	A	0.24S	A	6.6	A	0.6	A	—[h]	B
Distillate oil fired (1-02-005-01/02/03)	17S	A	0.24S	A	2.4	A	0.6	A	—[h]	A
No. 4 oil fired (1-02-005-04)	18S	A	0.24S	A	2.4	A	0.6	A	—[h]	B
Commercial/institutional/residential combustors										
No. 6 oil fired (1-03-004-01/02/03)	19S	A	0.24S	A	6.6	A	0.6	A	—[h]	A
No. 5 oil fired (1-03-004-04)	19S	A	0.24S	A	6.6	A	0.6	A	—[h]	B
Distillate oil fired (1-03-005-01/02/03)	17S	A	0.24S	A	2.4	A	0.6	A	—[h]	A
No. 4 oil fired (1-03-005-04)	18S	A	0.24S	A	2.4	A	0.6	A	—[h]	B
Residential furnace (No SCC)	17S	A	0.24S	A	2.2	A	0.6	A	0.3	A

Table 1.3-1 (cont.).

[a] SCC = Source Classification Code.

[b] References 1-6,23,42-46. S indicates that the weight % of sulfur in the oil should be multiplied by the value given.

[c] References 1-5,45-46,22.

[d] References 3-4,10,15,24,42-46,48-49. Expressed as NO_2. Test results indicate that at least 95% by weight of NO_x is NO for all boiler types except residential furnaces, where about 75% is NO. For utility vertical fired boilers use 12.6 kg/10^3 L at full load andnormal (> 15%) excess air. Nitrogen oxides emissions from residual oil combustion in industrial and commercial boilers are related to fuel nitrogen content, estimated by the following empirical relationship: kg NO_2 /10^3 L = 2.465 + 12.526(N), where N is the weight percent of nitrogen in the oil.

[e] References 3-5,8-10,23,42-46,48. CO emissions may increase by factors of 10 to 100 if the unit is improperly operated or not well maintained.

[f] Emission factors for CO_2 from oil combustion should be calculated using kg CO_2/10^3 L oil = 31.0 C (distillate) or 34.6 C (residual).

[g] References 3-5,7,21,23-24,42-46,47,49. Filterable PM is that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values include the sum of that particulate collected on the PM-10 filter of an EPA Method 201 or 201A sampling train and condensable emissions as measured by EPA Method 202.

[h] Particulate emission factors for residual oil combustion are, on average, a function of fuel oil grade and sulfur content:
No. 6 oil: 1.12(S) + 0.37 kg/10^3 L, where S is the weight % of sulfur in oil.
No. 5 oil: 1.2 kg/10^3 L
No. 4 oil: 0.84 kg/10^3 L
No. 2 oil: 0.24 kg/10^3 L

Table 1.3-2 (English Units). CRITERIA POLLUTANT EMISSION FACTORS FOR UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC)[a]	SO_2[b]		SO_3[c]		NO_x[d]		CO[e,f]		Filterable PM[g]	
	lb/10^3 gal	EMISSION FACTOR RATING	lb/10^3 gal	EMISSION FACTOR RATING	lb/10^3 gal	EMISSION FACTOR RATING	lb/10^3 gal	EMISSION FACTOR RATING	lb/10^3 gal	EMISSION FACTOR RATING
Utility boilers										
No. 6 oil fired, normal firing (1-01-004-01)	157S	A	5.7S	C	67	A	5	A	—[h]	A
No. 6 oil fired, tangential firing (1-01-004-04)	157S	A	5.7S	C	42	A	5	A	—[h]	A
No. 5 oil fired, normal firing (1-01-004-05)	157S	A	5.7S	C	67	A	5	A	—[h]	B
No. 5 oil fired, tangential firing (1-01-004-06)	157S	A	5.7S	C	42	A	5	A	—[h]	B
No. 4 oil fired, normal firing (1-01-005-04)	150S	A	5.7S	C	67	A	5	A	—[h]	B
No. 4 oil fired, tangential firing (1-01-005-05)	150S	A	5.7S	C	42	A	5	A	—[h]	B
Industrial boilers										
No. 6 oil fired (1-02-004-01/02/03)	157S	A	2S	A	55	A	5	A	—[h]	A
No. 5 oil fired (1-02-004-04)	157S	A	2S	A	55	A	5	A	—[h]	B
Distillate oil fired (1-02-005-01/02/03)	142S	A	2S	A	20	A	5	A	—[h]	A
No. 4 oil fired (1-02-005-04)	150S	A	2S	A	20	A	5	A	—[h]	B
Commercial/institutional/residential combustors										
No. 6 oil fired (1-03-004-01/02/03)	157S	A	2S	A	55	A	5	A	—[h]	A
No. 5 oil fired (1-03-004-04)	157S	A	2S	A	55	A	5	A	—[h]	B
Distillate oil fired (1-03-005-01/02/03)	142S	A	2S	A	20	A	5	A	—[h]	A
No. 4 oil fired (1-03-005-04)	150S	A	2S	A	20	A	5	A	—[h]	B
Residential furnace (No SCC)	142S	A	2S	A	18	A	5	A	3	A

Table 1.3-2 (cont.).

[a] SCC = Source Classification Code.

[b] References 1-6,23,42-46. S indicates that the weight % of sulfur in the oil should be multiplied by the value given.

[c] References 1-5,45-46,22.

[d] References 3-4,10,15,24,42-46,48-49. Expressed as NO_2. Test results indicate that at least 95% by weight of NO_x is NO for all boiler types except residential furnaces, where about 75% is NO. For utility vertical fired boilers use 105 $lb/10^3$ gal at full load and normal (> 15%) excess air. Nitrogen oxides emissions from residual oil combustion in industrial and commercial boilers are related to fuel nitrogen content, estimated by the following empirical relationship: lb $NO_2/10^3$ gal = 20.54 + 104.39(N), where N is the weight percent of nitrogen in the oil.

[e] References 3-5,8-10,23,42-46,48. CO emissions may increase by factors of 10 to 100 if the unit is improperly operated or not well maintained.

[f] Emission factors for CO_2 from oil combustion should be calculated using lb $CO_2/10^3$ gal oil = 259 C (distillate) or 288 C (residual).

[g] References 3-5,7,21,23-24,42-46,47,49. Filterable PM is that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values include the sum of that particulate collected on the PM-10 filter of an EPA Method 201 or 201A sampling train and condensable emissions as measured by EPA Method 202.

[h] Particulate emission factors for residual oil combustion are, on average, a function of fuel oil grade and sulfur content:
No. 6 oil: 9.19(S) + 3.22 $lb/10^3$ gal, where S is the weight % of sulfur in oil.
No. 5 oil: 10 $lb/10^3$ gal
No. 4 oil: 7 $lb/10^3$ gal
No. 2 oil: 2 $lb/10^3$ gal

Table 1.3-3 (Metric Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), METHANE, AND NONMETHANE TOC (NMTOC) FROM UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC)[a]	TOC[b]		Methane[b]		NMTOC[b]	
	kg/10³ L	EMISSION FACTOR RATING	kg/10³ L	EMISSION FACTOR RATING	kg/10³ L	EMISSION FACTOR RATING
Utility boilers						
No. 6 oil fired, normal firing (1-01-004-01)	0.125	A	0.034	A	0.091	A
No. 6 oil fired, tangential firing (1-01-004-04)	0.125	A	0.034	A	0.091	A
No. 5 oil fired, normal firing (1-01-004-05)	0.125	A	0.034	A	0.091	A
No. 5 oil fired, tangential firing (1-01-004-06)	0.125	A	0.034	A	0.091	A
No. 4 oil fired, normal firing (1-01-005-04)	0.125	A	0.034	A	0.091	A
No. 4 oil fired, tangential firing (1-01-005-05)	0.125	A	0.034	A	0.091	A
Industrial boilers						
No. 6 oil fired (1-02-004-01/02/03)	0.154	A	0.12	A	0.034	A
No. 5 oil fired (1-02-004-04)	0.154	A	0.12	A	0.034	A
Distillate oil fired (1-02-005-01/02/03)	0.030	A	0.006	A	0.024	A
No. 4 oil fired (1-02-005-04)	0.030	A	0.006	A	0.024	A
Commercial/institutional/ residential combustors						
No. 6 oil fired (1-03-004-01/02/03)	0.193	A	0.057	A	0.136	A
No. 5 oil fired (1-03-004-04)	0.193	A	0.057	A	0.136	A
Distillate oil fired (1-03-005-01/02/03)	0.067	A	0.026	A	0.041	A
No. 4 oil fired (1-03-005-04)	0.067	A	0.026	A	0.041	A
Residential furnace (No SCC)	0.299	A	0.214	A	0.085	A

[a] SCC = Source Classification Code.

[b] References 16-19. Volatile organic compound emissions can increase by several orders of magnitude if the boiler is improperly operated or is not well maintained.

Table 1.3-4 (English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), METHANE, AND NONMETHANE TOC (NMTOC) FROM UNCONTROLLED FUEL OIL COMBUSTION

Firing Configuration (SCC)[a]	TOC[b]		Methane[b]		NMTOC[b]	
	lb/10^3 gal	EMISSION FACTOR RATING	lb/10^3 gal	EMISSION FACTOR RATING	lb/10^3 gal	EMISSION FACTOR RATING
Utility boilers						
No. 6 oil fired, normal firing (1-01-004-01)	1.04	A	0.28	A	0.76	A
No. 6 oil fired, tangential firing (1-01-004-04)	1.04	A	0.28	A	0.76	A
No. 5 oil fired, normal firing (1-01-004-05)	1.04	A	0.28	A	0.76	A
No. 5 oil fired, tangential firing (1-01-004-06)	1.04	A	0.28	A	0.76	A
No. 4 oil fired, normal firing (1-01-005-04)	1.04	A	0.28	A	0.76	A
No. 4 oil fired, tangential firing (1-01-005-05)	1.04	A	0.28	A	0.76	A
Industrial boilers						
No. 6 oil fired (1-02-004-01/02/03)	1.28	A	1	A	0.28	A
No. 5 oil fired (1-02-004-04)	1.28	A	1	A	0.28	A
Distillate oil fired (1-02-005-01/02/03)	0.252	A	0.052	A	0.2	A
No. 4 oil fired (1-02-005-04)	0.252	A	0.052	A	0.2	A
Commercial/institutional/ residential combustors						
No. 6 oil fired (1-03-004-01/02/03)	1.605	A	0.475	A	1.13	A
No. 5 oil fired (1-03-004-04)	1.605	A	0.475	A	1.13	A
Distillate oil fired (1-03-005-01/02/03)	0.556	A	0.216	A	0.34	A
No. 4 oil fired (1-03-005-04)	0.556	A	0.216	A	0.34	A
Residential furnace (No SCC)	2.493	A	1.78	A	0.713	A

[a] SCC = Source Classification Code.

[b] References 16-19. Volatile organic compound emissions can increase by several orders of magnitude if the boiler is improperly operated or is not well maintained.

Table 1.3-5 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UTILITY BOILERS FIRING RESIDUAL OIL[a]

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size			Cumulative Emission Factor [kg/10^3 L (lb/10^3 gal)]					
		Controlled		Uncontrolled[c]		ESP Controlled[d]		Scrubber Controlled[e]	
	Uncontrolled	ESP	Scrubber	Factor	RATING	Factor	RATING	Factor	RATING
15	80	75	100	0.80A (6.7A)	C	0.0060A (0.05A)	E	0.06A (0.50A)	D
10	71	63	100	0.71A (5.9A)	C	0.005A (0.042A)	E	0.06A (0.050A)	D
6	58	52	100	0.58A (4.8A)	C	0.0042A (0.035A)	E	0.06A (0.50A)	D
2.5	52	41	97	0.52A (4.3A)	C	0.0033A (0.028A)	E	0.058A (0.48A)	D
1.25	43	31	91	0.43A (3.6A)	C	0.0025A (0.021A)	E	0.055A (0.46A)	D
1.00	39	28	84	0.39A (3.3A)	C	0.0022A (0.018A)	E	0.050A (0.42A)	D
0.625	20	20	64	0.20A (1.74)	C	0.0008A (0.007A)	E	0.038A (0.32A)	D
TOTAL	100	100	100	1A (8.3A)	C	0.008A (0.067A)	E	0.06A (0.50A)	D

[a] Reference 29. Source Classification Codes 1-01-004-01/04/05/06 and 1-01-005-04/05. ESP = electrostatic precipitator.

[b] Expressed as aerodynamic equivalent diameter.

[c] Particulate emission factors for residual oil combustion without emission controls are, on average, a function of fuel oil grade and sulfur content:

No. 6 oil: A = 1.12(S) + 0.37 kg/10^3 L, where S is the weight % of sulfur in the oil.
No. 5 oil: A = 1.2 kg/10^3 L
No. 4 oil: A = 0.84 kg/10^3 L

[d] Estimated control efficiency for ESP is 99.2%.

[e] Estimated control efficiency for scrubber is 94%.

Table 1.3-6 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR INDUSTRIAL BOILERS FIRING RESIDUAL OIL[a]

Particle Size[b] (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor[c] [Kg/10^3 l (lb/10^3 gal)]			
			Uncontrolled		Multiple Cyclone Controlled[e]	
	Uncontrolled	Multiple Cyclone Controlled	Factor	RATING	Factor	RATING
15	91	100	0.91A (7.59A)	D	0.20A (1.67A)	E
10	86	95	0.86A (7.17A)	D	0.19A (1.58A)	E
6	77	72	0.77A (6.42A)	D	0.14A (1.17A)	E
2.5	56	22	0.56A (4.67A)	D	0.04A (0.33A)	E
1.25	39	21	0.39A (3.25A)	D	0.04A (0.33A)	E
1.00	36	21	0.36A (3.00A)	D	0.04A (0.33A)	E
0.625	30	—[d]	0.30A (2.50A)	D	—[d]	NA
TOTAL	100	100	1A (8.34A)	D	0.2A (1.67A)	E

[a] Reference 29. Source Classification Codes 1-02-004-01/02/03/04 and 1-02-005-04. NA = not applicable.

[b] Expressed as aerodynamic equivalent diameter.

[c] Particulate emission factors for residual oil combustion without emission controls are, on average, a function of fuel oil grade and sulfur content:

No. 6 oil: $A = 1.12(S) + 0.38$ kg/10^3 L, where S is the weight % of sulfur in the oil.
No. 5 oil: $A = 1.2$ kg/10^3 L
No. 4 oil: $A = 0.84$ kg/10^3 L

[d] Insufficient data.

[e] Estimated control efficiency for multiple cyclone is 80%.

Table 1.3-7 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNCONTROLLED INDUSTRIAL BOILERS FIRING DISTILLATE OIL[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor [kg/10^3 L (lb/10^3 gal)]
	Uncontrolled	Uncontrolled
15	68	0.16 (1.33)
10	50	0.12 (1.00)
6	30	0.07 (0.58)
2.5	12	0.03 (0.25)
1.25	9	0.02 (0.17)
1.00	8	0.02 (0.17)
0.625	2	0.005 (0.04)
TOTAL	100	0.24 (2.00)

[a] Reference 29. Source Classification Codes 1-02-005-01/02/03.

[b] Expressed as aerodynamic equivalent diameter.

Table 1.3-8 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNCONTROLLED COMMERCIAL BOILERS BURNING RESIDUAL AND DISTILLATE OIL[a]

EMISSION FACTOR RATING: D

Particle Size[b] (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor[c] [kg/10^3 L (lb/10^3 gal)]	
	Uncontrolled, Residual Oil	Uncontrolled, Distillate Oil	Uncontrolled, Residual Oil	Uncontrolled, Distillate Oil
15	78	60	0.78A (6.50A)	0.14 (1.17)
10	62	55	0.62A (5.17A)	0.13 (1.08)
6	44	49	0.44A (3.67A)	0.12 (1.00)
2.5	23	42	0.23A (1.92A)	0.10 (0.83)
1.25	16	38	0.16A (1.33A)	0.09 (0.75)
1.00	14	37	0.14A (1.17A)	0.09 (0.75)
0.625	13	35	0.13A (1.08A)	0.08 (0.67)
TOTAL	100	100	1A (8.34A)	0.24 (2.00)

[a] Reference 29. Source Classification Codes: 1-03-004-01/02/03/04 and 1-03-005-01/02/03/04.

[b] Expressed as aerodynamic equivalent diameter.

[c] Particulate emission factors for residual oil combustion without emission controls are, on average, a function of fuel oil grade and sulfur content:
No. 6 oil: $A = 1.12(S) + 0.37$ kg/10^3 L, where S is the weight % of sulfur in the oil.
No. 5 oil: $A = 1.2$ kg/10^3 L
No. 4 oil: $A = 0.84$ kg/10^3 L
No. 2 oil: $A = 0.24$ kg/10^3 L

particulate emissions from fuel oil combustion. Uncontrolled and controlled size-specific emission factors are presented in Figure 1.3-1, Figure 1.3-2, Figure 1.3-3, and Figure 1.3-4. Distillate and residual oil categories aregiven separately, because their combustion produces significantly different particulate, SO_2, and NO_x emissions.

1.3.2.1 Particulate Matter Emissions[3-7,12-13,21,23-24]

Particulate matter emissions depend predominantly on the grade of fuel fired. Combustion of lighter distillate oils results in significantly lower PM formation than does combustion of heavier residual oils. Among residual oils, firing of Nos. 4 or 5 oils usually produces less PM than does the firing of heavier No. 6 oil.

In general, PM emissions depend on the completeness of combustion as well as on the oil ash content. The PM emitted by distillate oil-fired boilers is primarily carbonaceous particles resulting from incomplete combustion of oil and is not correlated to the ash or sulfur content of the oil. However, PM emissions from residual oil burning is related to the oil sulfur content. This is because low sulfur No. 6 oil, either refined from naturally low sulfur crude oil or desulfurized by one of

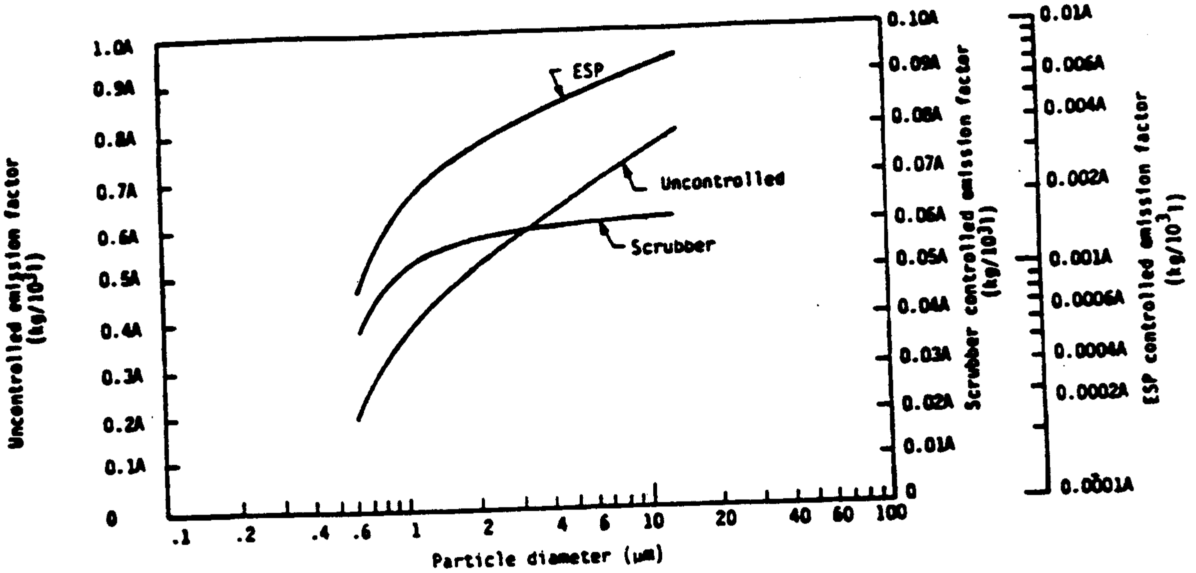

Figure 1.3-1. Cumulative size-specific emission factors for utility boilers firing residual oil.

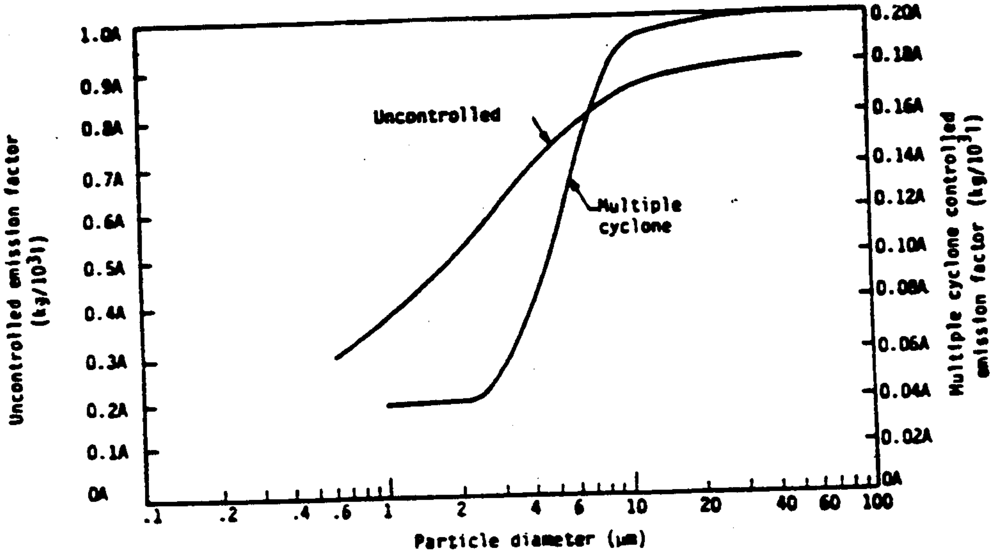

Figure 1.3-2. Cumulative size-specific emission factors for industrial boilers firing residual oil.

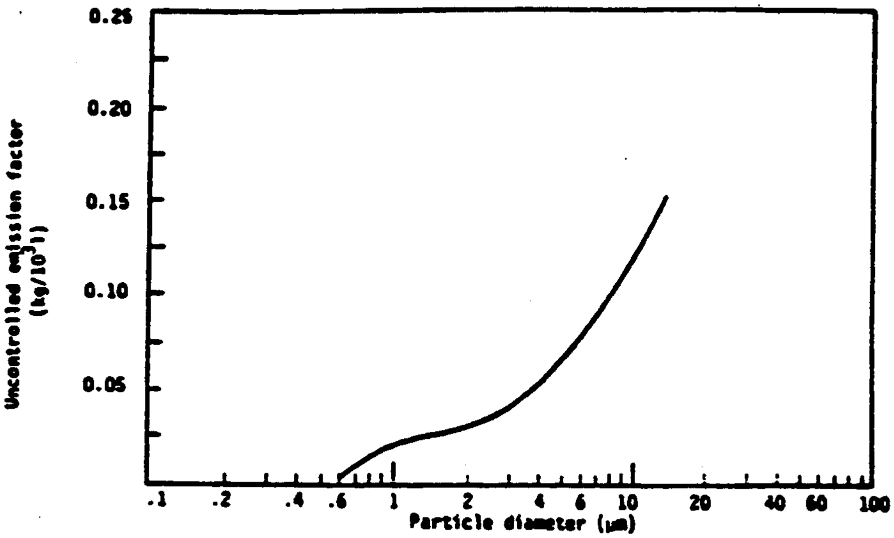

Figure 1.3-3. Cumulative size-specific emission factors for uncontrolled industrial boilers firing distillate oil.

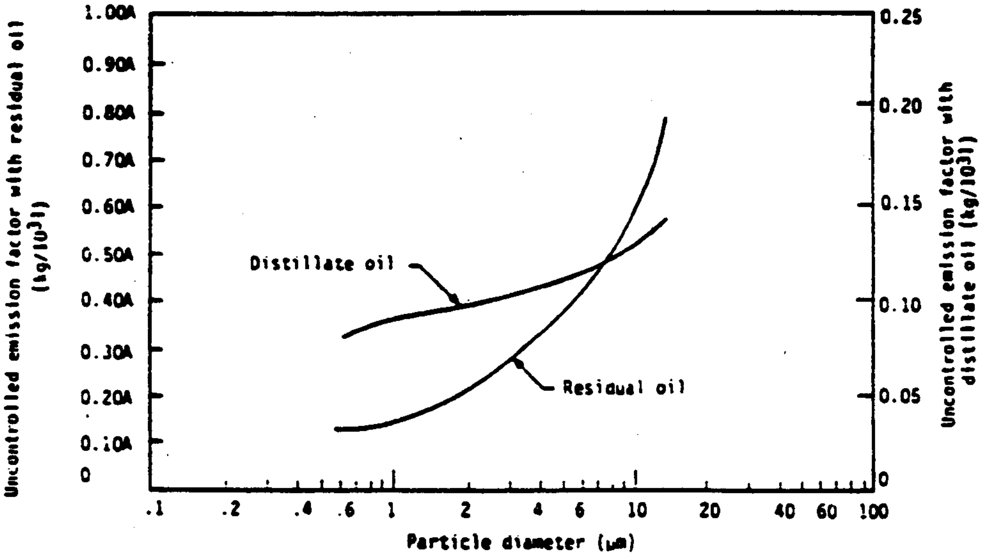

Figure 1.3-4. Cumulative size-specific emission factors for uncontrolled commercial boilers burning residual and distillate oil.

several processes, exhibits substantially lower viscosity and reduced asphaltene, ash, and sulfur contents, which results in better atomization and more complete combustion.

Boiler load can also affect particulate emissions in units firing No. 6 oil. At low load conditions, particulate emissions from utility boilers may be lowered by 30 to 40 percent and by as much as 60 percent from small industrial and commercial units. However, no significant particulate emissions reductions have been noted at low loads from boilers firing any of the lighter grades. At very low load conditions, proper combustion conditions may be difficult to maintain and particulate emissions may increase significantly.

1.3.2.2 Sulfur Oxides Emissions[1-6,22] -

Sulfur oxides (SO_x) emissions are generated during oil combustion from the oxidation of sulfur contained in the fuel. The emissions of SO_x from conventional combustion systems are predominantly in the form of SO_2. Uncontrolled SO_x emissions are almost entirely dependent on the sulfur content of the fuel and are not affected by boiler size, burner design, or grade of fuel being fired. On average, more than 95 percent of the fuel sulfur is converted to SO_2: about 1 to 5 percent is further oxidized to sulfur trioxide (SO_3); and about 1 to 3 percent is emitted as sulfate particulate. SO_3 readily reacts with water vapor (both in the atmosphere and in flue gases) to form a sulfuric acid mist.

1.3.2.3 Nitrogen Oxides Emissions[1-11,14,15,20,24-25,28-29,41] -

Oxides of nitrogen (NO_x) formed in combustion processes are due either to thermal fixation of atmospheric nitrogen in the combustion air ("thermal NO_x"), or to the conversion of chemically bound nitrogen in the fuel ("fuel NO_x"). The term NO_x refers to the composite of nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide is not included in NO_x but has taken on recent interest because of atmospheric effects. Test data have shown that for most external fossil fuel combustion systems, over 95 percent of the emitted NO_x is in the form of NO.

Experimental measurements of thermal NO_x formation have shown that NO_x concentration is exponentially dependent on temperature, and proportional to N_2 concentration in the flame, the square root of O_2 concentration in the flame, and the residence time. Thus, the formation of thermal NO_x is affected by four factors: (1) peak temperature, (2) fuel nitrogen concentration, (3) oxygen concentration, and (4) time of exposure at peak temperature. The emission trends due to changes in these factors are generally consistent for all types of boilers: an increase in flame temperature, oxygen availability, and/or residence time at high temperatures leads to an increase in NO_x production.

Fuel nitrogen conversion is the more important NO_x-forming mechanism in residual oil boilers. It can account for 50 percent of the total NO_x emissions from residual oil firing. The percent conversion of fuel nitrogen to NO_x varies greatly, however; typically from 20 to 90 percent of nitrogen in oil is converted to NO_x. Except in certain large units having unusually high peak flame temperatures, or in units firing a low nitrogen content residual oil, fuel NO_x generally accounts for over 50 percent of the total NO_x generated. Thermal fixation, on the other hand, is the dominant NO_x forming mechanism in units firing distillate oils, primarily because of the negligible nitrogen content in these lighter oils. Because distillate oil-fired boilers usually have lower heat release rates, the quantity of thermal NO_x formed in them is less than that of larger units.[50]

A number of variables influence how much NO_x is formed by these two mechanisms. One important variable is firing configuration. NO_x emissions from tangentially (corner) fired boilers are, on the average, less than those of horizontally opposed units. Also important are the firing practices employed during boiler operation. Low excess air (LEA) firing, flue gas recirculation (FGR), staged combustion (SC), reduced air preheat (RAP), low NO_x burners (LNBs), or some combination thereof may result in NO_x reductions of 5 to 60 percent. Load reduction (LR) can likewise decrease NO_x production. Nitrogen oxides emissions may be reduced from 0.5 to 1 percent for each percentage reduction in load from full load operation. It should be noted that most of these variables, with the exception of excess air, influence the NO_x emissions only of large oil fired boilers. Low excess air-firing is possible in many small boilers, but the resulting NO_x reductions are less significant.

Recent N_2O emissions data indicate that direct N_2O emissions from oil combustion units are considerably below the measurements made prior to 1988. Nevertheless, the N_2O formation and reaction mechanisms are still not well understood or well characterized. Additional sampling and research is needed to fully characterize N_2O emissions and to understand the N_2O formation mechanism. Emissions can vary widely from unit to unit, or even from the same unit at different operating conditions. It has been shown in some cases that N_2O increases with decreasing boiler temperature. For this update, average emission factors based on reported test data have been developed for conventional oil combustion systems. These factors are presented in Table 1.3-9.

Table 1.3-9 (Metric And English Units). EMISSION FACTORS FOR NITROUS OXIDE (N_2O), POLYCYCLIC ORGANIC MATTER (POM), AND FORMALDEHYDE (HCOH) FROM FUEL OIL COMBUSTION

EMISSION FACTOR RATING: E

Firing Configuration (SCC)[a]	Emission Factor, kg/10^3 L (lb/10^{12} Btu)		
	N_2O[b]	POM[c]	HCOH[c]
Utility/industrial/commercial boilers			
No. 6 oil fired (1-01-004-01, 1-02-004-01, 1-03-004-01)	0.013 (0.11)	3.2-3.6 (7.4-8.4)[d]	69-174 (161-405)
Distillate oil fired (1-01-005-01, 1-02-005-01, 1-03-005-01)	0.013 (0.11)	9.7 (22)[e]	100-174 (233-405)
Residential furnaces (No SCC)	0.006 (0.05)	ND	ND

[a] SCC = Source Classification Code. ND = no data.
[b] References 28-29.
[c] References 16-19.
[d] Particulate and gaseous POM.
[e] Particulate POM only.

The new source performance standards (NSPS) for PM, SO_2, and NO_x emissions from residual oil combustion in fossil fuel-fired boilers are shown in Table 1.3-10.

1.3.2.4 Carbon Monoxide Emissions[16-19] -

The rate of CO emissions from combustion sources depends on the oxidation efficiency of the fuel. By controlling the combustion process carefully, CO emissions can be minimized. Thus if a unit is operated improperly or not well maintained, the resulting concentrations of CO (as well as organic compounds) may increase by several orders of magnitude. Smaller boilers, heaters, and furnaces tend to emit more of these pollutants than larger combustors. This is because smaller units

Table 1.3-10 (Metric And English Units). NEW SOURCE PERFORMANCE STANDARDS FOR FOSSIL FUEL FIRED BOILERS

Standard/ Boiler Types/ Applicability Criteria	Boiler Size MW (Million Btu/hr)	Fuel Or Boiler Type	PM ng/J (lb/MMBtu) [% reduction]	SO_2 ng/J (lb/MMBtu) [% reduction]	NO_x ng/J (lb/MMBtu) [% reduction]
Subpart D	>73 (>250)	Gas	43 (0.10)	NA[d]	86 (0.20)
Industrial-Utility		Oil	43 (0.10)	340 (0.80)	129 (0.30)
Commence construction after 8/17/71		Bit./Subbit. Coal	43 (0.10)	520 (1.20)	300 (0.70)
Subpart Da	>73 (>250)	Gas	13 (0.03) [NA]	340 (0.80) [90][a]	86 (0.20) [25]
Utility Commence construction after 9/18/78		Oil	13 (0.03) [70]	340 (0.80) [90][a]	130 (0.30) [30]
		Bit./Subbit. Coal	13 (0.03) [99]	520 (1.20) [90][a]	260/210[c] (0.60/0.50) [65/65]
Subpart Db	>29 (>100)	Gas	NA[d]	NA[d]	43[f] (0.10)
Industrial-Commercial Institution		Distillate Oil	43 (0.10)	340[n] (0.80) [90]	43[f] (0.10)
Commence construction after 6/19/84[m]		Residual Oil	(Same as for distillate oil)	(Same as for distillate oil)	130[g] (0.30)
		Pulverized Bit./Subbit. Coal	22[e] (0.05)	520[e] (1.20) [90]	300 (0.70)
		Spreader Stoker & FBC	22[e] (0.05)	520[e] (1.20) [90]	260 (0.60)
		Mass-Feed Stoker	22[e] (0.05)	520[e] (1.20) [90]	210 (0.50)

Table 1.1-10 (cont.).

Standard/ Boiler Types/ Applicability Criteria	Boiler Size MW (Million Btu/hr)	Fuel Or Boiler Type	PM ng/J (lb/MMBtu) [% reduction]	SO_2 ng/J (lb/MMBtu) [% reduction]	NO_x ng/J (lb/MMBtu) [% reduction]
Subpart Dc	2.9 - 29 (10 - 100)	Gas	—[h]	—	—
Small Industrial Commercial-Institutional		Oil	—[h,j]	215 (0.50)	—
Commence construction after 6/9/89		Bit./Subbit. Coal	22[j,k] (0.05)	520[k] (1.20) [90]	—

[a] Zero percent reduction when emissions are less than 86 ng/J (0.20 lb/MMBtu). FBC = fluidized bed combustion. NA = not applicable.

[b] 70 percent reduction when emissions are less than 260 ng/J (0.60 lb/MMBtu).

[c] The first number applies to bituminous coal and the second to subbituminous coal.

[d] Standard applies when gas is fired in combination with coal; see 40 CFR 60, Subpart Db.

[e] Standard is adjusted for fuel combinations and capacity factor limits; see 40 CFR 60, Subpart Db.

[f] For furnace heat release rates greater than 730,000 J/s-m^3 (70,000 Btu/hr-ft^3), the standard is 86 ng/J (0.20 lb/MMBtu).

[g] For furnace heat release rates greater than 730,000 J/s-m^3 (70,000 Btu/hr-ft^3), the standard is 170 ng/J (0.40 lb/MMBtu).

[h] Standard applies when gas or oil is fired in combination with coal; see 40 CFR 60, Subpart Dc.

[j] 20 percent capacity limit applies for heat input capacities of 8.7 Mwt (30 MMBtu/hr) or greater.

[k] Standard is adjusted for fuel combinations and capacity factor limits; see 40 CFR 60, Subpart Dc.

[m] Additional requirements apply to facilities which commenced construction, modification, or reconstruction after 6/19/84 but on or before 6/19/86 (see 40 Code of Federal Regulations Part 60, Subpart Db).

[n] 215 ng/J (0.50 lb/million Btu) limit (but no percent reduction requirement) applies if facilities combust only very low sulfur oil (<0.5 wt. % sulfur).

usually have a higher ratio of heat transfer surface area to flame volume leading to reduced flame temperature and combustion intensity and, therefore, lower combustion efficiency than larger combustors.

The presence of CO in the exhaust gases of combustion systems results principally from incomplete fuel combustion. Several conditions can lead to incomplete combustion, including:

- insufficient oxygen (O_2) availability;
- poor fuel/air mixing;
- cold wall flame quenching;
- reduced combustion temperature;

- decreased combustion gas residence time; and
- load reduction (i. e., reduced combustion intensity).

Since various combustion modifications for NO_x reduction can produce one or more of the above conditions, the possibility of increased CO emissions is a concern for environmental, energy efficiency, and operational reasons.

1.3.2.5 Organic Compound Emissions[16-19,30-35,64] -

Small amounts of organic compounds are emitted from combustion. As with CO emissions, the rate at which organic compounds are emitted depends, to some extent, on the combustion efficiency of the boiler. Therefore, any combustion modification which reduces the combustion efficiency will most likely increase the concentrations of organic compounds in the flue gases.

Total organic compounds (TOCs) include VOCs, semi-volatile organic compounds, and condensible organic compounds. Emissions of VOCs are primarily characterized by the criteria pollutant class of unburned vapor phase hydrocarbons. Unburned hydrocarbon emissions can include essentially all vapor phase organic compounds emitted from a combustion source. These are primarily emissions of aliphatic, oxygenated, and low molecular weight aromatic compounds which exist in the vapor phase at flue gas temperatures. These emissions include all alkanes, alkenes, aldehydes, carboxylic acids, and substituted benzenes (e. g., benzene, toluene, xylene, and ethyl benzene).

The remaining organic emissions are composed largely of compounds emitted from combustion sources in a condensed phase. These compounds can almost exclusively be classed into a group known as polycyclic organic matter (POM), and a subset of compounds called polynuclear aromatic hydrocarbons (PNA or PAH). There are also PAH-nitrogen analogs. Information available in the literature on POM compounds generally pertains to these PAH groups.

Formaldehyde is formed and emitted during combustion of hydrocarbon-based fuels including coal and oil. Formaldehyde is present in the vapor phase of the flue gas. Formaldehyde is subject to oxidation and decomposition at the high temperatures encountered during combustion. Thus, larger units with efficient combustion (resulting from closely regulated air-fuel ratios, uniformly high combustion chamber temperatures, and relatively long gas retention times) have lower formaldehyde emission rates than do smaller, less efficient combustion units. Average emission factors for POM and formaldehyde from fuel oil combustors are presented in Table 1.3-9, together with N_2O emissions data.

1.3.2.6 Trace Element Emissions[16-19,36-40] -

Trace elements are also emitted from the combustion of oil. For this update of AP-42, trace metals included in the list of 189 hazardous air pollutants under Title III of the 1990 Clean Air Act Amendments are considered. The quantity of trace metals emitted depends on combustion temperature, fuel feed mechanism, and the composition of the fuel. The temperature determines the degree of volatilization of specific compounds contained in the fuel. The fuel feed mechanism affects the separation of emissions into bottom ash and fly ash.

The quantity of any given metal emitted, in general, depends on:

- the physical and chemical properties of the element itself;
- its concentration in the fuel;

- the combustion conditions; and
- the type of particulate control device used, and its collection efficiency as a function of particle size.

It has become widely recognized that some trace metals concentrate in certain waste particle streams from a combustor (bottom ash, collector ash, flue gas particulate), while others do not. Various classification schemes have been developed to describe this partitioning. The classification scheme used by Baig, et al. is as follows:

- Class 1: Elements which are approximately equally distributed between fly ash and bottom ash, or show little or no small particle enrichment.
- Class 2: Elements which are enriched in fly ash relative to bottom ash, or show increasing enrichment with decreasing particle size.
- Class 3: Elements which are intermediate between Classes 1 and 2.
- Class 4: Elements which are emitted in the gas phase.

By understanding trace metal partitioning and concentration in fine particulate, it is possible to postulate the effects of combustion controls on incremental trace metal emissions. For example, several NO_x controls for boilers reduce peak flame temperatures (e. g., SC, FGR, RAP, and LR). If combustion temperatures are reduced, fewer Class 2 metals will initially volatilize, and fewer will be available for subsequent condensation and enrichment on fine PM. Therefore, for combustors with particulate controls, lowered volatile metal emissions should result due to improved particulate removal. Flue gas emissions of Class 1 metals (the non-segregating trace metals) should remain relatively unchanged.

Lower local O_2 concentrations are also expected to affect segregating metal emissions from boilers with particle controls. Lower O_2 availability decreases the possibility of volatile metal oxidation to less volatile oxides. Under these conditions, Class 2 metals should remain in the vapor phase as they enter the cooler sections of the boiler. More redistribution to small particles should occur and emissions should increase. Again, Class 1 metal emissions should remain unchanged.

Other combustion NO_x controls which decrease local O_2 concentrations (e. g., SC and FGR) also reduce peak flame temperatures. Under these conditions, the effect of reduced combustion temperature is expected to be stronger than that of lower O_2 concentrations. Available trace metals emissions data for fuel oil combustion in boilers are summarized in Table 1.3-11.

1.3.3 Controls

The various control techniques and/or devices employed on oil combustion sources depend on the source category and the pollutant being controlled. Only controls for criteria pollutants are discussed here because controls for noncriteria emissions have not been demonstrated or commercialized for oil combustion sources.

Control techniques may be classified into three broad categories: fuel substitution, combustion modification, and postcombustion control. Fuel substitution involves using "cleaner" fuels to reduce emissions. Combustion modification and postcombustion control are both applicable and widely commercialized for oil combustion sources. Combustion modification is applied primarily

Table 1.3-11 (Metric And English Units). EMISSION FACTORS FOR TRACE ELEMENTS FROM FUEL OIL COMBUSTION SOURCES

EMISSION FACTOR RATING: E

Firing Configuration (SCC)[a]	Emission Factor, pg/J (lb/10^{12} Btu)[b]										
	Sb	As	Be	Cd	Cr	Co	Pb	Mn	Hg	Ni	Se
No. 6 oil fired (1-01-004-01/04 1-02-004-01, 1-03-004-01)	10-20 (24-46)	8.2-49 (19-114)	1.8 (4.2)	6.8-91 (16-211)	9.0-55 (21-128)	33-50 (77-121)	12-80 (28-194)	10-30 (23-74)	0.6-14 (1.4-32)	360-964 (837-2330)	16 (38)
Distillate oil fired (1-01-005-01, 1-02-005-01, 1-03-005-01)	ND	1.8 (4.2)	1.1 (2.5)	4.5 (11)	21-29 (48-67)	ND	3.8 (8.9)	6.0 (14)	1.3 (3.0)	73 (170)	ND

[a] SCC = Source Classification Code. ND = no data.

[b] References 16-19,36-40. The emission factors in this table represent the ranges of factors reported in the literature. If only one data point was found, it is still reported in this table.

for NO_x control purposes, although for small units, some reduction in PM emissions may be available through improved combustion practice. Postcombustion control is applied to emissions of particulate matter, SO_2, and, to some extent, NO_x, from oil combustion.

1.3.3.1 Fuel Substitution[3,5,12,56] -

Fuel substitution, or the firing of "cleaner" fuel oils, can substantially reduce emissions of a number of pollutants. Lower sulfur oils, for instance, will reduce SO_x emissions in all boilers, regardless of the size or type of boiler or grade of oil fired. Particulates generally will be reduced when a lighter grade of oil is fired. Nitrogen oxide emissions will be reduced by switching to either a distillate oil or a residual oil with less nitrogen. The practice of fuel substitution, however, may be limited by the ability of a given operation to fire a better grade of oil and by the cost and availability of that fuel.

1.3.3.2 Combustion Modification[1-4,8-9,13-14,20] -

Combustion modification includes any physical change in the boiler apparatus itself or in its operation. Regular maintenance of the burner system, for example, is important to ensure proper atomization and subsequent minimization of any unburned combustibles. Periodic tuning is important in small units for maximum operating efficiency and emissions control, particularly for PM and CO emissions. Combustion modifications, such as LEA, FGR, SC, and reduced load operation result in lowered NO_x emissions in large facilities.

Particulate Matter Control[56] -

Control of PM emissions from residential and commercial units is accomplished by improved burner servicing and by incorporating appropriate equipment design changes to improve oil atomization and combustion aerodynamics. Optimization of combustion aerodynamics using a flame retention device, swirl, and/or recirculation is considered to be the best approach toward achieving the triple goals of low PM emissions, low NO_x emissions, and high thermal efficiency.

Large industrial and utility boilers are generally well-designed and well-maintained so that soot and condensible organic compound emissions are minimized. Particulate matter emissions are more a result of entrained fly ash in such units. Therefore, postcombustion controls are necessary to reduce PM emissions from these sources.

NO_x Control[37,57-60] -

In boilers fired on crude oil or residual oil, the control of fuel NO_x is very important in achieving the desired degree of NO_x reduction since, typically, fuel NO_x accounts for 60 to 80 percent of the total NO_x formed. Fuel nitrogen conversion to NO_x is highly dependent on the fuel-to-air ratio in the combustion zone and, in contrast to thermal NO_x formation, is relatively insensitive to small changes in combustion zone temperature. In general, increased mixing of fuel and air increases nitrogen conversion which, in turn, increases fuel NO_x. Thus, to reduce fuel NO_x formation, the most common combustion modification technique is to suppress combustion air levels below the theoretical amount required for complete combustion. The lack of oxygen creates reducing conditions that, given sufficient time at high temperatures, cause volatile fuel nitrogen to convert to N_2 rather than NO.

In the formation of both thermal and fuel NO_x, all of the above reactions and conversions do not take place at the same time, temperature, or rate. The actual mechanisms for NO_x formation in a specific situation are dependent on the quantity of fuel-bound nitrogen, if any, and the temperature and stoichiometry of the flame zone. Although the NO_x formation mechanisms are different, both thermal and fuel NO_x are promoted by rapid mixing of fuel and combustion air. This rate of mixing may itself depend on fuel characteristics such as the atomization quality of liquid fuels. Additionally, thermal NO_x is greatly increased by increased residence time at high temperatures, as mentioned above. Thus, primary combustion modification controls for both thermal and fuel NO_x typically rely on the following control approaches:

- Decrease primary flame zone O_2 level by:
    - decreasing overall O_2 level;
    - controlling (delaying) mixing of fuel and air; and
    - use of fuel-rich primary flame zone.
- Decrease residence time at high temperatures by:
    - decreasing adiabatic flame temperature through dilution;
    - decreasing combustion intensity;
    - increasing flame cooling; and
    - decreased primary flame zone residence time.

Table 1.3-12 shows the relationship between these control strategies and the combustion modification NO_x control techniques currently in use on boilers firing fuel oil.

1.3.3.3 Postcombustion Control[54-56] -

Postcombustion control refers to removal of pollutants from combustion flue gases downstream of the combustion zone of the boiler. Flue gas cleaning is usually employed on large oil-fired boilers.

Particulate Matter Control[56] -

Large industrial and utility boilers are generally, well-designed and well-maintained. Hence, particulate collectors are usually the only method of controlling PM emissions from these sources. Use of such collectors is described below.

Mechanical collectors, a prevalent type of control device, are primarily useful in controlling particulates generated during soot blowing, during upset conditions, or when a very dirty heavy oil is fired. For these situations, high efficiency cyclonic collectors can achieve up to 85 percent control of particulate. Under normal firing conditions, or when a clean oil is combusted, cyclonic collectors are not nearly so effective because of the high percentage of small particles (less than 3 micrometers in diameter) emitted.

Electrostatic precipitators (ESPs) are commonly used in oil-fired power plants. Older precipitators, usually small, typically remove 40 to 60 percent of the emitted PM. Because of the low ash content of the oil, greater collection efficiency may not be required. Currently, new or rebuilt ESPs can achieve collection efficiencies of up to 90 percent.

Scrubbing systems have also been installed on oil-fired boilers to control both sulfur oxides and particulate. These systems can achieve SO_2 removal efficiencies of 90 to 95 percent and particulate control efficiencies of 50 to 60 percent.

NO_x Control[61] -

The variety of flue gas treatment NO_x control technologies is nearly as great as combustion modification techniques. Although these technologies differ greatly in cost, complexity, and effectiveness, they all involve the same basic chemical reaction: the combination of NO_x with ammonia (NH_3) to form nitrogen (N_2) and water (H_2O).

Table 1.3-12. COMBUSTION MODIFICATION NO_x CONTROLS FOR OIL-FIRED BOILERS[a]

Control Technique	Description Of Technique	Effectiveness Of Control (Percent NO_x Reduction)		Range Of Application	Commercial Availability/ R&D Status	Comments
		Residual Oil	Distillate Oil			
Low Excess Air (LEA)	Reduction of combustion air	0 to 28	0 to 24	Generally excess O_2 can be reduced to 2.5% representing a 3% drop from baseline	Available	Added benefits included increase in boiler efficiency. Limited by increase in CO, HC, and smoke emissions.
Staged Combustion (SC)	Fuel-rich firing burners with secondary combustion air ports	20 to 50	17 to 44	70-90% burner stoichiometries can be used with proper installation of secondary air ports	Technique is applicable on package and field-erected units. However, not commercially available for all design types.	Best implemented on new units. Retrofit is probably not feasible for most units, especially packaged ones.
Burners Out of Service (BOOS)	One or more burners on air only. Remainder firing fuel rich	10 to 30	NA	Applicable only for boilers with minimum of 4 burners. Best suited for square burner pattern with top burner or burners out of service. Only for retrofit application.	Available. Retrofit requires careful selection of BOOS pattern and control of air flow.	Retrofit often requires boiler de-rating unless fuel delivery system is modified.

Table 1.3-12 (cont.).

Control Technique	Description Of Technique	Effectiveness Of Control (Percent NO_x Reduction)		Range Of Application	Commercial Availability/ R&D Status	Comments
		Residual Oil	Distillate Oil			
Flue Gas Recirculation (FGR)	Recirculation of portion of flue gas to burners	15 to 30	58 to 73	Up to 25-30% of flue gas recycled. Can be implemented on all design types.	Available. Requires extensive modifications to the burner and windbox.	Best suited for new units. Costly to retrofit. Possible flame instability at high FGR rates.
Flue Gas Recirculation Plus Staged Combustion	Combined techniques of FGR and staged combustion	25 to 53	73 to 77	Max. FGR rates set at 25% for distillate oil and 20% for residual oil.	Combined techniques are still at experimental stage.	Retrofit may not be feasible. Best implemented on new units.
Load Reduction (LR)	Reduction of air and fuel flow to all burners in service	33% decrease to 25% increase in NO_x	31% decrease to 17% increase in NO_x	Applicable to all boiler types and sizes. Load can be reduced to 25% of maximum.	Available now as a retrofit application. Better implemented with improved firebox design.	Technique not effective when it necessitates an increase in excess O_2 levels. LR possibly implemented in new designs as reduced combustion intensity (enlarged furnace plan area).
Low NO_x Burners (LNB)	New burner designs with controlled air/fuel mixing and increased heat dissipation	20 to 50	20 to 50	New burners described generally applicable to all boilers. More specific information needed.	Commercially offered but not demonstrated.	Specific emissions data from industrial boilers equipped with LNB are lacking.

Table 1.3-12 (cont.).

Control Technique	Description Of Technique	Effectiveness Of Control (Percent NO_x Reduction)		Range Of Application	Commercial Availability/ R&D Status	Comments
		Residual Oil	Distillate Oil			
Ammonia Injection	Injection of NH_3 as a reducing agent in the flue gas	40 to 70	40 to 70	Applicable for large package and field-erected watertube boilers. May not be feasible for fire-tube boilers.	Commercially offered but not demonstrated.	Elaborate NH_3 injection, monitoring and control system required. Possible load restrictions on boiler and air preheater fouling when burning high sulfur oil.
Reduced Air Preheat (RAP)	Bypass of combustion air preheater	5 to 16	NA	Combustion air temperature can be reduced to ambient conditions (340K)	Available. Not implemented because of significant loss in thermal efficiency.	Application of this technique on new boilers requires installation of alternate heat recovery system (e. g., an economizer).

[a] NA = not applicable.

In selective catalytic reduction (SCR), the reaction takes place in the presence of a catalyst, improving performance. Noncatalytic systems rely on a direct reaction, usually at higher temperatures, to remove NO_x. Although removal efficiencies are lower, noncatalytic systems are typically less complex and often significantly less costly. Table 1.3-13 presents various catalytic and noncatalytic NO_x-reduction technologies.

SO_2 Control[62-63] -

Commercialized postcombustion flue gas desulfurization (FGD) processes use an alkaline reagent to absorb SO_2 in the flue gas and produce a sodium or a calcium sulfate compound. These solid sulfate compounds are then removed in downstream equipment. Flue gas desulfurization technologies are categorized as wet, semi-dry, or dry depending on the state of the reagent as it leaves the absorber vessel. These processes are either regenerable (such that the reagent material can be treated and reused) or are nonregenerable (in which case all waste streams are de-watered and discarded).

Wet regenerable FGD processes are attractive because they have the potential for better than 95 percent sulfur removal efficiency, have minimal waste water discharges, and produce a saleable sulfur product. Some of the current nonregenerable calcium-based processes can, however, produce a saleable gypsum product.

To date, wet systems are the most commonly applied. Wet systems generally use alkali slurries as the SO_x absorbent medium and can be designed to remove greater than 90 percent of the incoming SO_x. Lime/limestone scrubbers, sodium scrubbers, and dual alkali scrubbing are among the commercially proven wet FGD systems. Effectiveness of these devices depends not only on control device design but also operating variables. Table 1.3-14 summarizes commercially available postcombustion SO_2 control technologies.

Table 1.3-13. POSTCOMBUSTION NO_x REDUCTION TECHNOLOGIES

Technique	Description	Advantages	Disadvantages
1. Urea injection	Injection of urea into furnace to react with NO_x to form N_2 and H_2O	- Low capital cost - Relatively simple system - Moderate NO_x removal (30-60%) - Nontoxic chemical - Typically, low energy injection sufficient	- Temperature dependent - Design must consider boiler operating conditions and design - Reduction may be decreased at lower loads
2. Ammonia injection (Thermal-DeNO$_x$)	Injection of ammonia into furnace to react with NO_x to form N_2 and H_2O	- Low operating cost - Moderate NO_x removal (30-60%)	- Moderately high capital cost - Ammonia handling, storage, vaporization, and injection systems required (Ammonia is a toxic chemical)
3. Air Heater (AH) SCR	Air heater baskets replaced with catalyst coated baskets. Catalyst promotes reaction of ammonia with NO_x.	- Moderate NO_x removal (40-65%) - Moderate capital cost - No additional ductwork or reactor required - Low pressure drop - Can use urea as ammonia feedstock - Rotating air heater assists mixing, contact with catalyst	- Design must address pressure drop, maintain heat transfer - Due to rotation of air heater, only 50% of catalyst is active at any time
4. Duct SCR	A smaller version of conventional SCR is placed in existing ductwork	- Moderate capital cost - Moderate NO_x removal (30%) - No additional ductwork required	- Duct location unit specific temperature, access dependent - Some pressure drop must be accommodated

Table 1.3-13 (cont.).

Technique	Description	Advantages	Disadvantages
5. Activated Carbon SCR	Activated carbon catalyst, installed downstream of air heater, promotes reaction of ammonia with NO_x at low temperature.	- Active at low temperature - High surface area reduces reactor size - Low cost of catalyst - Can use urea as ammonia feedstock - Activated carbon is nonhazardous material - SO_x removal as well as NO_x removal	- High pressure drop - Not a fully commercial technology
6. Conventional SCR	Catalyst located in flue gas stream (usually upstream of air heater) promotes reaction of ammonia with NO_x.	- High NO_x removal (90%)	- Very high capital cost - High operating cost - Extensive ductwork to/from reactor - Large volume reactor must be sited - Increased pressure drop may require ID fan or larger FD fan - Reduced efficiency - Ammonia sulfate removal equipment for air heater - Water treatment of air heater wash

Table 1.3-14. POSTCOMBUSTION SO_2 CONTROLS FOR FUEL OIL COMBUSTION SOURCES

Control Technology	Process	Typical Control Efficiencies	Remarks
Wet scrubber	Lime/limestone	80-95+%	Applicable to high sulfur fuels, Wet sludge product
	Sodium carbonate	80-98%	1-125 MW (5-430 million Btu/hr) typical application range, High reagent costs
	Magnesium oxide/hydroxide	80-95+%	Can be regenerated
	Dual alkali	90-96%	Uses lime to regenerate sodium-based scrubbing liquor
Spray drying	Calcium hydroxide slurry, vaporizes in spray vessel	70-90%	Applicable to low and medium sulfur fuels, Produces dry product
Furnace injection	Dry calcium carbonate/hydrate injection in upper furnace cavity	25-50%	Commercialized in Europe, Several U.S. demonstration projects underway
Duct injection	Dry sorbent injection into duct, sometimes combined with water spray	25-50+%	Several R&D and demonstration projects underway, Not yet commercially available in the U.S.

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1.4 Natural Gas Combustion

1.4.1 General[1-2]

Natural gas is one of the major fuels used throughout the country. It is used mainly for industrial process steam and heat production; for residential and commercial space heating; and for electric power generation. Natural gas consists of a high percentage of methane (generally above 80 percent) and varying amounts of ethane, propane, butane, and inerts (typically nitrogen, carbon dioxide, and helium). Gas processing plants are required for the recovery of liquefiable constituents and removal of hydrogen sulfide before the gas is used (see Section 5.3, Natural Gas Processing). The average gross heating value of natural gas is approximately 8900 kilocalories per standard cubic meter (1000 British thermal units per standard cubic foot), usually varying from 8000 to 9800 kcal/scm (900 to 1100 Btu/scf).

1.4.2 Emissions And Controls[3-5]

Even though natural gas is considered to be a relatively clean-burning fuel, some emissions can result from combustion. For example, improper operating conditions, including poor air/fuel mixing, insufficient air, etc., may cause large amounts of smoke, carbon monoxide (CO), and organic compound emissions. Moreover, because a sulfur-containing mercaptan is added to natural gas to permit leak detection, small amounts of sulfur oxides will be produced in the combustion process.

Nitrogen oxides (NO_x) are the major pollutants of concern when burning natural gas. Nitrogen oxides emissions depend primarily on the peak temperature within the combustion chamber as well as the furnace-zone oxygen concentration, nitrogen concentration, and time of exposure at peak temperatures. Emission levels vary considerably with the type and size of combustor and with operating conditions (particularly combustion air temperature, load, and excess air level in boilers).

Currently, the two most prevalent NO_x control techniques being applied to natural gas-fired boilers (which result in characteristic changes in emission rates) are low NO_x burners and flue gas recirculation. Low NO_x burners reduce NO_x by accomplishing the combustion process in stages. Staging partially delays the combustion process, resulting in a cooler flame which suppresses NO_x formation. The three most common types of low NO_x burners being applied to natural gas-fired boilers are staged air burners, staged fuel burners, and radiant fiber burners. Nitrogen oxide emission reductions of 40 to 85 percent (relative to uncontrolled emission levels) have been observed with low NO_x burners. Other combustion staging techniques which have been applied to natural gas-fired boilers include low excess air, reduced air preheat, and staged combustion (e. g., burners-out-of-service and overfire air). The degree of staging is a key operating parameter influencing NO_x emission rates for these systems.

In a flue gas recirculation (FGR) system, a portion of the flue gas is recycled from the stack to the burner windbox. Upon entering the windbox, the gas is mixed with combustion air prior to being fed to the burner. The FGR system reduces NO_x emissions by two mechanisms. The recycled flue gas is made up of combustion products which act as inerts during combustion of the fuel/air mixture. This additional mass is heated in the combustion zone, thereby lowering the peak flame temperature and reducing the amount of NO_x formed. To a lesser extent, FGR also reduces NO_x formation by lowering the oxygen concentration in the primary flame zone. The amount of flue gas recirculated is a key operating parameter influencing NO_x emission rates for these systems. Flue gas recirculation is normally used in combination with low NO_x burners. When used in combination, these techniques are capable of reducing uncontrolled NO_x emissions by 60 to 90 percent.

Two post-combustion technologies that may be applied to natural gas-fired boilers to reduce NO_x emissions by further amounts are selective noncatalytic reduction and selective catalytic reduction. These systems inject ammonia (or urea) into combustion flue gases to reduce inlet NO_x emission rates by 40 to 70 percent.

Although not measured, all particulate matter (PM) from natural gas combustion has been estimated to be less than 1 micrometer in size. Particulate matter is composed of filterable and condensable fractions, based on the EPA sampling method. Filterable and condensable emission rates are of the same order of magnitude for boilers; for residential furnaces, most of the PM is in the form of condensable material.

The rates of CO and trace organic emissions from boilers and furnaces depend on the efficiency of natural gas combustion. These emissions are minimized by combustion practices that promote high combustion temperatures, long residence times at those temperatures, and turbulent mixing of fuel and combustion air. In some cases, the addition of NO_x control systems such as FGR and low NO_x burners reduces combustion efficiency (due to lower combustion temperatures), resulting in higher CO and organic emissions relative to uncontrolled boilers.

Emission factors for natural gas combustion in boilers and furnaces are presented in Tables 1.4-1, 1.4-2, and 1.4-3.[6] For the purposes of developing emission factors, natural gas combustors have been organized into four general categories: utility/large industrial boilers, small industrial boilers, commercial boilers, and residential furnaces. Boilers and furnaces within these categories share the same general design and operating characteristics and hence have similar emission characteristics when combusting natural gas. The primary factor used to demarcate the individual combustor categories is heat input.

Table 1.4-1 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) FROM NATURAL GAS COMBUSTION[a]

Combustor Type (Size, 10^6 Btu/hr Heat Input) (SCC)[b]	Filterable PM[c]			Condensable PM[d]		
	kg/10^6 m^3	lb/10^6 ft^3	RATING	kg/10^6 m^3	lb/10^6 ft^3	RATING
Utility/large industrial boilers (> 100) (1-01-006-01, 1-01-006-04)	16 - 80	1 - 5	B	ND	ND	NA
Small industrial boilers (10 - 100) (1-02-006-02)	99	6.2	B	120	7.5	D
Commercial boilers (0.3 - < 10) (1-03-006-03)	72	4.5	C	120	7.5	C
Residential furnaces (<0.3) (No SCC)	2.8	0.18	C	180	11	D

[a] References 9-14. All factors represent uncontrolled emissions. Units are kg of pollutant/10^6 cubic meters natural gas fired and lb of pollutant/10^6 cubic feet natural gas fired. Based on an average natural gas higher heating value of 8270 kcal/m^3 (1000 Btu/scf). The emission factors in this table may be converted to other natural gas heating values by multiplying the given emission factor by the ratio of the specified heating value to this average heating value. ND = no data. NA = not applicable.

[b] SCC = Source Classification Code.

[c] Filterable PM is that particulate matter collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[d] Condensable PM is that particulate matter collected using EPA Method 202, (or equivalent). Total PM is the sum of the filterable PM and condensable PM. All PM emissions can be assumed to be less than 10 micrometers in aerodynamic equivalent diameter (PM-10).

Table 1.4-2 (Metric And English Units). EMISSION FACTORS FOR SULFUR DIOXIDE (SO_2), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM NATURAL GAS COMBUSTION[a]

Combustor Type (Size, 10^6 Btu/hr Heat Input) (SCC)[b]	SO_2[c]			NO_x[d]			CO[e]		
	$kg/10^6\ m^3$	$lb/10^6\ ft^3$	RATING	$kg/10^6\ m^3$	$lb/10^6\ ft^3$	RATING	$kg/10^6\ m^3$	$lb/10^6\ ft^3$	RATING
Utility/large Industrial Boilers (>100) (1-01-006-01, 1-01-006-04)									
Uncontrolled	9.6	0.6	A	8800	550[f]	A	640	40	A
Controlled - Low NO_x burners	9.6	0.6	A	1300	81[f]	D	ND	ND	NA
Controlled - Flue gas recirculation	9.6	0.6	A	850	53[f]	D	ND	ND	NA
Small Industrial Boilers (10 - 100) (1-02-006-02)									
Uncontrolled	9.6	0.6	A	2240	140	A	560	35	A
Controlled - Low NO_x burners	9.6	0.6	A	1300	81[f]	D	980	61	D
Controlled - Flue gas recirculation	9.6	0.6	A	480	30	C	590	37	C
Commercial Boilers (0.3 - <10) (1-03-006-03)									
Uncontrolled	9.6	0.6	A	1600	100	B	330	21	C
Controlled - Low NO_x burners	9.6	0.6	A	270	17	C	425	27	C
Controlled - Flue gas recirculation	9.6	0.6	A	580	36	D	ND	ND	NA
Residential Furnaces (<0.3) (No SCC)									
Uncontrolled	9.6	0.6	A	1500	94	B	640	40	B

[a] Units are kg of pollutant/10^6 cubic meters natural gas fired and lb of pollutant/10^6 cubic feet natural gas fired. Based on an average natural gas fired higher heating value of 8270 kcal/m^3 (1000 Btu/scf). The emission factors in this table may be converted to other natural gas heating values by multiplying the given emission factor by the ratio of the specified heating value to this average heating value. ND = no data. NA = not applicable.

[b] SCC = Source Classification Code.

[c] Reference 7. Based on average sulfur content of natural gas, 4600 g/10^6 Nm^3 (2000 gr/10^6 scf).

Table 1.4-2 (cont.).

[d] References 10,15-19. Expressed as NO_2. For tangentially fired units, use 4400 kg/10^6 m^3 (275 lb/10^6 ft^3). At reduced loads, multiply factor by load reduction coefficient in Figure 1.4-1. Note that NO_x emissions from controlled boilers will be reduced at low load conditions.

[e] References 9-10,16-18,20-21.

[f] Emission factors apply to packaged boilers only.

Table 1.4-3 (Metric And English Units). EMISSION FACTORS FOR CARBON DIOXIDE (CO_2) AND TOTAL ORGANIC COMPOUNDS (TOC) FROM NATURAL GAS COMBUSTION[a]

Combustor Type (Size, 10^6 Btu/hr Heat Input) (SCC)[b]	CO_2[c]			TOC[d]		
	kg/10^6 m^3	lb/10^6 ft^3	RATING	kg/10^6 m^3	lb/10^6 ft^3	RATING
Utility/large industrial boilers (> 100) (1-01-006-01, 1-01-006-04)	ND[e]	ND	NA	28[f]	1.7[f]	C
Small industrial boilers (10 - 100) (1-02-006-02)	1.9 E+06	1.2 E+05	D	92[g]	5.8[g]	C
Commercial boilers (0.3 - < 10) (1-03-006-03)	1.9 E+06	1.2 E+05	C	128[h]	8.0[h]	C
Residential furnaces (No SCC)	2.0 E+06	1.3 E+05	D	180[h]	11[h]	D

[a] All factors represent uncontrolled emissions. Units are kg of pollutant/10^6 cubic meters and lb of pollutant/10^6 cubic feet. Based on an average natural gas higher heating value of 8270 kcal/m^3 (1000 Btu/scf). The emission factors in this table may be converted to other natural gas heating values by multiplying the given factor by the ratio of the specified heating value to this average heating value. NA = not applicable.

[b] SCC = Source Classification Code.

[c] References 10,22-23.

[d] References 9-10,18.

[e] ND = no data.

[f] Reference 8: methane comprises 17% of organic compounds.

[g] Reference 8: methane comprises 52% of organic compounds.

[h] Reference 8: methane comprises 34% of organic compounds.

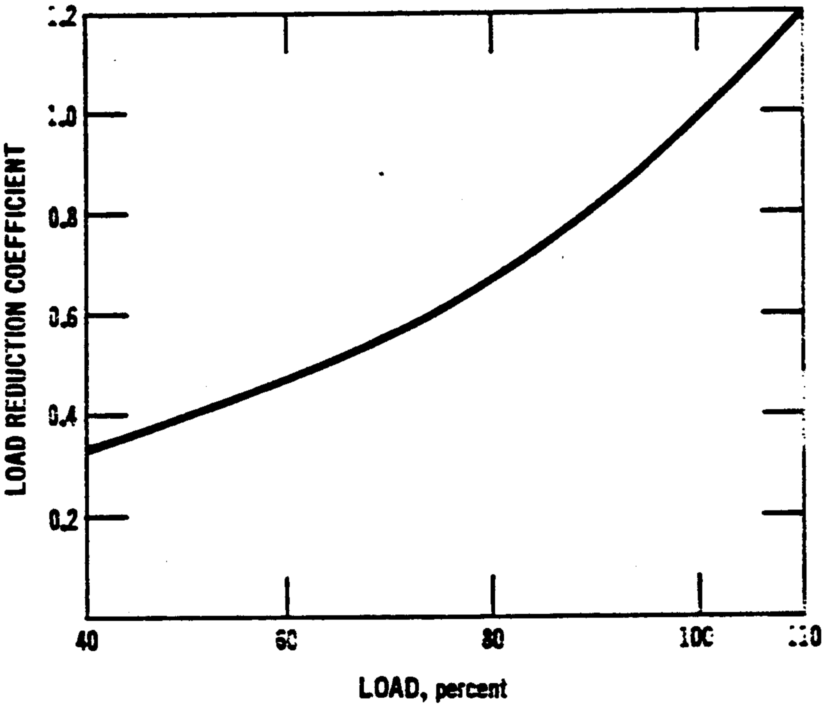

Figure 1.4-1. Load reduction coefficient as a function of boiler load. (Used to determine NO_x reductions at reduced loads in large boilers.)

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1.5 Liquefied Petroleum Gas Combustion

1.5.1 General[1]

Liquefied petroleum gas (LPG or LP-gas) consists of propane, propylene, butane, and butylenes; the product used for domestic heating is substantially propane. This gas, obtained mostly from gas wells (but also to a lesser extent as a refinery by-product) is stored as a liquid under moderate pressures. There are three grades of LPG available as heating fuels: commercial-grade propane, engine fuel-grade propane (also known as HD-5 propane), and commercial-grade butane. In addition, there are high purity grades of LPG available for laboratory work and for use as aerosol propellants. Specifications for the various LPG grades are available from the American Society for Testing and Materials and the Gas Processors Association. A typical heating value for commercial-grade propane and HD-5 propane is 6,090 kcal/liter (91,500 Btu/gallon), after vaporization; for commercial-grade butane, the value is 6,790 kcal/liter (102,000 Btu/gallon).

The largest market for LPG is the domestic/commercial market, followed by the chemical industry (where it is used as a petrochemical feedstock) and agriculture. Propane is also used as an engine fuel as an alternative to gasoline and as a stand-by fuel for facilities that have interruptible natural gas service contracts.

1.5.2 Emissions And Controls[1-4]

Liquefied petroleum gas is considered a "clean" fuel because it does not produce visible emissions. However, gaseous pollutants such as carbon monoxide (CO), organic compounds, and nitrogen oxides (NO_x) do occur. The most significant factors affecting these emissions are burner design, burner adjustment, and flue gas venting. Improper design, blocking and clogging of the flue vent, and insufficient combustion air result in improper combustion and the emissions of aldehydes, CO, hydrocarbons, and other organics. Nitrogen oxide emissions are a function of a number of variables, including temperature, excess air, fuel/air mixing, and residence time in the combustion zone. The amount of sulfur dioxide (SO_2) emitted is directly proportional to the amount of sulfur in the fuel. Emission factors for LPG combustion are presented in Tables 1.5-1 and 1.5-2.

Nitrogen oxides are the only pollutant for which emission controls have been developed. Propane and butane are being used in Southern California as backup fuel to natural gas, replacing distillate oil in this role pursuant to the phaseout of fuel oil in that region. Emission controls for NO_x have been developed for firetube and watertube boilers firing propane or butane. Vendors are now warranting retrofit systems to levels as low as 30 to 40 ppm (based on 3 percent oxygen). These low-NO_x systems use a combination of low NO_x burners and flue gas recirculation. Some burner vendors use water or steam injection into the flame zone for NO_x reduction. This is a trimming technique which may be necessary during backup fuel periods because LPG typically has a higher NO_x-forming potential than natural gas; conventional natural gas emission control systems may not be sufficient to reduce LPG emissions to mandated levels. Also, LPG burners are more prone to sooting under the modified combustion conditions required for low NO_x emissions. The extent of allowable combustion modifications for LPG may be more limited than for natural gas.

One NO_x control system that has been demonstrated on small commercial boilers is flue gas recirculation (FGR). Nitrogen oxide emissions from propane combustion can be reduced by as much as 50 percent by recirculating 16 percent of the flue gas. Nitrogen oxide emission reductions of over 60 percent have been achieved with FGR and low NO_x burners used in combination.

Table 1.5-1 (Metric Units). EMISSION FACTORS FOR LPG COMBUSTION[a]

EMISSION FACTOR RATING: E

	Butane Emission Factor (kg/1000 liters)		Propane Emission Factor (kg/1000 liters)	
Pollutant	Industrial Boilers[b] (1-02-010-01)	Commercial Boilers[c] (1-03-010-01)	Industrial Boilers[b] (1-02-010-02)	Commercial Boilers[c] (1-03-010-02)
Filterable particulate matter[d]	0.07	0.06	0.07	0.05
Sulfur oxides[e]	0.011S	0.011S	0.012S	0.012S
Nitrogen oxides[f]	2.5	1.8	2.3	1.7
Carbon dioxide	1,760	1,760	1,500	1,500
Carbon monoxide	0.4	0.3	0.4	0.2
Total organic compounds	0.07	0.07	0.06	0.06

[a] Assumes emissions (except SO_x and NO_x) are the same, on a heat input basis, as for natural gas combustion. The NO_x emission factors have been multiplied by a correction factor of 1.5, which is the approximate ratio of propane/butane NO_x emissions to natural gas NO_x emissions. Source Classification Codes in parentheses.

[b] Heat input capacities generally between 3 and 29 MW.

[c] Heat input capacities generally between 0.1 and 3 MW.

[d] Filterable particulate matter (PM) is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[e] Expressed as SO_2. S equals the sulfur content expressed in gr/100 ft^3 gas vapor. For example, if the butane sulfur content is 0.18 gr/100 ft^3, the emission factor would be (0.011 x 0.18) = 0.0020 kg of SO_2/1000 liters butane burned.

[f] Expressed as NO_2.

Table 1.5-2 (English Units). EMISSION FACTORS FOR LPG COMBUSTION[a]

EMISSION FACTOR RATING: E

Pollutant	Butane Emission Factor (lb/1000 gal)		Propane Emission Factor (lb/1000 gal)	
	Industrial Boilers[b] (1-02-010-01)	Commercial Boilers[c] (1-03-010-01)	Industrial Boilers[b] (1-02-010-02)	Commercial Boilers[c] (1-03-010-02)
Filterable particulate matter[d]	0.6	0.5	0.6	0.4
Sulfur oxides[e]	0.09S	0.09S	0.10S	0.10S
Nitrogen oxides[f]	21	15	19	14
Carbon dioxide	14,700	14,700	12,500	12,500
Carbon monoxide	3.6	2.1	3.2	1.9
Total organic compounds	0.6	0.6	0.5	0.5

[a] Assumes emissions (except SO_x and NO_x) are the same, on a heat input basis, as for natural gas combustion. The NO_x emission factors have been multiplied by a correction factor of 1.5, which is the approximate ratio of propane/butane NO_x emissions to natural gas NO_x emissions. Source Classification Codes in parentheses.

[b] Heat input capacities generally between 10 and 100 million Btu/hour.

[c] Heat input capacities generally between 0.3 and 10 million Btu/hour.

[d] Filterable particulate matter (PM) is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[e] Expressed as SO_2. S equals the sulfur content expressed in gr/100 ft^3 gas vapor. For example, if the butane sulfur content is 0.18 gr/100 ft^3, the emission factor would be (0.09 x 0.18) = 0.016 lb of SO_2/1000 gal butane burned.

[f] Expressed as NO_2.

References For Section 1.5

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3. *Nitrous Oxide Reduction With The Weishaupt Flue Gas Recirculation System*, Weishaupt Research and Development Institute, January 1987.

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1.6 Wood Waste Combustion In Boilers

1.6.1 General[1-5]

The burning of wood waste in boilers is mostly confined to those industries where it is available as a byproduct. It is burned both to obtain heat energy and to alleviate possible solid waste disposal problems. In boilers, wood waste is normally burned in the form of hogged wood, sawdust, shavings, chips, sanderdust, or wood trim. Heating values for this waste range from about 2,200 to 2,700 kcal/kg (4,000 to 5,000 Btu/lb) of fuel on a wet, as-fired basis. The moisture content of as-fired wood is typically near 50 weight percent, but may vary from 5 to 75 weight percent depending on the waste type and storage operations.

Generally, bark is the major type of waste burned in pulp mills; either a mixture of wood and bark waste or wood waste alone is burned most frequently in the lumber, furniture, and plywood industries. As of 1980, there were approximately 1,600 wood-fired boilers operating in the U. S., with a total capacity of over 30 GW (1.0 x 10^{11} Btu/hr).

1.6.2 Firing Practices[5-7]

Various boiler firing configurations are used for burning wood waste. One common type of boiler used in smaller operations is the Dutch oven. This unit is widely used because it can burn fuels with very high moisture content. Fuel is fed into the oven through an opening in the top of a refractory-lined furnace. The fuel accumulates in a cone-shaped pile on a flat or sloping grate. Combustion is accomplished in two stages: (1) drying and gasification, and (2) combustion of gaseous products. The first stage takes place in the primary furnace, which is separated from the secondary furnace chamber by a bridge wall. Combustion is completed in the secondary chamber before gases enter the boiler section. The large mass of refractory helps to stabilize combustion rates but also causes a slow response to fluctuating steam demand.

In another boiler type, the fuel cell oven, fuel is dropped onto suspended fixed grates and is fired in a pile. Unlike the Dutch oven, the refractory-lined fuel cell also uses combustion air preheating and positioning of secondary and tertiary air injection ports to improve boiler efficiency. Because of their overall design and operating similarities, however, fuel cell and Dutch oven boilers have comparable emission characteristics.

The most common firing method employed for wood-fired boilers larger than 45,000 kg/hr (100,000 lb/hr) steam generation rate is the spreader stoker. With this boiler, wood enters the furnace through a fuel chute and is spread either pneumatically or mechanically across the furnace, where small pieces of the fuel burn while in suspension. Simultaneously, larger pieces of fuel are spread in a thin, even bed on a stationary or moving grate. The burning is accomplished in three stages in a single chamber: (1) moisture evaporation; (2) distillation and burning of volatile matter; and (3) burning of fixed carbon. This type of operation has a fast response to load changes, has improved combustion control, and can be operated with multiple fuels. Natural gas or oil is often fired in spreader stoker boilers as auxiliary fuel. This is done to maintain constant steam when the wood waste supply fluctuates and/or to provide more steam than can be generated from the waste supply alone. Although spreader stokers are the most common stokers among larger wood-fired boilers, overfeed and underfeed stokers are also utilized for smaller units.

Another boiler type sometimes used for wood combustion is the suspension-firing boiler. This boiler differs from a spreader stoker in that small-sized fuel (normally less than 2 mm) is blown into the boiler and combusted by supporting it in air rather than on fixed grates. Rapid changes in combustion rate and, therefore, steam generation rate are possible because the finely divided fuel particles burn very quickly.

A recent development in wood firing is the fluidized bed combustion (FBC) boiler. A fluidized bed consists of inert particles through which air is blown so that the bed behaves as a fluid. Wood waste enters in the space above the bed and burns both in suspension and in the bed. Because of the large thermal mass represented by the hot inert bed particles, fluidized beds can handle fuels with moisture contents up to near 70 percent (total basis). Fluidized beds can also handle dirty fuels (up to 30 percent inert material). Wood fuel is pyrolyzed faster in a fluidized bed than on a grate due to its immediate contact with hot bed material. As a result, combustion is rapid and results in nearly complete combustion of the organic matter, thereby minimizing emissions of unburned organic compounds.

1.6.3 Emissions And Controls[6-11]

The major emission of concern from wood boilers is particulate matter (PM), although other pollutants, particularly carbon monoxide (CO) and organic compounds, may be emitted in significant quantities under poor operating conditions. These emissions depend on a number of variables, including (1) the composition of the waste fuel burned, (2) the degree of flyash reinjection employed, and (3) furnace design and operating conditions.

The composition of wood waste depends largely on the industry from which it originates. Pulping operations, for example, produce great quantities of bark that may contain more than 70 weight percent moisture, sand, and other non-combustibles. As a result, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are well controlled. On the other hand, some operations, such as furniture manufacturing, generate a clean, dry wood waste (e. g., 2 to 20 weight percent moisture) which produces relatively low particulate emission levels when properly burned. Still other operations, such as sawmills, burn a varying mixture of bark and wood waste that results in PM emissions somewhere between these two extremes.

Furnace design and operating conditions are particularly important when firing wood waste. For example, because of the high moisture content that may be present in wood waste, a larger than usual area of refractory surface is often necessary to dry the fuel before combustion. In addition, sufficient secondary air must be supplied over the fuel bed to burn the volatiles that account for most of the combustible material in the waste. When proper drying conditions do not exist, or when secondary combustion is incomplete, the combustion temperature is lowered, and increased PM, CO, and organic compound emissions may result. Short-term emissions can fluctuate with significant variations in fuel moisture content.

Flyash reinjection, which is commonly used with larger boilers to improve fuel efficiency, has a considerable effect on PM emissions. Because a fraction of the collected flyash is reinjected into the boiler, the dust loading from the furnace and, consequently, from the collection device increase significantly per unit of wood waste burned. More recent boiler installations typically separate the collected particulate into large and small fractions in sand classifiers. The larger particles, which are mostly carbon, are reinjected into the furnace. The smaller particles, mostly inorganic ash and sand, are sent to ash disposal.

Currently, the four most common control devices used to reduce PM emissions from wood-fired boilers are mechanical collectors, wet scrubbers, electrostatic precipitators (ESPs), and fabric filters. The use of multitube cyclone (or multiclone) mechanical collectors provides particulate control for many hogged boilers. Often, two multiclones are used in series, allowing the first collector to remove the bulk of the dust and the second to remove smaller particles. The efficiency of this arrangement is from 65 to 95 percent. The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. With gas-side pressure drops exceeding 4 kPa (15 inches of water), particulate collection efficiencies of 90 percent or greater have been reported for venturi scrubbers operating on wood-fired boilers.

Fabric filters (i. e., baghouses) and ESPs are employed when collection efficiencies above 95 percent are required. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector precleaners which remove larger-sized particles. Collection efficiencies of 93 to 99.8 percent for PM have been observed for ESPs operating on wood-fired boilers.

A variation of the ESP is the electrostatic gravel bed filter. In this device, PM in flue gases is removed by impaction with gravel media inside a packed bed; collection is augmented by an electrically charged grid within the bed. Particulate collection efficiencies are typically near 95 percent.

Fabric filters have had limited applications to wood-fired boilers. The principal drawback to fabric filtration, as perceived by potential users, is a fire danger arising from the collection of combustible carbonaceous fly ash. Steps can be taken to reduce this hazard, including the installation of a mechanical collector upstream of the fabric filter to remove large burning particles of fly ash (i. e., "sparklers"). Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood. This fuel produces fine particulates with a high salt content. Fabric filters are capable of high fine particle collection efficiencies; in addition, the salt content of the particles has a quenching effect, thereby reducing fire hazards. In two tests of fabric filters operating on salt-laden wood-fired boilers, particulate collection efficiencies were above 98 percent.

Emissions of nitrogen oxides (NO_x) from wood-fired boilers are lower than those from coal-fired boilers due to the lower nitrogen content of wood and the lower combustion temperatures which characterize wood-fired boilers. For stoker and FBC boilers, overfire air ports may be used to lower NO_x emissions by staging the combustion process. In those areas of the U. S. where NO_x emissions must be reduced to their lowest levels, the application of selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) to waste wood-fired boilers has either been accomplished (SNCR) or is being contemplated (SCR). Both systems are post-combustion NO_x reduction techniques in which ammonia (or urea) is injected into the flue gas to selectively reduce NO_x to nitrogen and water. In one application of SNCR to an industrial wood-fired boiler, NO_x reduction efficiencies varied between 35 and 75 percent as the ammonia-to-NO_x ratio increased from 0.4 to 3.2.

Emission factors and emission factor ratings for wood waste boilers are summarized in Tables 1.6-1, 1.6-2, 1.6-3, 1.6-4, 1.6-5, 1.6-6, and 1.6-7.[21-22] Emission factors are for uncontrolled combustors unless otherwise indicated. Cumulative particle size distribution data and associated emission factors are presented in Tables 1.6-8 and 1.6-9. Uncontrolled and controlled size-specific emission factors are plotted in Figure 1.6-1 and Figure 1.6-2. All emission factors presented are based on the feed rate of wet, as-fired wood with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating values.

Table 1.6-1 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM), PARTICULATE MATTER LESS THAN 10 MICROMETERS (PM-10), AND LEAD FROM WOOD WASTE COMBUSTION[a]

Source Category (SCC)[b]	PM[c]			PM-10[d]			Lead[e]		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Bark-fired boilers (1-01-009-01, 1-02-009-01, 1-02-009-04, 1-03-009-01)									
Uncontrolled	23.5	47	B	8.4	17	D	1.4 E-03	2.9 E-03	D
Mechanical collector									
with flyash reinjection	7	14	B	5.5	11	D	ND[f]	ND	
without flyash reinjection	4.5	9.0	B	1.6	3.2	D			
Wet scrubber	1.5	2.9	D	1.3	2.5	D	ND	ND	
Wood/bark-fired boilers (1-01-009-02, 1-02-009-02, 1-02-009-05, 1-03-009-02)									
Uncontrolled	3.6	7.2	C	3.2	6.5	E	ND	ND	
Mechanical collector									
with flyash reinjection	3.0	6.0	C	2.7	5.5	E	1.6 E-04[g]	3.2 E-04[g]	D
without flyash reinjection	2.7	5.3	C	0.08	1.7	E	1.6 E-04[g]	3.2 E-04[g]	
Wet scrubber	0.24	0.48	D	0.23	0.47	E	1.8 E-04	3.5 E-04	D
Electrostatic precipitator	0.02	0.04	D	ND	ND		8.0 E-05	1.6 E-05	D
Wood-fired boilers (1-01-009-03, 1-02-009-03, 1-02-009-06, 1-03-009-03)									
Uncontrolled	4.4	8.8	C	ND	ND		ND	ND	
Mechanical collector without flyash reinjection	2.1	4.2	C	1.3[h]	2.6[h]	D	1.5 E-04	3.1 E-04	D
Electrostatic precipitator	0.08	0.17	D	ND	ND		5.5 E-03	1.1 E-03	D

Table 1.6-1 (cont.).

[a] Units are kg of pollutant/Mg of wood waste burned and lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg (4500 Btu/lb) higher heating value.

[b] SCC = Source Classification Code.

[c] References 11-15.

[d] References 13,16.

[e] References 11,13-15,17.

[f] ND = no data.

[g] Due to lead's relative volatility, it is assumed that flyash reinjection does not have a significant effect on lead emissions following mechanical collectors.

[h] Based on one test in which 61 percent of emitted PM was less than 10 micrometer in size.

Table 1.6-2 (Metric And English Units). EMISSION FACTORS FOR NITROGEN OXIDES (NO_x), SULFUR OXIDES (SO_x), AND CARBON MONOXIDE (CO) FROM WOOD WASTE COMBUSTION[a]

Source Category (SCC)[b]	NO_x[c]			SO_x[d]			CO[e]		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Fuel cell/Dutch oven boiler (no SCC)	0.19 (0.0017 - 0.75)	0.38 (0.0033 - 1.5)	C	0.037 (0.005 - 0.1)	0.075 (0.01 - 0.2)	B	3.3 (0.33 - 11)	6.6 (0.65 - 21)	C
Stoker boilers (no SCC)	0.75 (0.33 - 1.8)	1.5 (0.66 - 3.6)	C	0.037 (0.005 - 0.1)	0.075 (0.01 - 0.2)	B	6.8 (0.95 - 40)	13.6 (1.9 - 80)	C
FBC boilers (no SCC)	1.0	2.0	D	0.037 (0.005 - 0.1)	0.075 (0.01 - 0.2)	B	0.7 (0.24 - 1.2)	1.4 (0.47 - 2.4)	D

[a] Units are kg of pollutant/Mg of wood waste burned and lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating value. FBC = fluidized bed combustion.

[b] SCC = Source Classification Code.

[c] References 12-14,18-20. NO_x formation is primarily a function of wood nitrogen content. Higher values in the range (parentheses) should be used for wood nitrogen contents above a typical value of 0.08 weight percent, as fired.

[d] Reference 23. Lower limit of the range (in parentheses) should be used for wood and higher values for bark.

[e] References 11-15,18,24-26. Higher values in the range (in parentheses) should be used if combustion conditions are less than adequate, such as unusually wet wood or high air-to-fuel ratios.

Table 1.6-3 (Metric And English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC) AND CARBON DIOXIDE (CO_2) FROM WOOD WASTE COMBUSTION[a]

Source Category (SCC)[b]	TOC[c]			CO_2[d]		
	kg/Mg	lb/ton	RATING	kg/Mg	lb/ton	RATING
Fuel cell/Dutch oven boilers (no SCC)	0.09	0.18	C	1100	2100	B
Stoker boilers (no SCC)	0.11	0.22	C	1100	2100	B
FBC boilers (no SCC)	ND	ND		1100	2100	B

[a] Units are kg of pollutant/Mg of wood waste burned and lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg (4500 Btu/lb) higher heating value. FBC = fluidized bed combustion. ND = no data.

[b] SCC = Source Classification Code.

[c] References 11,14-15,18. Emissions measured as total hydrocarbons, converted from kg carbon/Mg fuel (lb carbon/ton fuel).

[d] References 11,14-15,17,27.

Table 1.6-4 (Metric Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM WOOD WASTE COMBUSTION[a]

Organic Compound[b]	Emission Factor Range[c] (kg/Mg)	Average Emission Factor (kg/Mg)	EMISSION FACTOR RATING
Phenols	3.2 E-05 - 6.0 E-05	1.9 E-04	C
Acenaphthene	4.3 E-08 - 2.1 E-06	1.7 E-06	C
Fluorene	8.5 E-08 - 1.4 E-05	4.8 E-06	C
Phenanthrene	1.0 E-06 - 9.0 E-05	2.8 E-05	C
Anthracene	4.3 E-08 - 1.7 E-04	1.9 E-05	C
Fluoranthene	4.3 E-08 - 4.3 E-04	4.5 E-05	C
Pyrene	2.1 E-07 - 2.9 E-05	8.5 E-06	C
Benzo(a)anthracene	4.3 E-08 - 3.2 E-06	9.0 E-07	C
Benzo(b+k)fluoranthene	1.7 E-07 - 9.5 E-05	1.9 E-05	C
Benzo(a)pyrene	4.3 E-08 - 1.5 E-07	9.5 E-08	D
Benzo(g,h,i)perylene	4.3 E-08 - 1.7 E-06	6.0 E-07	C
Chrysene	4.3 E-08 - 1.5 E-04	2.1 E-05	C
Indeno(1,2,3,c,d)pyrene	4.3 E-08 - 3.0 E-07	1.7 E-07	D
Polychlorinated dibenzo-p-dioxins	1.5 E-09 - 1.7 E-08	6.0 E-09[d,e]	C
Polychlorinated dibenzo-p-furans	2.3 E-09 - 3.6 E-08	1.5 E-08[d,f]	C
Acenaphthylene	3.0 E-07 - 3.4 E-05	2.2 E-05	C
Pyrene		4.5 E-06[g]	D
Methyl anthracene		7.0 E-05[g]	D
Acrolein		2.0 E-06[g]	D
Solicyladehyde		1.1 E-05[g]	D
Benzaldehyde		6.0 E-06[g]	D
Formaldehyde	1.2 E-04 - 1.6 E-02	3.3 E-03	C
Acetaldehyde	3.0 E-05 - 1.2 E-02	1.5 E-03	C
Benzene	4.3 E-05 - 7.0 E-03	1.8 E-03	C
Naphthalene	2.5 E-05 - 2.9 E-03	1.1 E-03	C
2,3,7,8-Tetrachlorodibenzo-p-dioxin	1.1 E-011 - 2.6 E-011	1.8 E-11	D

[a] Units are kg of pollutant/Mg of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg higher heating value. Source Classification Codes are 1-01-009-01/02/03, 1-02-009-01/02/03/04/05/06/07, and 1-03-009-01/02/03.

[b] Pollutants in this table represent organic species measured for wood waste combustors. Other organic species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c] References 11-15,18,26-28.

[d] Emission factors are for total dioxins and furans, not toxic equivalents.

[e] Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 6.5 E-07 kg/Mg with a D rating.

[f] Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 2.8 E-07 kg/Mg with a D rating.

[g] Based on data from one source test.

Table 1.6-5 (English Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM WOOD WASTE COMBUSTION[a]

Organic Compound[b]	Emission Factor Range[c] (lb/ton)	Average Emission Factor (lb/ton)	EMISSION FACTOR RATING
Phenols	6.4 E-05 - 1.2 E-04	3.9 E-04	C
Acenaphthene	8.6 E-08 - 4.3 E-06	3.4 E-06	C
Fluorene	1.7 E-07 - 2.8 E-05	9.6 E-06	C
Phenanthrene	2.0 E-06 - 1.8 E-04	5.7 E-05	C
Anthracene	8.6 E-08 - 3.5 E-04	3.8 E-05	C
Fluoranthene	8.6 E-08 - 8.6 E-04	9.0 E-05	C
Pyrene	4.3 E-07 - 5.9 E-05	1.7 E-05	C
Benzo(a)anthracene	8.6 E-08 - 6.4 E-06	1.8 E-06	C
Benzo(b+k)fluoranthene	3.4 E-07 -1.9 E-04	2.9 E-05	C
Benzo(a)pyrene	8.6 E-08 - 3.0 E-07	1.9 E-07	D
Benzo(g,h,i)perylene	8.6 E-08 - 3.5 E-06	1.2 E-06	C
Chrysene	8.6 E-08 - 3.0 E-04	4.3 E-05	C
Indeno(1,2,3,c,d)pyrene	8.6 E-08 - 6.0 E-07	3.4 E-07	D
Polychlorinated dibenzo-p-dioxins	3.0 E-09 - 3.3 E-08	1.2 E-08[d,e]	C
Polychlorinated dibenzo-p-furans	4.6 E-09 - 7.2 E-08	2.9 E-08[d,f]	C
Acenaphthylene	6.0 E-07 - 6.8 E-05	4.4 E-05	C
Pyrene		9.0 E-06[g]	D
Methyl anthracene		1.4 E-04[g]	D
Acrolein		4.0 E-06[g]	D
Solicyladehyde		2.3 E-05[g]	D
Benzaldehyde		1.2 E-05[g]	D
Formaldehyde	2.3 E-04 - 3.3 E-02	6.6 E-03	C
Acetaldehyde	6.1 E-05 - 2.4 E-02	3.0 E-03	C
Benzene	8.6 E-05 - 1.4 E-02	3.6 E-03	C
Naphthalene	5.0 E-05 - 5.8 E-03	2.3 E-03	C
2,3,7,8-Tetrachlorodibenzo-p-dioxin	2.12 E-011 - 5.11 E-011	3.6 E-11	D

[a] Units are lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 4500 Btu/lb higher heating value. Source Classification Codes are 1-01-009-01/02/03, 1-02-009-01/02/03/04/05/06/07, and 1-03-009-01/02/03.

[b] Pollutants in this table represent organic species measured for wood waste combustors. Other organic species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c] References 11-15,18,26-28.

[d] Emission factors are for total dioxins and furans, not toxic equivalents.

[e] Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 1.3 E-06 lb/ton with a D rating.

[f] Excludes data from combustion of salt-laden wood. For salt-laden wood, emission factor is 5.5 E-07 lb/ton with a D rating.

[g] Based on data from one source test.

Table 1.6-6 (Metric Units). EMISSION FACTORS FOR SPECIATED METALS FROM WOOD WASTE COMBUSTION[a]

Trace Element[b]	Emission Factor Range[c] (kg/Mg)	Average Emission Factor (kg/Mg)	EMISSION FACTOR RATING
Chromium (VI)	1.5 E-05 - 2.9 E-05	2.3 E-05	D
Copper	7.0 E-06 - 6.0 E-04	9.5 E-05	C
Zinc	4.9 E-05 - 1.1 E-02	2.2 E-03	C
Barium		2.2 E-03[d]	D
Potassium		3.9 E-01[d]	D
Sodium		9.0 E-03[d]	D
Iron	4.3 E-04 - 3.3 E-02	2.2 E-02	D
Lithium		3.5 E-05[d]	D
Boron		4.0 E-04[d]	D
Chlorine		3.9 E-03[d]	D
Vanadium		6.0 E-05[d]	D
Cobalt[b]		6.5 E-05[d]	D
Thorium		8.5 E-06[d]	D
Tungsten		5.5 E-06[d]	D
Dysprosium		6.5 E-06[d]	D
Samarium		1.0 E-05[d]	D
Neodymium		1.3 E-05[d]	D
Praeseodymium		1.5 E-05[d]	D
Iodine		8.0 E-06[d]	D
Tin		1.5 E-05[d]	D
Molybdenum		9.5 E-05[d]	D
Niobium		1.7 E-05[d]	D
Zirconium		1.7 E-04[d]	D
Yttrium		2.8 E-05[d]	D
Rubidium		6.0 E-04[d]	D
Bromine		1.8 E-04[d]	D
Germanium		1.7 E-06[d]	D
Arsenic	7.0 E-07 - 1.2 E-04	4.4 E-05	C
Cadmium	1.3 E-06 - 2.7 E-04	8.5 E-06	C
Chromium (Total)	3. 0E-06 - 2.3 E-04	6.5 E-05	C
Manganese	1.5 E-04 - 2.6 E-02	4.4 E-03	C
Mercury	1.3 E-06 - 1.0 E-05	3.7 E-06	C
Nickel	1.7 E-05 - 2.9 E-03	2.8 E-04	C
Selenium	8.5 E-06 - 9.0 E-06	8.8 E-06	D

[a] Units are kg of pollutant/Mg of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg higher heating value. Source Classification Codes are 1-01-009-01/02/03, 1-02-009-01/02/03/04/05/06/07, and 1-03-009-01/02/03.

[b] Pollutants in this table represent metal species measured for wood waste combustors. Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c] References 11-15.

[d] Based on data from one source test.

Table 1.6-7 (English Units). EMISSION FACTORS FOR SPECIATED METALS FROM WOOD WASTE COMBUSTION[a]

Trace Element[b]	Emission Factor Range[c] (lb/ton)	Average Emission Factor (lb/ton)	EMISSION FACTOR RATING
Chromium (VI)	3.1 E-05 - 5.9 E-05	4.6 E-05	D
Copper	1.4 E-05 - 1.2 E-03	1.9 E-04	C
Zinc	9.9 E-05 - 2.3 E-02	4.4 E-03	D
Barium		4.4 E-03[d]	D
Potassium		7.8 E-01[d]	D
Sodium		1.8 E-02[d]	D
Iron	8.6 E-04 - 8.7 E-02	4.4 E-02	D
Lithium		7.0 E-05[d]	D
Boron		8.0 E-04[d]	D
Chlorine		7.8 E-03[d]	D
Vanadium		1.2 E-04[d]	D
Cobalt		1.3 E-04[d]	D
Thorium		1.7 E-05[d]	D
Tungsten		1.1 E-05[d]	D
Dysprosium		1.3 E-05[d]	D
Samarium		2.0 E-05[d]	D
Neodymium		2.6 E-05[d]	D
Praeseodymium		3.0 E-05[d]	D
Iodine		1.8 E-05[d]	D
Tin		3.1 E-05[d]	D
Molybdenum		1.9 E-04[d]	D
Niobium		3.5 E-05[d]	D
Zirconium		3.5 E-04[d]	D
Yttrium		5.6 E-05[d]	D
Rubidium		1.2 E-03[d]	D
Bromine		3.9 E-04[d]	D
Germanium		2.5 E-06[d]	D
Arsenic	1.4 E-06 - 2.4 E-04	8.8 E-05	C
Cadmium	2.7 E-06 - 5.4 E-04	1.7 E-05	C
Chromium (Total)	6.0 E-06 - 4.6 E-04	1.3 E-04	C
Manganese	3.0 E-04 - 5.2 E-02	8.9 E-03	C
Mercury	2.6 E-06 - 2.1 E-05	6.5 E-06	C
Nickel	3.4 E-05 - 5.8 E-03	5.6 E-04	C
Selenium	1.7 E-05 - 1.8 E-05	1.8 E-05	D

[a] Units are lb of pollutant/ton of wood waste burned. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 4500 Btu/lb higher heating value. Source Classification Codes are 1-010-09-01/02/03, 1-02-009-01/02/03/04/05/06/07, and 1-03-009-01/02/03.

[b] Pollutants in this table represent metal species measured for wood waste combustors. Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical limits.

[c] References 11-15.

[d] Based on data from one source test.

Table 1.6-8 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE SPECIFIC EMISSION FACTORS FOR BARK-FIRED BOILERS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (µm)	Cumulative Mass % ≤ Stated Size				Cumulative Emission Factor[c] (kg/Mg [lb/ton] Bark, As Fired)			
		Controlled				Controlled		
	Uncontrolled	Multiple Cyclone[d]	Multiple Cyclone[e]	Scrubber[f]	Uncontrolled	Multiple Cyclone[d]	Multiple Cyclone[e]	Scrubber[f]
15	42	90	40	92	10.1 (20.2)	6.3 (12.6)	1.8 (3.6)	1.32 (2.64)
10	35	79	36	87	8.4 (16.8)	5.5 (11.0)	1.62 (3.24)	1.25 (2.50)
6	28	64	30	78	6.7 (13.4)	4.5 (9.0)	1.35 (2.7)	1.12 (2.24)
2.5	21	40	19	56	5.0 (10.0)	2.8 (5.6)	0.86 (1.72)	0.81 (1.62)
1.25	15	26	14	29	3.6 (7.2)	1.8 (3.6)	0.63 (1.26)	0.42 (0.84)
1.00	13	21	11	23	3.1 (6.2)	1.5 (3.0)	0.5 (1.0)	0.33 (0.66)
0.625	9	15	8	14	2.2 (4.4)	1.1 (2.2)	0.36 (0.72)	0.20 (0.40)
Total	100	100	100	100	24 (47)	7 (14)	4.5 (9.0)	1.44 (2.88)

[a] Reference 16. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2,500 kcal/kg (4,500 Btu/lb) higher heating value. Source Classification Codes are 1-01-009-01, 1-02-009-01, 1-02-009-04, and 1-03-009-01.

[b] Expressed as aerodynamic equivalent diameter.

[c] Units are kg of pollutant/Mg of wood waste burned and lb of pollutant/ton of wood waste burned. Data limited to spreader stoker boilers.

[d] With flyash reinjection.

[e] Without flyash reinjection.

[f] Assumed control efficiency for scrubber is 94%.

Table 1.6-9 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE SPECIFIC EMISSION FACTORS FOR WOOD/BARK-FIRED BOILERS[a]

EMISSION FACTOR RATING: E

	Cumulative Mass % ≤ Stated Size					Cumulative Emission Factor[c] (kg/Mg [lb/ton] Bark, As Fired)				
		Controlled					Controlled			
Particle Size[b] (µm)	Uncontrolled[d]	Multiple Cyclone[d]	Multiple Cyclone[e]	Scrubber[f]	DEGF	Uncontrolled[c]	Multiple Cyclone[g]	Multiple Cyclone[e]	Scrubber[f]	DEGF[g]
15	94	96	35	98	77	3.38 (6.77)	2.88 (5.76)	0.95 (1.90)	0.216 (0.431)	0.123 (0.246)
10	90	91	32	98	74	3.24 (6.48)	2.73 (5.46)	0.86 (1.72)	0.216 (0.432)	0.118 (0.236)
6	86	80	27	98	69	3.10 (6.20)	2.40 (4.80)	0.73 (1.46)	0.216 (0.432)	0.110 (0.220)
2.5	76	54	16	98	65	2.74 (5.47)	1.62 (3.24)	0.43 (0.86)	0.216 (0.432)	0.104 (0.208)
1.25	69	30	84	96	61	2.48 (4.97)	0.90 (1.80)	0.22 (0.44)	0.211 (0.422)	0.098 (0.196)
1.00	67	24	6	95	58	2.41 (4.82)	0.72 (1.44)	0.16 (0.32)	0.209 (0.418)	0.093 (0.186)
0.625	ND	16	3	ND	51	ND	0.48 (0.96)	0.081 (0.162)	ND	0.082 (0.164)
Total	100	100	100	100	100	3.6 (7.2)	3.0 (6.0)	2.7 (5.4)	0.24 (0.48)	0.16 (0.32)

[a] Reference 16. Emission factors are based on wet, as-fired wood waste with average properties of 50 weight percent moisture and 2500 kcal/kg (4500 Btu/lb) higher heating value. Source Classification Codes are 1-01-009-02, 1-02-009-02, 1-02-009-05, and 1-03-009-02. ND = no data.

[b] Expressed as aerodynamic equivalent diameter.

[c] Units are kg of pollutant/Mg of wood/bark burned and lb of pollutant/ton of wood/bark burned.

[d] From data on underfeed stokers. May also be used as size distribution for wood-fired boilers.

[e] From data on spreader stokers without flyash reinjection.

[f] From data on Dutch ovens. Assumed control efficiency is 94%.

[g] From data on spreader stokers with flyash reinjection.

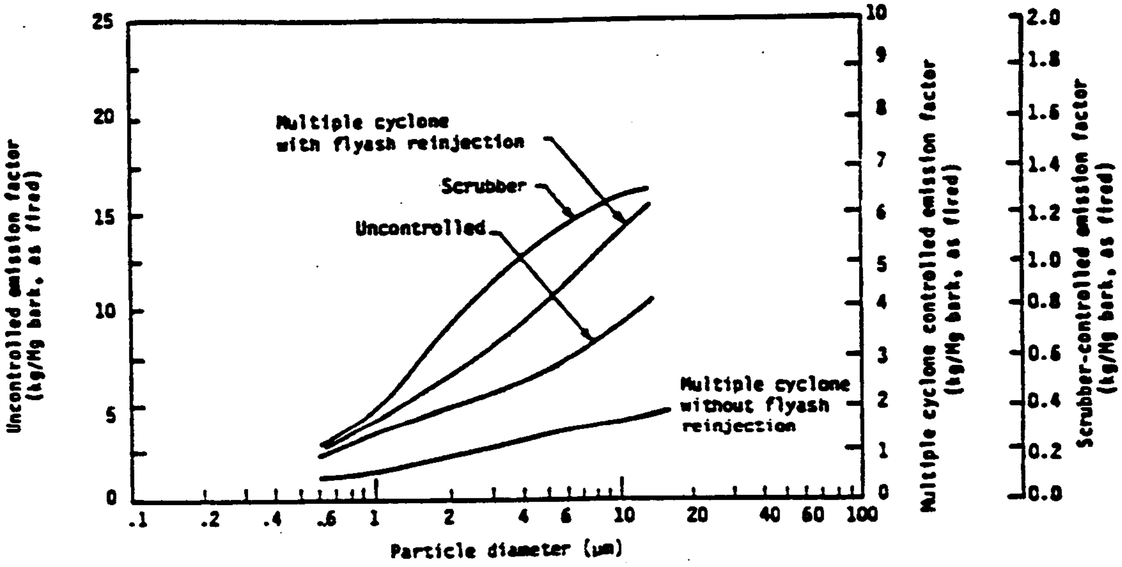

Figure 1.6-1. Cumulative size-specific particulate matter emission factors for bark-fired boilers.

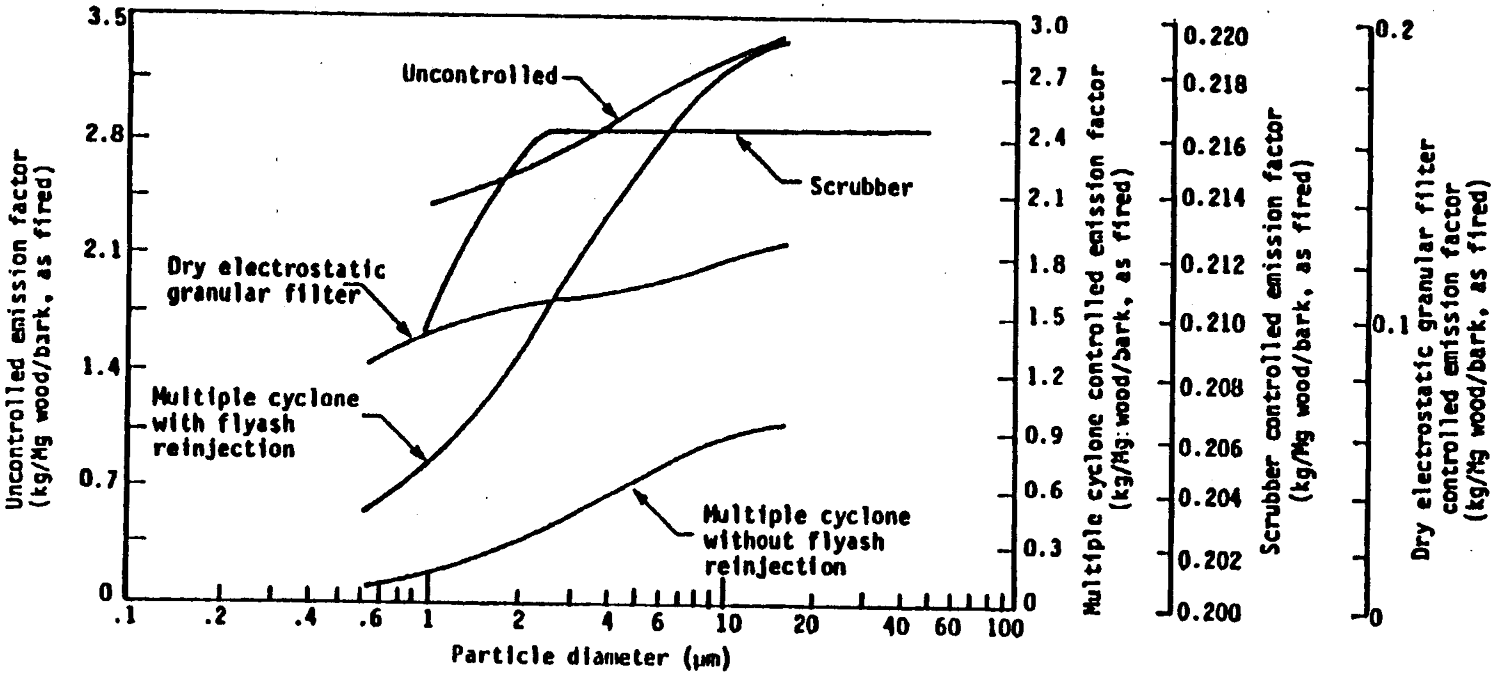

Figure 1.6-2. Cumulative size-specific particulate matter emission factors for wood/bark-fired boilers.

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1.7 Lignite Combustion

1.7.1 General[1-4]

Lignite is a coal in the early stages of coalification, with properties intermediate to those of bituminous coal and peat. The 2 geographical areas of the U. S. with extensive lignite deposits are centered in the States of North Dakota and Texas. The lignite in both areas has a high moisture content (30 to 40 weight percent) and a low heating value (1,400 to 1,900 kcal/kg [2,500 to 3,400 Btu/lb], on a wet basis). Consequently, lignite is burned near where it is mined. A small amount is used in industrial and domestic situations, but lignite is mainly used for steam/electric production in power plants. Lignite combustion has advanced from small stokers and the first pulverized coal (PC) and cyclone-fired units to large (greater than 800 MW) PC power plants.

The major advantages of firing lignite are that it is relatively abundant (in the North Dakota and Texas regions), relatively low in cost, and low in sulfur content. The disadvantages are that more fuel and larger facilities are necessary to generate a unit of power than is the case with bituminous coal. The reasons for this are: (1) lignite's higher moisture content means that more energy is lost in evaporating water, which reduces boiler efficiency; (2) more energy is required to grind lignite to combustion-specified size, especially in PC-fired units; (3) greater tube spacing and additional soot blowing are required because of lignite's higher ash fouling tendencies; and (4) because of its lower heating value, more lignite must be handled to produce a given amount of power. Lignite usually is not cleaned or dried before combustion (except for incidental drying in the crusher or pulverizer and during transport to the burner). No major problems exist with the handling or combustion of lignite when its unique characteristics are taken into account.

1.7.2 Emissions [2-11,17]

The major pollutants generated from firing lignite, as with any coal, are particulate matter (PM), sulfur oxides (SO_x), and nitrogen oxides (NO_x). Emissions rates of organic compounds and carbon monoxide (CO) are much lower than those for the major pollutants under normal operating conditions.

Emission levels for PM appear most dependent on the firing configuration of the boiler. Pulverized coal-fired units and spreader stokers fire much or all of the lignite in suspension; they emit a greater quantity of flyash per unit of fuel burned than do cyclones and other stokers. Cyclone furnaces collect much of the ash as molten slag in the furnace itself. Stokers (other than spreader) retain a large fraction of the ash in the fuel bed and bottom ash.

The NO_x emissions from lignite combustion are mainly a function of the boiler design, firing configuration, and excess air level. Stokers produce lower NO_x levels than PC units and cyclones, mainly because most stokers are relatively small and have lower peak flame temperatures. The boilers constructed since implementation of the 1971 and 1979 New Source Performance Standards (NSPS) (40 Code of Federal Regulations, Part 60, Subparts D and Da, respectively) have NO_x controls integrated into the boiler design and have comparable NO_x emission levels to the small stokers. In most boilers, regardless of firing configuration, lower excess combustion air results in lower NO_x emissions. However, lowering the amount of excess air in a lignite-fired boiler can also affect the potential for ash fouling.

The rate of SO_x emissions from lignite combustion are a function of the alkali (especially sodium) content of the ash. For combustion of most fossil fuels, over 90 percent of the fuel sulfur is emitted as sulfur dioxide (SO_2) because of the low alkali content of the fuels. By contrast, a significant fraction of the sulfur in lignite reacts with alkaline ash components during combustion and is retained in the boiler bottom ash and flyash. Tests have shown that less than 50 percent of the available sulfur may be emitted as SO_2 when a high-sodium lignite is burned, whereas more than 90 percent may be emitted from a low-sodium lignite. As an approximate average, about 75 percent of the lignite sulfur will be emitted as SO_2; the remainder will be retained in the ash as various sulfate salts.

1.7.3 Controls[2,11-17]

Most lignite-fired utility boilers are equipped with electrostatic precipitators (ESPs) with collection efficiencies as high as 99.5 percent for total PM. Older and smaller ESPs have lower collection efficiencies of approximately 95 percent for total PM. Older industrial and commercial units also may be equipped with cyclone collectors that normally achieve 60 to 80 percent collection efficiency for total PM.

Flue gas desulfurization (FGD) systems (comparable to those used on bituminous coal-fired boilers) are in current operation on several lignite-fired utility boilers. Flue gases are treated through wet or dry desulfurization processes of either the throwaway type (in which all waste streams are discarded) or the recovery/regenerable type (in which the SO_x absorbent is regenerated and reused). Wet systems generally use alkali slurries as the SO_x absorption medium and can reduce SO_x emissions by 90 percent or more. Spray dryers (or dry scrubbers) spray a solution or slurry of alkaline material into a reaction vessel as a fine mist that mixes with the flue gas. The SO_2 reacts with the alkaline mist to form salts. The solids from the spray dryer and the salts formed are collected in a particulate control device.

Over 50 percent reduction of NO_x emissions can be achieved by changing the burner geometry, controlling air flow in the furnace, or making other changes in operating procedures. Overfire air and low NO_x burners are two demonstrated NO_x control techniques for lignite combustion.

Baseline emission factors for NO_x, SO_x, and CO are presented in Tables 1.7-1 and 1.7-2. Baseline emission factors for total PM and nitrous oxide (N_2O) are given in Table 1.7-3. Specific emission factors for the cumulative particle size distributions are provided in Tables 1.7-4 and 1.7-5. Uncontrolled and controlled size-specific emission factors are presented in Figure 1.7-1 and Figure 1.7-2. Lignite combustion and bituminous coal combustion are quite similar with respect to emissions of carbon dioxide (CO_2) and organic compounds. As a result, the bituminous coal emission factors for these pollutants presented in Section 1.1 of this document may also be used to estimate emissions from lignite combustion.

Emission factors for trace elements from uncontrolled lignite combustion are summarized in Tables 1.7-6 and 1.7-7, based on currently available data.

Controlled emission factors for NO_x, CO, and PM are presented in Tables 1.7-8 and 1.7-9. Controlled SO_2 emissions will depend primarily on applicable regulations and FGD equipment performance, if applicable. Section 1.1 contains a discussion of FGD performance capabilities which is also applicable to lignite-fired boilers. Controlled emission factors for selected hazardous air pollutants are provided in Tables 1.7-10 and 1.7-11.

Table 1.7-1 (Metric Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM UNCONTROLLED LIGNITE COMBUSTION[a]

Firing Configuration (SCC)[b]	SO_x[c]		NO_x[d]		CO[e]	
	Emission Factor	RATING	Emission Factor	RATING	Emission Factor	RATING
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	15S[f]	C	3.7	C		
Pulverized coal, dry bottom, wall fired (SCC 1-01-003-01)	15S	C	5.6	C	0.13	C
Cyclone (SCC 1-01-003-03)	15S	C	6.3	C		
Spreader stoker (SCC 1-01-003-06)	15S	C	2.9	C		
Other stoker (SCC 1-01-003-04)[f]	15S	C	ND			
Atmospheric fluidized bed (no SCC)	5S	D	1.8	C	0.08	C

[a] Units are kg of pollutant/Mg of fuel burned. ND = no data.

[b] SCC = Source Classification Code.

[c] Reference 2.

[d] References 2-3,7-8,15-16.

[e] References 7,16.

[f] S = Weight % sulfur content of lignite, wet basis. For high sodium ash ($Na_2O > 8\%$), use 11S. For low sodium ash ($Na_2O < 2\%$), use 17S. If ash sodium content is unknown, use 15S.

Table 1.7-2 (English Units). EMISSION FACTORS FOR SULFUR OXIDES (SO_x), NITROGEN OXIDES (NO_x), AND CARBON MONOXIDE (CO) FROM UNCONTROLLED LIGNITE COMBUSTION[a]

Firing Configuration (SCC)[b]	SO_x[c]		NO_x[d]		CO[e]	
	Emission Factor	RATING	Emission Factor	RATING	Emission Factor	RATING
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	30S[f]	C	7.3	C		
Pulverized coal, dry bottom, wall fired (SCC 1-01-003-01)	30S	C	11.1	C	0.25	C
Cyclone (SCC 1-01-003-03)	30S	C	12.5	C		
Spreader stoker (SCC 1-01-003-06)	30S	C	5.8	C		
Other stoker (SCC 1-01-003-04)	30S	C	ND			
Atmospheric fluidized bed (no SCC)	10S	D	3.6	C	0.15	C

[a] Units are lb of pollutant/ton of fuel burned.

[b] SCC = Source Classification Code.

[c] Reference 2.

[d] References 2-3,7-8,15-16.

[e] References 7,16.

[f] S = Weight % sulfur content of lignite, wet basis. For high sodium ash ($Na_2O > 8\%$), use 22S. For low sodium ash ($Na_2O < 2\%$), use 34S. If ash sodium content is unknown, use 30S.

Table 1.7-3 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) AND NITROUS OXIDE (N_2O) FROM LIGNITE COMBUSTION[a]

Firing Configuration (SCC)	PM[b]		N_2O[c]	
	Emission Factor	RATING	Emission Factor	RATING
Pulverized coal, dry bottom, tangential (SCC 1-01-003-02)	3.3A (6.5A)	E		
Pulverized coal, dry bottom, wall fired (SCC 1-01-003-01)	2.6A (5.1A)	E		
Cyclone (SCC 1-01-003-03)	3.4A (6.7A)	C		
Spreader stoker (SCC 1-01-003-06)	4.0A (8.0A)	E		
Other stoker (SCC 1-01-003-04)	1.7A (3.4A)	E		
Atmospheric fluidized bed			1.2 (2.5)	E

[a] Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. SCC = Source Classification Code.

[b] References 5-6,12,14. A = weight % ash content of lignite, wet basis.

[c] Reference 18.

Table 1.7-4 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR BOILERS FIRING PULVERIZED LIGNITE[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor[c]	
	Uncontrolled	Multiple Cyclone Controlled	Uncontrolled	Multiple Cyclone Controlled[d]
15	51	77	1.7A (3.4A)	0.51A (1.0A)
10	35	67	1.2A (2.3A)	0.44A (0.88A)
6	26	57	0.86A (1.7A)	0.38A (0.75A)
2.5	10	27	0.33A (0.66A)	0.18A (0.36A)
1.25	7	16	0.23A (0.47A)	0.11A (0.21A)
1.00	6	14	0.20A (0.40A)	0.093A (0.19A)
0.625	3	8	0.10A (0.19A)	0.053A (0.11A)
TOTAL			3.3A (6.6A)	0.66A (1.3A)

[a] Reference 13. Based on tangential-fired units. For wall-fired units, multiply emission factors in the table by 0.79.

[b] Expressed as aerodynamic equivalent diameter.

[c] Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. A = weight % ash content of coal, wet basis.

[d] Estimated control efficiency for multiple cyclone is 80%.

Table 1.7-5 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR LIGNITE-FIRED SPREADER STOKERS[a]

EMISSION FACTOR RATING: E

Particle Size[b] (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor[c]	
	Uncontrolled	Multiple Cyclone Controlled	Uncontrolled	Multiple Cyclone Controlled[d]
15	28	55	1.1A (2.2A)	0.44A (0.88A)
10	20	41	0.80A (1.6A)	0.33A (0.66A)
6	14	31	0.56A (1.1A)	0.25A (0.50A)
2.5	7	26	0.28A (0.56A)	0.21A (0.42A)
1.25	5	23	0.20A (0.40A)	0.18A (0.37A)
1.00	5	22	0.20A (0.40A)	0.18A (0.35A)
0.625	4	—[e]	0.16A (0.33A)	—[e]
TOTAL			4.0A (8.0A)	0.80A (1.6A)

[a] Reference 13.

[b] Expressed as aerodynamic equivalent diameter.

[c] Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. A = weight % ash content of lignite, wet basis.

[d] Estimated control efficiency for multiple cyclone is 80%.

[e] Insufficient data.

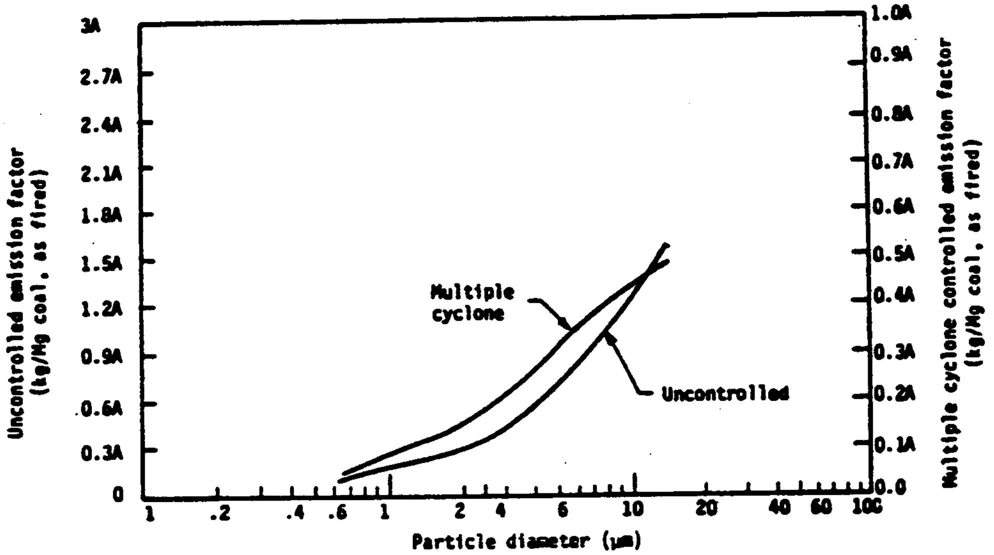

Figure 1.7-1. Cumulative size-specific emission factors for boilers firing pulverized lignite.

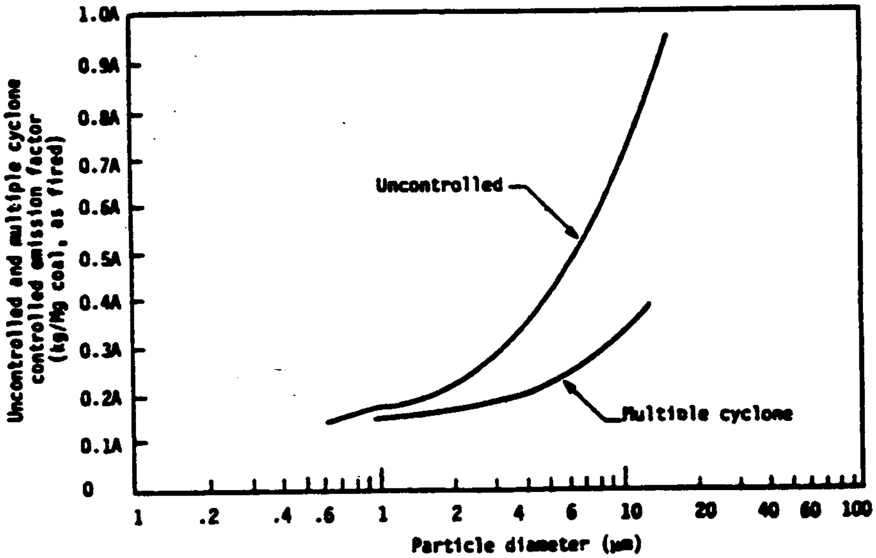

Figure 1.7-2. Cumulative size-specific emission factors for lignite-fired spreader stokers.

Table 1.7-6 (Metric Units). EMISSION FACTORS FOR TRACE ELEMENTS FROM UNCONTROLLED LIGNITE COMBUSTION[a]

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	pg/J						
	As	Be	Cd	Cr	Mn	Hg	Ni
Pulverized, wet bottom (no SCC)	1175	56	21 - 33	525 - 809	1917 - 7065	9	70 - 504
Pulverized, dry bottom (no SCC)	598	56	21	645 - 809	7043	9	404 - 504
Cyclone furnace (SCC 1-01-003-03)	101 - 272	56	13	109 - 809	1635	9	68 - 504
Stoker, configuration unknown (no SCC)		51			5130	9	303 - 504
Spreader stoker (SCC 1-01-003-06)	231 - 473		10 - 20	486 - 809			
Traveling grate (overfed) stoker (SCC 1-01-003-04)	473 - 904		20 - 39				

[a] References 19-20. Units are picograms (10^{-12}) of pollutant/joule of fuel burned. SCC = Source Classification Code.

Table 1.7-7 (English Units). EMISSION FACTORS FOR TRACE ELEMENTS FROM UNCONTROLLED LIGNITE COMBUSTION[a]

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	lb/10^{12} Btu						
	As	Be	Cd	Cr	Mn	Hg	Ni
Pulverized, wet bottom (no SCC)	2730	131	49 - 77	1220 - 1880	4410 - 16,250	21	154 - 1160
Pulverized, dry bottom (no SCC)	1390	131	49	1500 - 1880	16,200	21	928 - 1160
Cyclone furnace (SCC 1-01-003-03)	235 - 632	131	31	253 - 1880	3,760	21	157 - 1160
Stoker configuration unknown (no SCC)		118			11,800	21	
Spreader stoker (SCC 1-01-003-06)	538 - 1100		23 - 47	1130 - 1880			696 - 1160
Traveling grate (overfed) stoker (SCC 1-01-003-04)	1100 - 2100		47 - 90				

[a] References 19-20. Units are lb of pollutant/10^{12} Btu of fuel burned. SCC = Source Classification Code.

Table 1.7-8 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR NITROGEN OXIDES (NO_x) AND CARBON MONOXIDE (CO) FROM CONTROLLED LIGNITE COMBUSTION[a]

Firing Configuration (SCC)	NO_x[b]		CO[c]	
	kg/Mg (lb/ton)	EMISSION FACTOR RATING	kg/Mg (lb/ton)	EMISSION FACTOR RATING
Pulverized coal, dry bottom, tangential overfire air (no SCC)	3.3 (6.6)	C	0.05 (0.10)	D
Pulverized coal, dry bottom, tangential overfire air/low NO_x burners (no SCC)	2.3 (4.6)	C	0.24 (0.48)	D

[a] Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. SCC = Source Classification Code.

[b] References 15-16.

[c] Reference 15.

Table 1.7-9 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM) EMISSIONS FROM CONTROLLED LIGNITE COMBUSTION[a]

Firing Configuration (SCC)	Control Device	PM	
		Emission Factor	RATING
Subpart D Boilers, Pulverized coal, Tangential and wall-fired (no SCC)	Baghouse	0.04A (0.08A)	C
	Wet scrubber	0.03A (0.05A)	C
Subpart Da Boilers, Pulverized coal, Tangential fired (no SCC)	Wet scrubber	0.005A (0.01A)	C
Atmospheric fluidized bed	Limestone addition	0.03A (0.07A)	D

[a] References 15-16. A = weight % ash content of lignite, wet basis. Units are kg of pollutant/Mg of fuel burned and lb of pollutant/ton of fuel burned. SCC = Source Classification Code.

Table 1.7-10 (Metric Units). EMISSION FACTORS FOR TRACE METALS AND POLYCYCLIC ORGANIC MATTER (POM) FROM CONTROLLED LIGNITE COMBUSTION[a]

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	Control Device	Emission Factor, pg/J		
		Cr	Mn	POM
Pulverized coal (SCC 1-01-003-01)	Multi-cyclones	29 - 32		
	ESP	8.6		
	High efficiency cold-side ESP			0.99
Pulverized wet bottom (no SCC)	ESP		15	
Pulverized dry bottom (no SCC)	Multi-cyclones			0.78 - 7.9[b]
	ESP		18	1.1[b]
Cyclone furnace (SCC 1-01-003-03)	Multi-cyclones		711	
	ESP	<3.3	57	0.05[c] - 0.68[b]
Stoker, configuration unknown (no SCC)	Multi-cyclones	13	47	
	ESP	<2.3		
Spreader stoker (SCC 1-01-003-06)	Multi-cyclones			6.3[c]

[a] References 19-20. Units are picograms (10^{-12}) of pollutant/joule of fuel burned. SCC = Source Classification Code.

[b] Primarily trimethyl propenyl naphthalene.

[c] Primarily biphenyl.

Table 1.7-11 (English Units). EMISSION FACTORS FOR TRACE METALS AND POLYCYCLIC ORGANIC MATTER (POM) FROM CONTROLLED LIGNITE COMBUSTION[a]

EMISSION FACTOR RATING: E

Firing Configuration (SCC)	Control Device	Emission Factor, lb/10^{12} Btu		
		Cr	Mn	POM
Pulverized coal (SCC 1-01-003-01)	Multi-cyclones	67 - 74		
	ESP	20		
	High efficiency cold-side ESP			2.3
Pulverized wet bottom (no SCC)	ESP		34	
Pulverized dry bottom (no SCC)	Multi-cyclones			$1.8 - 18^b$
	ESP		42	2.6^b
Cyclone furnace (SCC 1-01-003-03)	Multi-cyclones		1656	
	ESP	<28	133	$0.11^c - 1.6^b$
Stoker, configuration unknown (no SCC)	Multi-cyclones	30	110	
	ESP	<5.4		
Spreader stoker (SCC 1-01-003-06)	Multi-cyclones			15^c

[a] References 19-20. Units are lb of pollutant/10^{12} Btu of fuel burned. SCC = Source Classification Code.

[b] Primarily trimethyl propenyl naphthalene.

[c] Primarily biphenyl.

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1.8 Bagasse Combustion In Sugar Mills

1.8.1 Process Description[1-5]

Bagasse is the matted cellulose fiber residue from sugar cane that has been processed in a sugar mill. Previously, bagasse was burned as means of solid waste disposal. However, as the cost of fuel oil, natural gas, and electricity have increased, the designation of bagasse has changed from refuse to a fuel.

The U. S. sugar cane industry is located in the tropical and subtropical regions of Florida, Texas, Louisiana, Hawaii, and Puerto Rico. Except for Hawaii, where sugar cane production takes place year round, sugar mills operate seasonally from 2 to 5 months per year.

Sugar cane is a large grass with a bamboo-like stalk that grows 8 to 15 feet tall. Only the stalk contains sufficient sucrose for processing into sugar. All other parts of the sugar cane (i. e., leaves, top growth, and roots) are termed "trash." The objective of harvesting is to deliver the sugar cane to the mill with a minimum of trash or other extraneous material. The cane is normally burned in the field to remove a major portion of the trash and to control insects and rodents. See Section 13.1 for methods to estimate these emissions. The three most common methods of harvesting are hand cutting, machine cutting, and mechanical raking. The cane that is delivered to a particular sugar mill will vary in trash and dirt content depending on the harvesting method and weather conditions. Inside the mill, cane preparation for extraction usually involves washing the cane to remove trash and dirt, chopping, and then crushing. Juice is extracted in the milling portion of the plant by passing the chopped and crushed cane through a series of grooved rolls. The cane remaining after milling is bagasse.

Bagasse is a fuel of varying composition, consistency, and heating value. These characteristics depend on the climate, type of soil upon which the cane is grown, variety of cane, harvesting method, amount of cane washing, and the efficiency of the milling plant. In general, bagasse has a heating value between 1,700 and 2,200 kcal/kg (3,000 and 4,000 Btu/lb) on a wet, as-fired basis.. Most bagasse has a moisture content between 45 and 55 percent by weight.

Fuel cells, horseshoe boilers, and spreader stoker boilers are used to burn bagasse. Horseshoe boilers and fuel cells differ in the shapes of their furnace area but in other respects are similar in design and operation. In these boilers (most common among older plants), bagasse is gravity-fed through chutes and piles onto a refractory hearth. Primary and overfire combustion air flows through ports in the furnace walls; burning begins on the surface pile. Many of these units have dumping hearths that permit ash removal while the unit is operating.

In more-recently built sugar mills, bagasse is burned in spreader stoker boilers. Bagasse fed to these boilers enters the furnace through a fuel chute and is spread pneumatically or mechanically across the furnace, where part of the fuel burns while in suspension. Simultaneously, large pieces of fuel are spread in a thin, even bed on a stationary or moving grate. The flame over the grate radiates heat back to the fuel to aid combustion. The combustion area of the furnace is lined with heat exchange tubes (waterwalls).

1.8.2 Emissions And Controls[1-3]

The most significant pollutant emitted by bagasse-fired boilers is particulate matter, caused by the turbulent movement of combustion gases with respect to the burning bagasse and resultant ash. Emissions of SO_2 and NO_x are lower than conventional fossil fuels due to the characteristically low levels of sulfur and nitrogen associated with bagasse.

Auxiliary fuels (typically fuel oil or natural gas) may be used during startup of the boiler or when the moisture content of the bagasse is too high to support combustion. If fuel oil is used during these periods, SO_2 and NO_x emissions will increase. Soil characteristics such as particle size can affect the magnitude of PM emissions from the boiler. Mill operations can also influence the bagasse ash content by not properly washing and preparing the cane. Upsets in combustion conditions can cause increased emissions of carbon monoxide (CO) and unburned organics, typically measured as volatile organic compounds (VOCs) and total organic compounds (TOCs).

Mechanical collectors and wet scrubbers are commonly used to control particulate emissions from bagasse-fired boilers. Mechanical collectors may be installed in single cyclone, double cyclone, or multiple cyclone (i. e., multiclone) arrangements. The reported PM collection efficiency for mechanical collectors is 20 to 60 percent. Due to the abrasive nature of bagasse fly ash, mechanical collector performance may deteriorate over time due to erosion if the system is not well maintained.

The most widely used wet scrubbers for bagasse-fired boilers are impingement and venturi scrubbers. Impingement scrubbers normally operate at gas-side pressure drops of 5 to 15 inches of water; typical pressure drops for venturi scrubbers are over 15 inches of water. Impingement scrubbers are in greater use due to lower energy requirements and fewer operating and maintenance problems. Reported PM collection efficiencies for both scrubber types are 90 percent or greater.

Gaseous emissions (e. g., SO_2, NO_x, CO, and organics) may also be absorbed to a significant extent in a wet scrubber. Alkali compounds are sometimes utilized in the scrubber to prevent low pH conditions. If CO_2-generating compounds (such as sodium carbonate or calcium carbonate) are used, CO_2 emissions will increase.

Fabric filters and electrostatic precipitators have not been used to a significant extent for controlling PM from bagasse-fired boilers due to potential fire hazards (fabric filters) and relatively higher costs (both devices).

Emission factors and emission factor ratings for bagasse-fired boilers are shown in Tables 1.8-1 and 1.8-2.

Fugitive dust may be generated by truck traffic and cane handling operations at the sugar mill. Particulate matter emissions from these sources may be estimated by consulting Section 13.2.

Table 1.8-1 (Metric Units). EMISSION FACTORS FOR BAGASSE-FIRED BOILERS[a]

Pollutant	g/kg Steam[b]	kg/Mg Bagasse[c]	EMISSION FACTOR RATING
Particulate matter[d]			
Uncontrolled	3.9	7.8	C
Controlled			
Mechanical collector	2.1	4.2	D
Wet scrubber	0.4	0.8	B
PM-10[d]			
Controlled			
Wet scrubber	0.34	0.68	D
Carbon dioxide			
Uncontrolled[e]	390	780	A
Nitrogen oxides			
Uncontrolled[f]	0.3	0.6	C
Polycyclic organic matter			
Uncontrolled[g]	2.5 E-4	5.0 E-4	D

[a] Source Classification Code is 1-02-011-01.

[b] Units are gram of pollutant/kg of steam produced, where 1 kg of wet bagasse fired produces 2 kg of steam.

[c] Units are kg of pollutant/Mg of wet, as-fired bagasse containing approximately 50 percent moisture, by weight.

[d] References 2,6-14. Includes only filterable PM (i. e., that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[e] References 6-14. CO_2 emissions will increase following a wet scrubber in which CO_2-generating reagents (such as sodium carbonate or calcium carbonate) are used.

[f] References 13-14.

[g] Reference 13. Based on measurements collected downstream of PM control devices which may have provided some removal of polycyclic organic matter (POM) condensed on PM.

Table 1.8-2 (English Units). EMISSION FACTORS FOR BAGASSE-FIRED BOILERS[a]

Pollutant	lb/1,000 lb Steam[b]	lb/ton Bagasse[c]	EMISSION FACTOR RATING
Particulate matter[d]			
Uncontrolled	3.9	15.6	C
Controlled			
Mechanical collector	2.1	8.4	D
Wet scrubber	0.4	1.6	B
PM-10[d]			
Controlled			
Wet scrubber	0.34	1.36	D
Carbon dioxide			
Uncontrolled[e]	390	1,560	A
Nitrogen oxides			
Uncontrolled[f]	0.3	1.2	C
Polycyclic organic matter			
Uncontrolled[g]	2.5 E-4	1.0 E-3	D

[a] Source Classification Code is 1-02-011-01.

[b] Units are lb of pollutant/1,000 lb of steam produced, where 1 lb of wet bagasse fired produces 2 lb of steam.

[c] Units are lb of pollutant/ton of wet, as-fired bagasse containing approximately 50% moisture, by weight.

[d] References 2,6-14. Includes only filterable PM (i. e., that particulate collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[e] References 6-14. CO_2 emissions will increase following a wet scrubber in which CO_2-generating reagents (such as sodium carbonate or calcium carbonate) are used.

[f] References 13-14.

[g] Reference 13. Based on measurements collected downstream of PM control devices which may have provided some removal of polycyclic organic matter (POM) condensed on PM.

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1.9 Residential Fireplaces

1.9.1 General[1,2]

Fireplaces are used primarily for aesthetic effects and secondarily as a supplemental heating source in houses and other dwellings. Wood is the most common fuel for fireplaces, but coal and densified wood "logs" may also be burned. The user intermittently adds fuel to the fire by hand.

Fireplaces can be divided into 2 broad categories: (1) masonry (generally brick and/or stone, assembled on site, and integral to a structure) and (2) prefabricated (usually metal, installed on site as a package with appropriate duct work).

Masonry fireplaces typically have large fixed openings to the fire bed and have dampers above the combustion area in the chimney to limit room air and heat losses when the fireplace is not being used. Some masonry fireplaces are designed or retrofitted with doors and louvers to reduce the intake of combustion air during use.

Prefabricated fireplaces are commonly equipped with louvers and glass doors to reduce the intake of combustion air, and some are surrounded by ducts through which floor level air is drawn by natural convection, heated, and returned to the room. Many varieties of prefabricated fireplaces are now available on the market. One general class is the freestanding fireplace, the most common of which consists of an inverted sheet metal funnel and stovepipe directly above the fire bed. Another class is the "zero clearance" fireplace, an iron or heavy gauge steel firebox lined inside with firebrick and surrounded by multiple steel walls with spaces for air circulation. Some zero clearance fireplaces can be inserted into existing masonry fireplace openings, and thus are sometimes called "inserts." Some of these units are equipped with close fitting doors and have operating and combustion characteristics similar to wood stoves. (See Section 1.10, Residential Wood Stoves.)

Masonry fireplaces usually heat a room by radiation, with a significant fraction of the combustion heat lost in the exhaust gases and through fireplace walls. Moreover, some of the radiant heat entering the room goes toward warming the air that is pulled into the residence to make up for that drawn up the chimney. The net effect is that masonry fireplaces are usually inefficient heating devices. Indeed, in cases where combustion is poor, where the outside air is cold, or where the fire is allowed to smolder (thus drawing air into a residence without producing appreciable radiant heat energy), a net heat loss may occur in a residence using a fireplace. Fireplace heating efficiency may be improved by a number of measures that either reduce the excess air rate or transfer back into the residence some of the heat that would normally be lost in the exhaust gases or through fireplace walls. As noted above, such measures are commonly incorporated into prefabricated units. As a result, the energy efficiencies of prefabricated fireplaces are slightly higher than those of masonry fireplaces.

1.9.2 Emissions[1-13]

The major pollutants of concern from fireplaces are unburnt combustibles, including carbon monoxide, gaseous organics and particulate matter (i. e., smoke). Significant quantities of unburnt combustibles are produced because fireplaces are inefficient combustion devices, with high uncontrolled excess air rates and without any sort of secondary combustion. The latter is especially important in wood burning because of its high volatile matter content, typically 80 percent by dry weight. In addition to unburnt combustibles, lesser amounts of nitrogen oxides and sulfur oxides are emitted.

Hazardous Air Pollutants (HAPs) are a minor, but potentially important component of wood smoke. A group of HAPs known as polycyclic organic matter (POM) includes potential carcinogens such as benzo(a)pyrene (BaP). POM results from the combination of free radical species formed in the flame zone, primarily as a consequence of incomplete combustion. Under reducing conditions, radical chain propagation is enhanced, allowing the buildup of complex organic material such as POM. The POM is generally found in or on smoke particles, although some sublimation into the vapor phase is probable.

Another important constituent of wood smoke is creosote. This tar-like substance will burn if the fire is hot enough, but at insufficient temperatures, it may deposit on surfaces in the exhaust system. Creosote deposits are a fire hazard in the flue, but they can be reduced if the chimney is insulated to prevent creosote condensation or if the chimney is cleaned regularly to remove any buildup.

Fireplace emissions are highly variable and are a function of many wood characteristics and operating practices. In general, conditions which promote a fast burn rate and a higher flame intensity enhance secondary combustion and thereby lower emissions. Conversely, higher emissions will result from a slow burn rate and a lower flame intensity. Such generalizations apply particularly to the earlier stages of the burning cycle, when significant quantities of combustible volatile matter are being driven out of the wood. Later in the burning cycle, when all volatile matter has been driven out of the wood, the charcoal that remains burns with relatively few emissions.

Emission factors and their ratings for wood combustion in residential fireplaces are given in Tables 1.9-1 and 1.9-2.

Table 1.9-1 (Metric Units). EMISSION FACTORS FOR WOOD COMBUSTION IN RESIDENTIAL FIREPLACES[a]

Device	Pollutant	Emission Factor (g/kg)	RATING
Fireplace	PM-10[b]	17.3	B
	Carbon Monoxide[c]	126.3	B
	Sulfur Oxides[d]	0.2	A
	Nitrogen Oxides[e]	1.3	C
	Carbon Dioxide[f]	1700	C
	Total VOCs[g]	114.5	D
	POM[h]	0.8 E-3	E[j]
	Aldehydes[k]	1.2	E[j]

[a] Units are in grams of pollutant/kg of dry wood burned. Source Classification Code 21-04-008-001.

[b] References 2,5,7,13; contains filterable and condensable particulate matter (PM); PM emissions are considered to be 100% PM-10 (i. e., PM with an aerodynamic diameter of 10 μm or less).

[c] References 2,4,5,9,13.

[d] References 1,8.

[e] References 4,9; expressed as NO_2.

[f] References 5,13.

[g] References 4-5,8. Data used to calculate the average emission factor were collected by various methods. While the emission factor may be representative of the source population in general, factors may not be accurate for individual sources.

[h] Reference 2.

[j] Data used to calculate the average emission factor were collected from a single fireplace and are not representative of the general source population.

[k] References 4,11.

Table 1.9-2 (English Units). EMISSION FACTORS FOR WOOD COMBUSTION IN RESIDENTIAL FIREPLACES[a]

Device	Pollutant	Emission Factor (lb/ton)	RATING
Fireplace	PM-10[b]	34.6	B
	Carbon Monoxide[c]	252.6	B
	Sulfur Oxides[d]	0.4	A
	Nitrogen Oxides[e]	2.6	C
	Carbon Dioxide[f]	3400	C
	Total VOCs[g]	229.0	D
	POM[h]	1.6 E-3	E[j]
	Aldehydes[k]	2.4	E[j]

[a] Units are in lb of pollutant/ton of dry wood burned. Source Classification Code 21-04-008-001.

[b] References 2,5,7,13; contains filterable and condensable particulate matter (PM); PM emissions are considered to be 100% PM-10 (i. e., PM with an aerodynamic diameter of 10 μm or less).

[c] References 2,4,5,9,13.

[d] References 1,8.

[e] References 4,9; expressed as NO_2.

[f] References 5,13.

[g] References 4-5,8. Data used to calculate the average emission factor were collected by various methods. While the emission factor may be representative of the source population in general, factors may not be accurate for individual sources.

[h] Reference 2.

[j] Data used to calculate the average emission factor were collected from a single fireplace and are not representative of the general source population.

[k] References 4,11.

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1.10 Residential Wood Stoves

1.10.1 General[1-2]

Wood stoves are commonly used in residences as space heaters. They are used both as the primary source of residential heat and to supplement conventional heating systems.

Five different categories should be considered when estimating emissions from wood burning devices due to differences in both the magnitude and the composition of the emissions:

- the conventional wood stove,
- the noncatalytic wood stove,
- the catalytic wood stove,
- the pellet stove, and
- the masonry heater.

Among these categories, there are many variations in device design and operation characteristics.

The conventional stove category comprises all stoves without catalytic combustors not included in the other noncatalytic categories (i. e., noncatalytic and pellet). Conventional stoves do not have any emission reduction technology or design features and, in most cases, were manufactured before July 1, 1986. Stoves of many different airflow designs may be in this category, such as updraft, downdraft, crossdraft, and S-flow.

Noncatalytic wood stoves are those units that do not employ catalysts but do have emission reducing technology or features. Typical noncatalytic design includes baffles and secondary combustion chambers.

Catalytic stoves are equipped with a ceramic or metal honeycomb device, called a combustor or converter, that is coated with a noble metal such as platinum or palladium. The catalyst material reduces the ignition temperature of the unburned volatile organic compounds (VOC) and carbon monoxide (CO) in the exhaust gases, thus augmenting their ignition and combustion at normal stove operating temperatures. As these components of the gases burn, the temperature inside the catalyst increases to a point at which the ignition of the gases is essentially self-sustaining.

Pellet stoves are those fueled with pellets of sawdust, wood products, and other biomass materials pressed into manageable shapes and sizes. These stoves have active air flow systems and unique grate design to accommodate this type of fuel. Some pellet stove models are subject to the 1988 New Source Performance Standards (NSPS), while others are exempt due to a high air-to-fuel ratio (i. e., greater than 35-to-1).

Masonry heaters are large, enclosed chambers made of masonry products or a combination of masonry products and ceramic materials. These devices are exempt from the 1988 NSPS due to their weight (i. e., greater than 800 kg). Masonry heaters are gaining popularity as a cleaner burning and heat efficient form of primary and supplemental heat, relative to some other types of wood heaters. In a masonry heater, a complete charge of wood is burned in a relatively short period of time. The use of masonry materials promotes heat transfer. Thus, radiant heat from the heater warms the surrounding area for many hours after the fire has burned out.

1.10.2 Emissions

The combustion and pyrolysis of wood in wood stoves produce atmospheric emissions of particulate matter, carbon monoxide, nitrogen oxides, organic compounds, mineral residues, and to a lesser extent, sulfur oxides. The quantities and types of emissions are highly variable, depending on a number of factors, including stage of the combustion cycle. During initial burning stages, after a new wood charge is introduced, emissions (primarily VOCs) increase dramatically. After the initial period of high burn rate, there is a charcoal stage of the burn cycle characterized by a slower burn rate and decreased emissions. Emission rates during this stage are cyclical, characterized by relatively long periods of low emissions and shorter episodes of emission spikes.

Particulate emissions are defined in this discussion as the total catch measured by the EPA Method 5H (Oregon Method 7) sampling train.[1] A small portion of wood stove particulate emissions includes "solid" particles of elemental carbon and wood. The vast majority of particulate emissions is condensed organic products of incomplete combustion equal to or less than 10 micrometers in aerodynamic diameter (PM-10). Although reported particle size data are scarce, one reference states that 95 percent of the particles emitted from a wood stove were less than 0.4 micrometers in size.[3]

Sulfur oxides (SO_x) are formed by oxidation of sulfur in the wood. Nitrogen oxides (NO_x) are formed by oxidation of fuel and atmospheric nitrogen. Mineral constituents, such as potassium and sodium compounds, are released from the wood matrix during combustion.

The high levels of organic compound and CO emissions are results of incomplete combustion of the wood. Organic constituents of wood smoke vary considerably in both type and volatility. These constituents include simple hydrocarbons of carbon numbers 1 through 7 (C1 - C7) (which exist as gases or which volatilize at ambient conditions) and complex low volatility substances that condense at ambient conditions. These low volatility condensable materials generally are considered to have boiling points below 300°C (572°F).

Polycyclic organic matter (POM) is an important component of the condensable fraction of wood smoke. POM contains a wide range of compounds, including organic compounds formed through incomplete combustion by the combination of free radical species in the flame zone. This group which is classified as a hazardous air pollutant (HAP) under Title III of the 1990 Clean Air Act Amendments contains the sub-group of hydrocarbons called polycyclic aromatic hydrocarbons (PAH).

Emission factors and their ratings for wood combustion in residential wood stoves, pellet stoves, and masonry heaters are presented in Tables 1.10-1, 1.10-2, 1.10-3, 1.10-4, 1.10-5, 1.10-6, and 1.10-7. The analysis leading to the revision of these emission factors is contained in the emission factor documentation.[29] These tables include emission factors for criteria pollutants (PM-10, CO, NO_x, SO_x), CO_2, total organic compounds (TOC), speciated organic compounds, PAH, and some elements. The emission factors are presented by wood heater type. PM-10 and CO emission factors are further classified by stove certification category. Phase II stoves are those certified to meet the July 1, 1990, EPA standards; Phase I stoves meet only the July 1, 1988, EPA standards; and Pre-Phase I stoves do not meet any of the EPA standards but in most cases do necessarily meet the Oregon 1986 certification standards.[1] The emission factors for PM and CO in Tables 1.10-1 and

Table 1.10-1 (Metric Units). EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]

		Wood Stove Type			Pellet Stove Type[c] (SCC 21-04-008-053)		Masonry Heater (SCC 21-04-008-055)
Pollutant/EPA Certification[b]	EMISSION FACTOR RATING	Conventional (SCC 21-04-008-051)	Noncatalytic (SCC 21-04-008-050)	Catalytic (SCC 21-04-008-030)	Certified	Exempt	Exempt[d]
PM-10[e]							
Pre-Phase I	B	15.3	12.9	12.1			
Phase I	B		10.0	9.8			
Phase II	B		7.3	8.1	2.1		
All	B	15.3	9.8	10.2	2.1	4.4	2.8
Carbon Monoxide[e]							
Pre-Phase I	B	115.4					
Phase I	B			52.2			
Phase II	B		70.4		19.7		
All	B	115.4	70.4	52.2	19.7	26.1	74.5
Nitrogen Oxides[e]		1.4[f]		1.0[g]	6.9[g]		
Sulfur Oxides[e]	B	0.2	0.2	0.2	0.2		
Carbon Dioxide[h]	C				1476	1836	1925
TOC[j]	E	24.3		12.1			
Methane	E	2.4		4.3			
TNMOC	E	21.9		7.8			

[a] Units are in grams of pollutant/kg of dry wood burned. SCC = Source Classification Code.

[b] Pre-Phase I = Not certified to 1988 EPA emission standards; Phase I = Certified to 1988 EPA emission standards; Phase II = Certified to 1990 EPA emission standards; All = Average of emission factors for all devices.

[c] Certified = Certified pursuant to 1988 NSPS; Exempt = Exempt from 1988 NSPS (i. e., air:fuel > 35:1).

[d] Exempt = Exempt from 1988 NSPS (i. e., device weight >800 kg).

[e] References 6-14,23-27,29. PM-10 is defined as equivalent to total catch by EPA method 5H train.

[f] EMISSION FACTOR RATING: C.

[g] EMISSION FACTOR RATING: E.

[h] References 13,24-27,29.

[j] References 13,17-18. TOC = total organic compounds; TNMOC = total nonmethane organic compounds. Data show a high degree of variability within the source population. Factors may not be accurate for individual sources.

Table 1.10-2 (English Units). EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a]

Pollutant/EPA Certification[b]	EMISSION FACTOR RATING	Wood Stove Type			Pellet Stove Type[c] (SCC 21-04-008-053)		Masonry Heater (SCC 21-04-008-055)
		Conventional (SCC 21-04-008-051)	Noncatalytic (SCC 21-04-008-050)	Catalytic (SCC 21-04-008-030)	Certified	Exempt	Exempt[d]
PM-10[e]							
Pre-Phase I	B	30.6	25.8	24.2			
Phase I	B		20.0	19.6			
Phase II	B		14.6	16.2	4.2		
All	B	30.6	19.6	20.4	4.2	8.8	5.6
Carbon Monoxide[e]							
Pre-Phase I	B	230.8					
Phase I	B			104.4			
Phase II	B		140.8	107.0	39.4		
All	B	230.8	140.8	104.4	39.4	52.2	149.0
Nitrogen Oxides[e]		2.8[f]		2.0[g]	13.8[g]		
Sulfur Oxides[e]	B	0.4	0.4	0.4	0.4		
Carbon Dioxide[h]	C				2952	3671	3849
TOC[j]	E	48.6		24.2			
Methane	E	4.8		8.6			
TNMOC	E	43.8		15.6			

[a] Units are in lb of pollutant/ton of dry wood burned. SCC = Source Classification Code.

[b] Pre-Phase I = Not certified to 1988 EPA emission standards; Phase I = Certified to 1988 EPA emission standards; Phase II = Certified to 1990 EPA emission standards; All = Average of emission factors for all devices.

[c] Certified = Certified pursuant to 1988 NSPS; Exempt = Exempt from 1988 NSPS (i. e., air:ratio > 35:1).

[d] Exempt = Exempt from 1988 NSPS (i. e., device weight >800 kg).

[e] References 6-14,23-27,29. PM-10 is defined as equivalent to total catch by EPA method 5H train.

[f] EMISSION FACTOR RATING: C.

[g] EMISSION FACTOR RATING: E.

[h] References 13,24-27,29.

[j] References 13,17-18. TOC = Total organic compounds; TNMOC = Total nonmethane organic compounds. Data show a high degree of variability within the source population. Factors may not be accurate for individual sources.

Table 1.10-3 (Metric And English Units). ORGANIC COMPOUND EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a,b]

EMISSION FACTOR RATING: E

	Wood Stove Type			
	Conventional (SCC 21-04-008-051)		Catalytic (SCC 21-04-008-030)	
Compounds	g/kg	lb/ton	g/kg	lb/ton
Ethane	0.735	1.470	0.688	1.376
Ethylene	2.245	4.490	1.741	3.482
Acetylene	0.562	1.124	0.282	0.564
Propane	0.179	0.358	0.079	0.158
Propene	0.622	1.244	0.367	0.734
i-Butane	0.014	0.028	0.005	0.010
n-Butane	0.028	0.056	0.007	0.014
Butenes[c]	0.596	1.192	0.357	0.714
Pentenes[d]	0.308	0.616	0.075	0.150
Benzene	0.969	1.938	0.732	1.464
Toluene	0.365	0.730	0.260	0.520
Furan	0.171	0.342	0.062	0.124
Methyl Ethyl Ketone	0.145	0.290	0.031	0.062
2-Methyl Furan	0.328	0.656	0.042	0.084
2,5-Dimethyl Furan	0.081	0.162	0.011	0.002
Furfural	0.243	0.486	0.073	0.146
o-Xylene	0.101	0.202	0.093	0.186

[a] Reference 17. Units are in grams of pollutant/kg of dry wood burned and lb of pollutant/ton of dry wood burned. SCC = Source Classification Code.

[b] Data show a high degree of variability within the source population. Factors may not be accurate for individual sources.

[c] 1-butene, i-butene, t-2-butene, c-2-butene, 2-me-1-butene, 2-me-butene are reported as butenes.

[d] 1-pentene, t-2-pentene, and c-2-pentene are reported as pentenes.

Table 1.10-4 (Metric Units). POLYCYCLIC AROMATIC HYDROCARBON (PAH) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a,b]

EMISSION FACTOR RATING: E

Pollutant	Stove Type			
	Conventional[c] (SCC 21-04-008-051)	Noncatalytic[d] (SCC 21-04-008-050)	Catalytic[e] (SCC 21-04-008-030)	Exempt Pellet[f] (SCC 21-04-008-053)
PAH				
Acenaphthene	0.005	0.005	0.003	
Acenaphthylene	0.106	0.016	0.034	
Anthracene	0.007	0.004	0.004	
Benzo(a)Anthracene	0.010	<0.001	0.012	
Benzo(b)Fluoranthene	0.003	0.002	0.002	1.30 E-05
Benzo(g,h,i)Fluoranthene		0.014	0.003	
Benzo(k)Fluoranthene	0.001	<0.001	0.001	
Benzo(g,h,i)Perylene	0.002	0.010	0.001	
Benzo(a)Pyrene	0.002	0.003	0.002	
Benzo(e)Pyrene	0.006	0.001	0.002	
Biphenyl		0.011		
Chrysene	0.006	0.005	0.005	3.76 E-05
Dibenzo(a,h)Anthracene	0.000	0.002	0.001	
7,12-Dimethylbenz(a)Anthracene		0.002		
Fluoranthene	0.010	0.004	0.006	2.74 E-05
Fluorene	0.012	0.007	0.007	
Indeno(1,2,3,cd)Pyrene	0.000	0.010	0.002	
9-Methylanthracene		0.002		
12-Methylbenz(a)Anthracene		0.001		
3-Methylchlolanthrene		<0.001		
1-Methylphenanthrene		0.015		
Naphthalene	0.144	0.072	0.093	
Nitronaphthalene		0.000		
Perylene		0.001		
Phenanthrene	0.039	0.059	0.024	1.66 E-05
Phenanthrol		0.000		
Phenol		<0.001		
Pyrene	0.012	0.004	0.005	2.42 E-05
PAH Total	0.365	0.250	0.207	

[a] Units are in grams of pollutant/kg of dry wood burned. SCC = Source Classification Code.

[b] Data show a high degree of variability within the source population and/or came from a small number of sources. Factors may not be accurate for individual sources.

[c] Reference 17.

[d] References 15,18-20.

[e] References 14-18.

[f] Reference 27. Exempt = Exempt from 1988 NSPS (i. e., air:fuel > 35:1).

Table 1.10-5 (English Units). POLYCYCLIC AROMATIC HYDROCARBON (PAH) EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a,b]

EMISSION FACTOR RATING: E

	Stove Type			
Pollutant	Conventional[c] (SCC 21-04-008-051)	Noncatalytic[d] (SCC 21-04-008-050)	Catalytic[e] (SCC 21-04-008-050)	Exempt Pellet[f] (SCC 21-04-004-053)
PAH				
Acenaphthene	0.010	0.010	0.006	
Acenaphthylene	0.212	0.032	0.068	
Anthracene	0.014	0.009	0.008	
Benzo(a)Anthracene	0.020	<0.001	0.024	
Benzo(b)Fluoranthene	0.006	0.004	0.004	2.60 E-05
Benzo(g,h,i)Fluoranthene		0.028	0.006	
Benzo(k)Fluoranthene	0.002	<0.001	0.002	
Benzo(g,h,i)Perylene	0.004	0.020	0.002	
Benzo(a)Pyrene	0.004	0.006	0.004	
Benzo(e)Pyrene	0.012	0.002	0.004	
Biphenyl		0.022		
Chrysene	0.012	0.010	0.010	7.52 E-05
Dibenzo(a,h)Anthracene	0.000	0.004	0.002	
7,12-Dimethylbenz(a)Anthracene		0.004		
Fluoranthene	0.020	0.008	0.012	5.48 E-05
Fluorene	0.024	0.014	0.014	
Indeno(1,2,3,cd)Pyrene	0.000	0.020	0.004	
9-Methylanthracene		0.004		
12-Methylbenz(a)Anthracene		0.002		
3-Methylchlolanthrene		<0.001		
1-Methylphenanthrene		0.030		
Naphthalene	0.288	0.144	0.186	
Nitronaphthalene		0.000		
Perylene		0.002		
Phenanthrene	0.078	0.118	0.489	3.32 E-05
Phenanthrol		0.000		
Phenol		<0.001		
Pyrene	0.024	0.008	0.010	4.84 E-05
PAH Total	0.730	0.500	0.414	

[a] Units are in lb of pollutant/ton of dry wood burned. SCC = Source Classification Code.

[b] Data show a high degree of variability within the source population and/or came from a small number of sources. Factors may not be accurate for individual sources.

[c] Reference 17.

[d] References 15,18-20.

[e] References 14-18.

[f] Reference 27. Exempt = Exempt from 1988 NSPS (i. e., air:fuel > 35:1).

1.10-2 are averages, derived entirely from field test data obtained under actual operating conditions. Still, there is a potential for higher emissions from some wood stove, pellet stove, and masonry heater models.

Table 1.10-6 (Metric And English Units). TRACE ELEMENT EMISSION FACTORS FOR RESIDENTIAL WOOD COMBUSTION[a,b]

EMISSION FACTOR RATING: E

	Wood Stove Type					
	Conventional (SCC 21-04-008-051)		Noncatalytic (SCC 21-04-008-050)		Catalytic (SCC 21-04-008-030)	
Element	g/kg	lb/ton	g/kg	lb/ton	g/kg	lb/ton
Cadmium (Cd)	1.1 E-05	2.2 E-05	1.0 E-05	2.0 E-05	2.3 E-05	4.6 E-05
Chromium (Cr)	<1.0 E-06	<1.0 E-06	<1.0 E-05	<1.0 E-06	<1.0 E-06	<1.0 E-06
Manganese (Mn)	8.7 E-05	1.7 E-04	7.0 E-05	1.4 E-04	1.1 E-04	2.2 E-04
Nickel (Ni)	7.0 E-06	1.4 E-05	1.0 E-05	2.0 E-05	1.0 E-06	2.2 E-06

[a] References 14,17. Units are in grams of pollutant/kg of dry wood burned and lb of pollutant/ton of dry wood burned.

[b] The data used to develop these emission factors showed a high degree of variability within the source population. Factors may not be accurate for individual sources.

Table 1.10-7. SUMMARY OF WOOD HEATER NET EFFICIENCIES[a]

Wood Heater Type	Source Classification Code	Net Efficiency (%)	Reference
Wood Stoves			
Conventional	21-04-008-051	54	26
Noncatalytic	21-04-008-050	68	9, 12, 26
Catalytic	21-04-008-030	68	6, 26
Pellet Stoves[b]			
Certified	21-04-008-053	68	11
Exempt		56	27
Masonry Heaters			
All	21-04-008-055	58	28

[a] Net efficiency is a function of both combustion efficiency and heat transfer efficiency. The percentages shown here are based on data collected from in-home testing.

[b] Certified = Certified pursuant to 1988 NSPS. Exempt = Exempt from 1988 NSPS (i. e., air:fuel >35:1).

As mentioned, particulate emissions are defined as the total emissions equivalent to that collected by EPA Method 5H. This method employs a heated filter followed by three impingers, an unheated filter, and a final impinger. Particulate emissions factors are presented as values equivalent to that collected with Method 5H. Conversions are employed, as appropriate, for data collected with other methods.

Table 1.10-7 shows net efficiency by device type, determined entirely from field test data. Net or overall efficiency is the product of combustion efficiency multiplied by heat transfer efficiency. Wood heater efficiency is an important parameter used, along with emission factors and percent degradation, when calculating PM-10 emission reduction credits. Percent degradation is related to the loss in effectiveness of a wood stove control device or catalyst over a period of operation. Control degradation for any stove, including noncatalytic wood stoves, may also occur as a result of deteriorated seals and gaskets, misaligned baffles and bypass mechanisms, broken refractories, or other damaged functional components. The increase in emissions which can result from control degradation has not been quantified. However, recent wood stove testing in Colorado and Oregon should produce results which allow estimation of emissions as a function of stove age.

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1.11 Waste Oil Combustion

1.11.1 General[1]

Waste, or used oil can be burned in a variety of combustion systems including industrial boilers; commercial/institutional boilers; space heaters; asphalt plants; cement and lime kilns; other types of dryers and calciners; and steel production blast furnaces. Boilers and space heaters consume the bulk of the waste oil burned. Space heaters are small combustion units (generally less than 0.1 MW [250,000 Btu/hr input]) that are common in automobile service stations and automotive repair shops where supplies of waste crankcase oil are available.

Boilers designed to burn No. 6 (residual) fuel oils or one of the distillate fuel oils can be used to burn waste oil, with or without modifications for optimizing combustion. As an alternative to boiler modification, the properties of waste oil can be modified by blending it with fuel oil, to the extent required to achieve a clean-burning fuel mixture.

1.11.2 Emissions And Controls[1-3]

Waste oil includes used crankcase oils from automobiles and trucks, used industrial lubricating oils (such as metal working oils), and other used industrial oils (such as heat transfer fluids). When discarded, these oils become waste oils due to a breakdown of physical properties and to contamination by the materials they come in contact with. The different types of waste oils may be burned as mixtures or as single fuels where supplies allow; for example, some space heaters in automotive service stations burn waste crankcase oils.

Contamination of the virgin oils with a variety of materials leads to an air pollution potential when these oils are burned. Potential pollutants include particulate matter (PM), small particles below 10 micrometers in size (PM-10), toxic metals, organic compounds, carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x), hydrogen chloride, and global warming gases (carbon dioxide [CO_2], methane [CH_4]).

Ash levels in waste oils are normally much higher than ash levels in either distillate oils or residual oils. Waste oils have substantially higher concentrations of most of the trace elements reported relative to those concentrations found in virgin fuel oils. However, because of the shift to unleaded gasoline, the concentration of lead in waste crankcase oils has continued to decrease in recent years. Without air pollution controls, higher concentrations of ash and trace metals in the waste fuel translate to higher emission levels of PM and trace metals than is the case for virgin fuel oils.

Low efficiency pretreatment steps, such as large particle removal with screens or coarse filters, are common prefeed procedures at oil-fired boilers. Reductions in total PM emissions can be expected from these techniques but little or no effects have been noticed on the levels of PM-10 emissions.

Constituent chlorine in waste oils typically exceeds the concentration of chlorine in virgin distillate and residual oils. High levels of halogenated solvents are often found in waste oil as a result of inadvertent or deliberate additions of the contaminant solvents to the waste oils. Many efficient combustors can destroy more than 99.99 percent of the chlorinated solvents present in the fuel.

However, given the wide array of combustor types which burn waste oils, the presence of these compounds in the emission stream cannot be ruled out.

The flue gases from waste oil combustion often contain organic compounds other than chlorinated solvents. At ppmw levels, several hazardous organic compounds have been found in waste oils. Benzene, toluene, polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-d-dioxins are a few of the hazardous compounds that have been detected in waste oil samples. Additionally, these hazardous compounds may be formed in the combustion process as products of incomplete combustion.

Emission factors and emission factor ratings for waste oil combustion are shown in Tables 1.11-1, 1.11-2, 1.11-3, 1.11-4, and 1.11-5. Emission factors have been determined for emissions from uncontrolled small boilers and space heaters combusting waste oil. The use of both blended and unblended fuels is included in the mix of combustion operations.

Emissions from waste oil used in batch asphalt plants may be estimated using the procedures outlined in Section 4.5.

Table 1.11-1 (Metric And English Units). EMISSION FACTORS FOR PARTICULATE MATTER (PM), PARTICULATE MATTER LESS THAN 10 MICROMETERS (PM-10), AND LEAD FROM WASTE OIL COMBUSTORS[a]

Source Category (SCC)[b]	PM			PM-10			Lead		
	kg/m^3	lb/1000 gal	RATING	kg/m^3	lb/1000 gal	RATING	kg/m^3	lb/1000 gal	RATING
Small boilers[c] (1-03-013-02)	7.3A[d]	61A	C	6.1A	51A	C	6.6L[e]	55L	D
Space heaters[f]									
Vaporizing burner (1-05-001-14, 1-05-002-14)	0.3A	2.8A	D	ND	ND		0.049L	0.41L	D
Atomizing burner (1-05-001-13, 1-05-002-13)	7.7A	64A	D	6.8A	57A	E	6.0L	50L	D

[a] Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned. ND = no data.

[b] SCC = Source Classification Code.

[c] References 2,4-6.

[d] A = weight percent ash in fuel. Multiply numeric value by A to obtain emission factor.

[e] L = weight percent lead in fuel. Multiply numeric value by L to obtain emission factor.

[f] References 6-7.

Table 1.11-2 (Metric And English Units). EMISSION FACTORS FOR NITROGEN OXIDES (NO_x), SULFUR OXIDES (SO_x), AND CARBON MONOXIDE (CO) FROM WASTE OIL COMBUSTORS[a]

Source Category (SCC)[b]	NO_x			SO_x			CO		
	kg/m^3	lb/1000 gal	RATING	kg/m^3	lb/1000 gal	RATING	kg/m^3	lb/1000 gal	RATING
Small boilers[c] (1-03-013-02)	2.3	19	C	17.6S[d]	147S	C	0.60	5	D
Space heaters[e]									
Vaporizing burner (1-05-001-14, 1-05-002-14)	1.3	11	D	12.0S	100S	D	0.20	1.7	D
Atomizing burner (1-05-001-13, 1-05-002-13)	1.9	16	D	12.8S	107S	D	0.25	2.1	D

[a] Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned.

[b] SCC = Source Classification Code.

[c] References 2,4,6,8.

[d] S = weight percent sulfur in fuel. Multiply numeric value by S to obtain emission factor.

[e] References 6-7.

Table 1.11-3 (Metric And English Units). EMISSION FACTORS FOR TOTAL ORGANIC COMPOUNDS (TOC), HYDROGEN CHLORIDE (HCl), AND CARBON DIOXIDE (CO_2) FROM WASTE OIL COMBUSTORS[a]

Source Category (SCC)[b]	TOC			HCl			CO_2		
	kg/m^3	lb/1000 gal	RATING	kg/m^3	lb/1000 gal	RATING	kg/m^3	lb/1000 gal	RATING
Small boilers[c] (1-03-013-02)	0.01	0.1	D	7.9Cl[d]	66Cl	C	2,400	20,000	C
Space heaters[e]									
Vaporizing burner (1-05-001-14, 1-05-002-14)	0.01	0.1	D	ND	ND		2,700	23,000	D
Atomizing burner (1-05-001-13, 1-05-002-13)	0.01	0.1	D	ND	ND		2,900	24,000	D

[a] Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned. ND = no data.

[b] SCC = Source Classification Code.

[c] References 2,4,6-7,9.

[d] Cl = weight percent chlorine in fuel. Multiply numeric value by Cl to obtain emission factor.

[e] References 4,6-7,9.

Table 1.11-4 (Metric And English Units). EMISSION FACTORS FOR SPECIATED METALS FROM WASTE OIL COMBUSTORS[a]

EMISSION FACTOR RATING: D

Pollutant	Small Boilers[b] (SCC 1-03-013-02)		Space Heaters: Vaporizing Burner[c] (SCC 1-05-001-14, 1-05-002-14)		Space Heaters: Atomizing Burner[c] (SCC 1-05-001-13, 1-05-002-13)	
	kg/m^3	lb/1000 gal	kg/m^3	lb/1000 gal	kg/m^3	lb/1000 gal
Antimony	ND	ND	4.1 E-05	3.4 E-04	5.4 E-04	4.5 E-03
Arsenic	1.3 E-02	1.1 E-01	3.0 E-04	2.5 E-03	7.2 E-03	6.0 E-02
Beryllium	ND	ND	ND	ND	2.1 E-04	1.8 E-03
Cadmium	1.1 E-03	9.3 E-03	1.8 E-05	1.5 E-04	1.4 E-03	1.2 E-02
Chromium	2.4 E-03	2.0 E-02	2.3 E-02	1.9 E-01	2.2 E-02	1.8 E-01
Cobalt	2.5 E-05	2.1 E-04	6.8 E-04	5.7 E-03	6.2 E-04	5.2 E-03
Manganese	8.2 E-03	6.8 E-02	2.6 E-04	2.2 E-03	6.0 E-03	5.0 E-02
Nickel	1.3 E-03	1.1 E-02	6.0 E-03	5.0 E-02	1.9 E-02	1.6 E-01
Selenium	ND	ND	ND	ND	ND	ND
Phosphorous	ND	ND	4.3 E-03	3.6 E-02	ND	ND

[a] Pollutants in this table represent metal species measured for waste oil combustors. Other metal species may also have been emitted but were either not measured or were present at concentrations below analytical detection limits. Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned. SCC = Source Classification Code. ND = no data.

[b] Reference 6.

[c] References 6-7.

Table 1.11-5 (Metric And English Units). EMISSION FACTORS FOR SPECIATED ORGANIC COMPOUNDS FROM WASTE OIL COMBUSTORS[a]

EMISSION FACTOR RATING: D

Pollutant	Space Heaters: Vaporizing Burner (SCC 1-05-001-14, 1-05-002-14)		Space Heaters: Atomizing Burner (SCC 1-05-001-13, 1-05-002-13)	
	kg/m^3	lb/1000 gal	kg/m^3	lb/1000 gal
Phenol	2.9 E-04	2.4 E-03	3.3 E-06	2.8 E-05
Dichlorobenzene	8.0 E-07	6.7 E-06	ND	ND
Naphthalene	1.6 E-03	1.3 E-02	1.1 E-04	9.4 E-04
Phenanthrene/anthracene	1.3 E-03	1.1 E-02	1.5 E-05	9.9 E-05
Dibutylphthalate	ND	ND	4.0 E-06	3.4 E-05
Butylbenzylphthalate	6.1 E-05	5.1 E-04	ND	ND
Bis(2-ethylhexyl)phthalate	2.6 E-04	2.2 E-03	ND	ND
Pyrene	8.4 E-04	7.0 E-03	6.1 E-06	5.1 E-05
Benz(a)anthracene/chrysene	4.8 E-04	4.0 E-03	ND	ND
Benzo(a)pyrene	4.8 E-04	4.0 E-03	ND	ND
Trichloroethylene	ND	ND	ND	ND

[a] Reference 6. Pollutants in this table represent organic species measured for waste oil combustors. Other organic species may also have been emitted but were either not measured or were present at concentrations below analytical detection limits. Units are kg of pollutant/cubic meter of waste oil burned and lb of pollutant/1000 gallons of waste oil burned. SCC = Source Classification Code. ND = no data.

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2. SOLID WASTE DISPOSAL

As defined in the Solid Waste Disposal Act of 1965, the term "solid waste" means garbage, refuse, and other discarded solid materials, including solid-waste materials resulting from industrial, commercial, and agricultural operations, and from community activities. It includes both combustibles and noncombustibles.

Solid waste may be classified into four general categories: urban, industrial, mineral, and agricultural. Urban waste is only a relatively small part of the total solid wastes produced, but this category has a large potential for air pollution. The majority of urban refuse is buried in landfills to decompose anaerobically, mostly into global warming gases but also into a number of reduced sulfur compounds. In heavily populated areas, solid waste is often burned to reduce the bulk of material requiring final disposal. Medical waste, depending on its source, may be considered either urban or industrial waste. Because of the infection potential and special characteristics of medical waste, it requires special disposal methods. Sludges can be either urban or industrial and, because of their unique characteristics, they also require special disposal methods. Agricultural wastes are unique in the volume of organic material that may need to be disposed of in a short time. Therefore, unique disposal methods may be used for this solid waste category.

2.1 Refuse Combustion

Refuse combustion involves the burning of garbage and other nonhazardous solids, commonly called municipal solid waste (MSW). Types of combustion devices used to burn refuse include single chamber units, multiple chamber units, and trench incinerators.

2.1.1 General[1-3]

As of January 1992, there were over 160 municipal waste combustor (MWC) plants operating in the United States with capacities greater than 36 megagrams per day (Mg/day) (40 tons per day [tpd]), with a total capacity of approximately 100,000 Mg/day (110,000 tpd of MSW).[1] It is projected that by 1997, the total MWC capacity will approach 150,000 Mg/day (165,000 tpd), which represents approximately 28 percent of the estimated total amount of MSW generated in the United States by the year 2000.

Federal regulations for MWCs are currently under 3 subparts of 40 CFR Part 60. Subpart E covers MWC units that began construction after 1971 and have capacities to combust over 45 Mg/day (50 tpd) of MSW. Subpart Ea establishes new source performance standards (NSPS) for MWC units which began construction or modification after December 20, 1989 and have capacities over 225 Mg/day (250 tpd). An emission guideline (EG) was established under Subpart Ca covering MWC units which began construction or modification prior to December 20, 1989 and have capacities of greater than 225 Mg/day (250 tpd). The Subpart Ea and Ca regulations were promulgated on February 11, 1991.

Subpart E includes a standard for particulate matter (PM). Subparts Ca and Ea currently establish standards for PM, tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans (CDD/CDF), hydrogen chloride (HCl), sulfur dioxide (SO_2), nitrogen oxides (NO_x) (Subpart Ea only), and carbon monoxide (CO). Additionally, standards for mercury (Hg), lead (Pb), cadmium (Cd), and NO_x (for Subpart Ca) are currently being considered for new and existing facilities, as required by Section 129 of the Clean Air Act Amendments (CAAA) of 1990.

In addition to requiring revisions of the Subpart Ca and Ea regulations to include these additional pollutants, Section 129 also requires the EPA to review the standards and guidelines for the pollutants currently covered under these subparts. It is likely that the revised regulations will be more stringent. The regulations are also being expanded to cover new and existing MWC facilities with capacities of 225 Mg/day (250 tpd) or less. The revised regulations will likely cover facilities with capacities as low as 18 to 45 Mg/day (20 to 50 tpd). These facilities are currently subject only to State regulations.

2.1.1.1 Combustor Technology -

There are 3 main classes of technologies used to combust MSW: mass burn, refuse-derived fuel (RDF), and modular combustors. This section provides a general description of these 3 classes of combustors. Section 2.1.2 provides more details regarding design and operation of each combustor class.

With mass burn units, the MSW is combusted without any preprocessing other than removal of items too large to go through the feed system. In a typical mass burn combustor, refuse is placed on a grate that moves through the combustor. Combustion air in excess of stoichiometric amounts is supplied both below (underfire air) and above (overfire air) the grate. Mass burn combustors are usually erected at the site (as opposed to being prefabricated at another location), and range in size from 46 to 900 Mg/day (50 to 1,000 tpd) of MSW throughput per unit. The mass burn combustor category can be divided into mass burn waterwall (MB/WW), mass burn rotary waterwall combustor (MB/RC), and mass burn refractory wall (MB/REF) designs. Mass burn waterwall designs have water-filled tubes in the furnace walls that are used to recover heat for production of steam and/or electricity. Mass burn rotary waterwall combustors use a rotary combustion chamber constructed of water-filled tubes followed by a waterwall furnace. Mass burn refractory designs are older and typically do not include any heat recovery. Process diagrams for a typical MB/WW combustor, a MB/RC combustor, and one type of MB/REF combustor are presented in Figure 2.1-1, Figure 2.1-2, and Figure 2.1-3, respectively.

Refuse-derived fuel combustors burn processed waste that varies from shredded waste to finely divided fuel suitable for co-firing with pulverized coal. Combustor sizes range from 290 to 1,300 Mg/day (320 to 1,400 tpd). A process diagram for a typical RDF combustor is shown in Figure 2.1-4. Waste processing usually consists of removing noncombustibles and shredding, which generally raises the heating value and provides a more uniform fuel. The type of RDF used depends on the boiler design. Most boilers designed to burn RDF use spreader stokers and fire fluff RDF in a semi-suspension mode. A subset of the RDF technology is fluidized bed combustors (FBC).

Modular combustors are similar to mass burn combustors in that they burn waste that has not been pre-processed, but they are typically shop fabricated and generally range in size from 4 to 130 Mg/day (5 to 140 tpd) of MSW throughput. One of the most common types of modular combustors is the starved air or controlled air type, which incorporates two combustion chambers. A process diagram of a typical modular starved-air (MOD/SA) combustor is presented in Figure 2.1-5. Air is supplied to the primary chamber at sub-stoichiometric levels. The incomplete combustion products (CO and organic compounds) pass into the secondary combustion chamber where additional air is added and combustion is completed. Another type of modular combustor design is the modular excess air (MOD/EA) combustor which consists of 2 chambers as with MOD/SA units, but is functionally similar to mass burn units in that it uses excess air in the primary chamber.

2.1.2 Process Description[4]

Types of combustors described in this section include:

- Mass burn waterwall,
- Mass burn rotary waterwall,
- Mass burn refractory wall,
- Refuse-derived fuel-fired,
- Fluidized bed,
- Modular starved air, and
- Modular excess air.

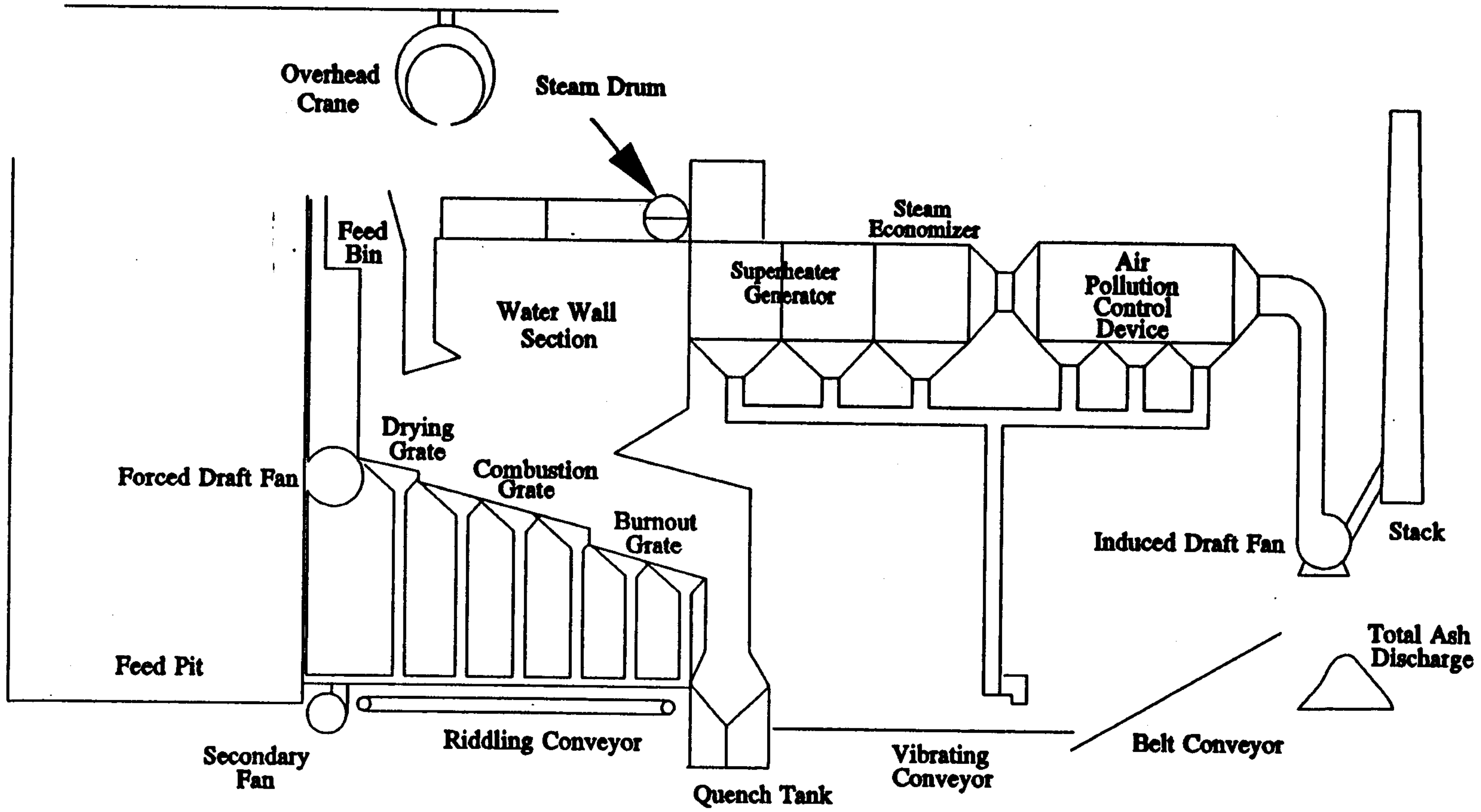

Figure 2.1-1. Typical mass burn waterfall combustor.

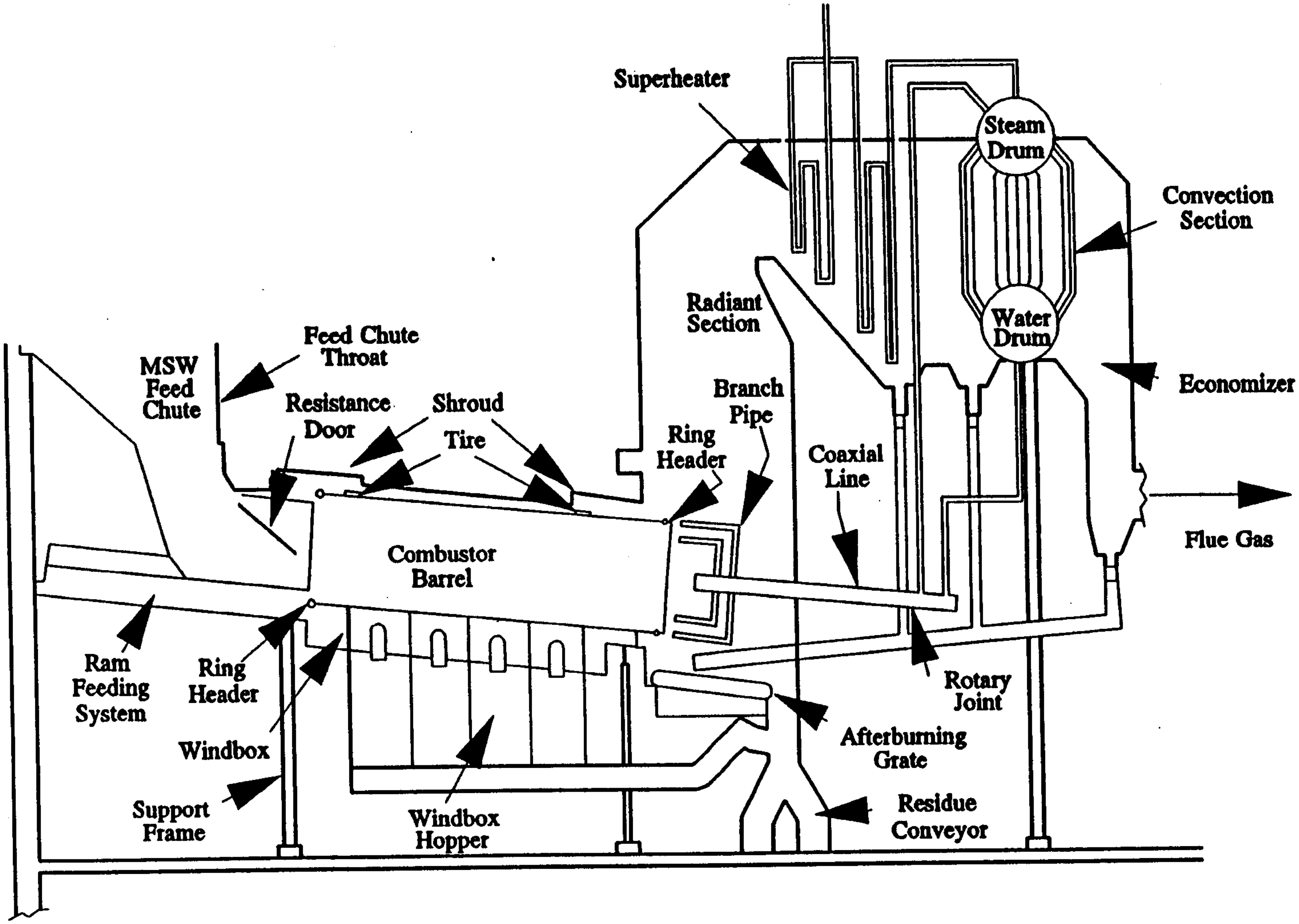

Figure 2.1-2. Simplified process flow diagram for a rotary waterwall combustor.

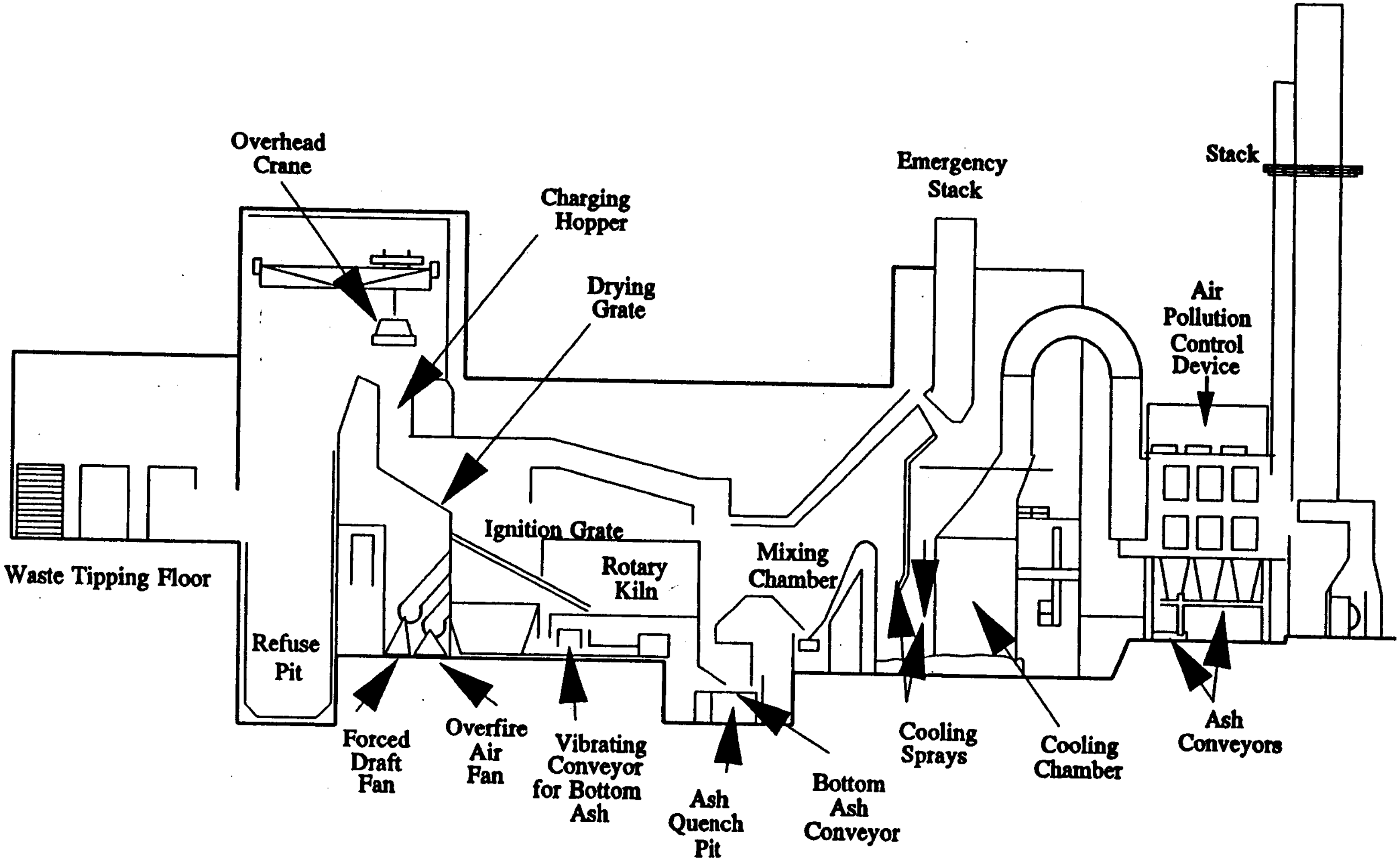

Figure 2.1-3. Mass burn refractory wall combustor with grate/rotary kiln.

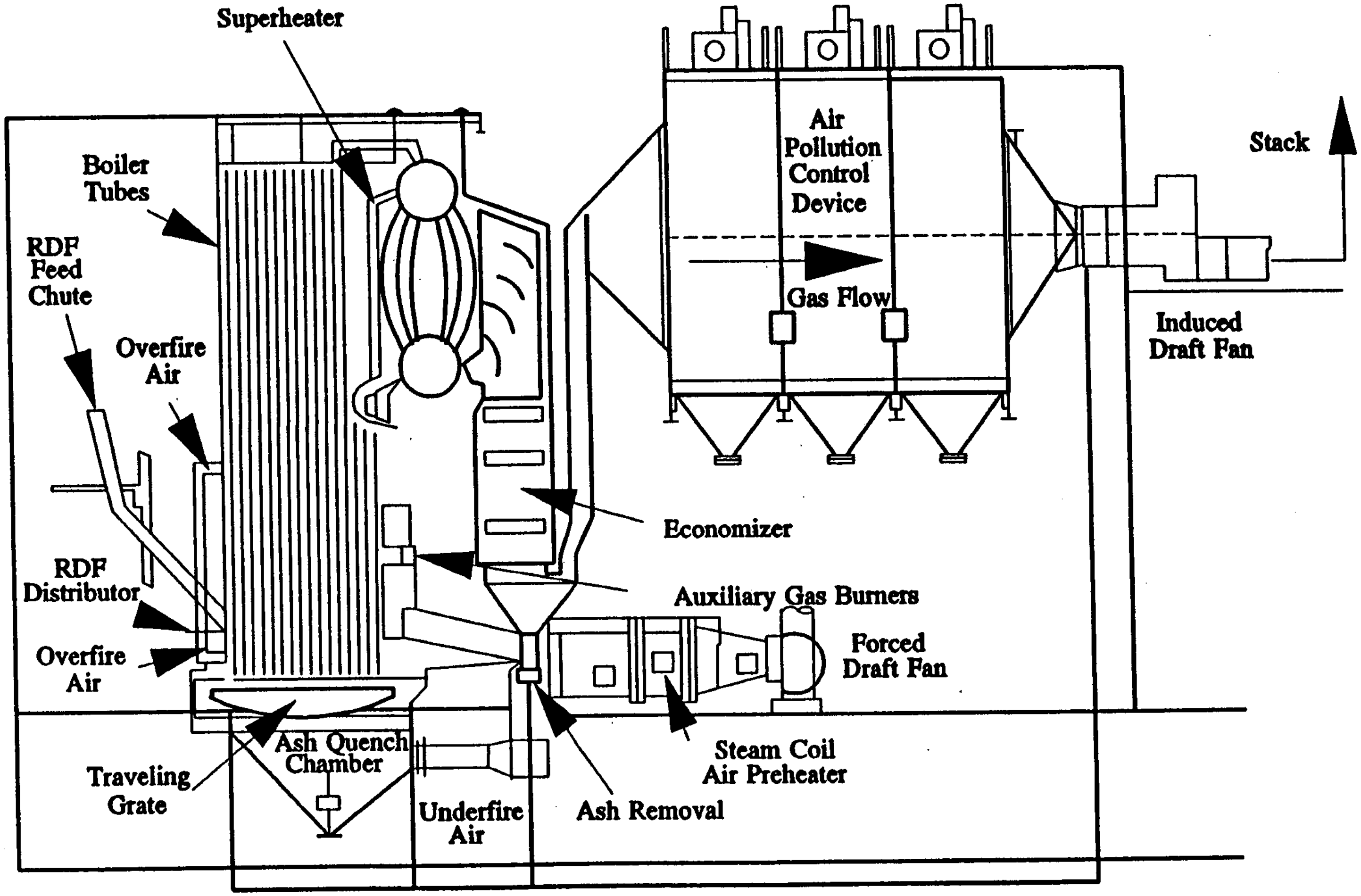

Figure 2.1-4. Typical RDF-fired spreader stoker boiler.

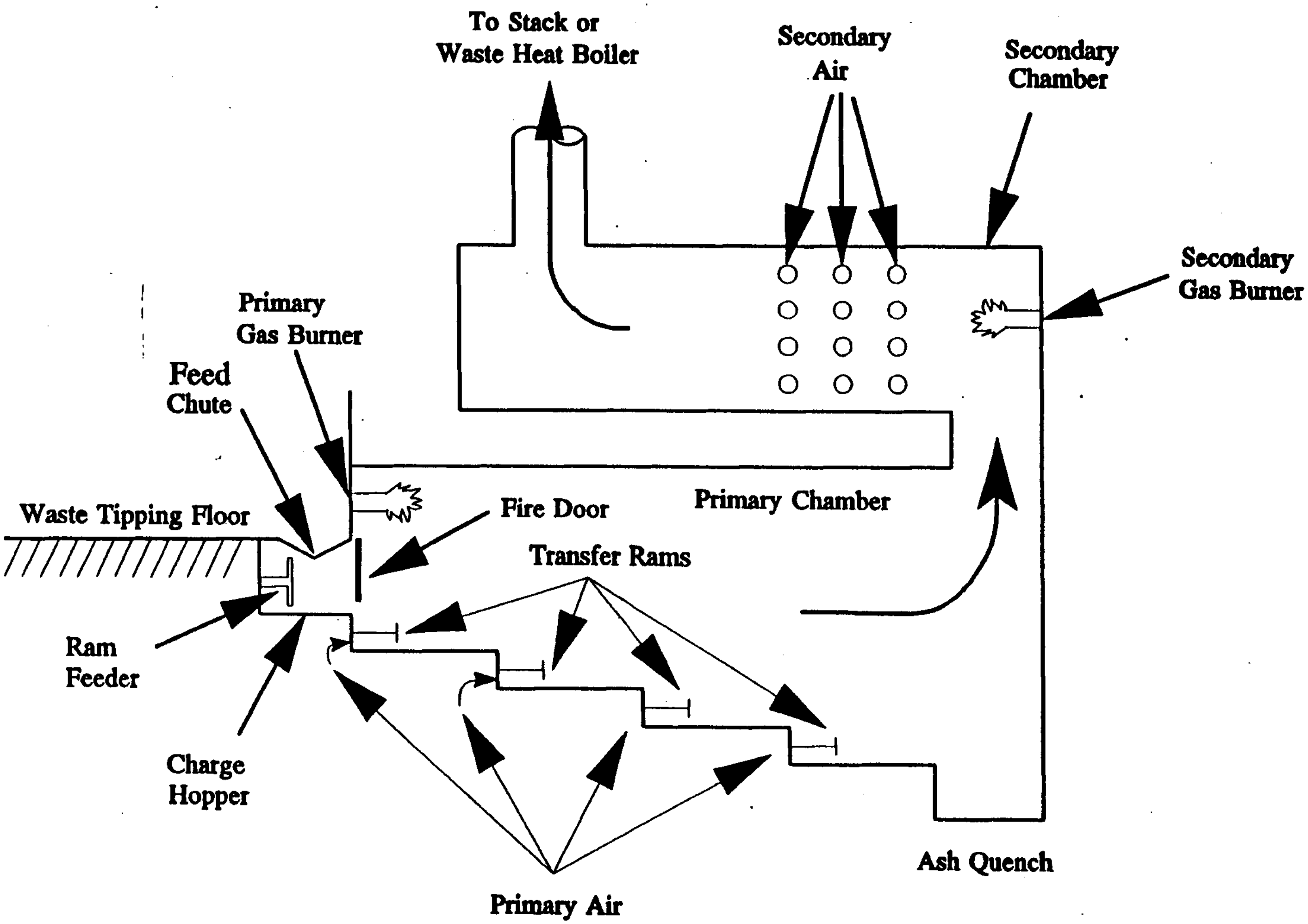

Figure 2.1-5. Typical modular starved-air combustor with transfer rams.

2.1.2.1 Mass Burn Waterwall Combustors -

The MB/WW design represents the predominant technology in the existing population of large MWCs, and it is expected that over 50 percent of new units will be MB/WW designs. In MB/WW units, the combustor walls are constructed of metal tubes that contain circulating pressurized water used to recover heat from the combustion chamber. In the lower actively burning region of the chamber where corrosive conditions may exist, the walls are generally lined with castable refractory. Heat is also recovered in the convective sections (i. e., superheater, economizer) of the combustor.

With this type of system, unprocessed waste (after removal of large, bulky items) is delivered by an overhead crane to a feed hopper, which conveys the waste into the combustion chamber. Earlier MB/WW designs utilized gravity feeders, but it is now more typical to feed by means of single or dual hydraulic rams.

Nearly all modern MB/WW facilities utilize reciprocating grates or roller grates to move the waste through the combustion chamber. The grates typically include 3 sections. On the initial grate section, referred to as the drying grate, the moisture content of the waste is reduced prior to ignition. The second grate section, referred to as the burning grate, is where the majority of active burning takes place. The third grate section, referred to as the burnout or finishing grate, is where remaining combustibles in the waste are burned. Smaller units may have only 2 individual grate sections. Bottom ash is discharged from the finishing grate into a water-filled ash quench pit or ram discharger. From there, the moist ash is discharged to a conveyor system and transported to an ash load-out or storage area prior to disposal. Dry ash systems have been used in some designs, but their use is not widespread.

Combustion air is added from beneath the grate by way of underfire air plenums. The majority of MB/WW systems supply underfire air to the individual grate sections through multiple plenums, which enhance the ability to control burning and heat release from the waste bed. Overfire air is injected through rows of high-pressure nozzles located in the side walls of the combustor to oxidize fuel-rich gases evolved from the bed and complete the combustion process. Properly designed and operated overfire air systems are essential for good mixing and burnout of organics in the flue gas. Typically, MB/WW MWCs are operated with 80 to 100 percent excess air.

The flue gas exits the combustor and passes through additional heat recovery sections to one or more air pollution control devices (APCD). The types of APCDs that may be used are discussed in Section 2.1.4.

2.1.2.2 Mass Burn Rotary Waterwall Combustors -

A more unique mass burn design is the MB/RC. Plants of this design range in size from 180 to 2,400 Mg/day (200 to 2,700 tpd), with typically 2 or 3 units per plant. This type of system uses a rotary combustion chamber. Following pre-sorting of objects too large to fit in the combustor, the waste is ram fed to the inclined rotary combustion chamber, which rotates slowly, causing the waste to advance and tumble as it burns. Underfire air is injected through the waste bed, and overfire air is provided above the waste bed. Bottom ash is discharged from the rotary combustor to an afterburner grate and then into a wet quench pit. From there, the moist ash is conveyed to an ash load-out or storage area prior to disposal.

Approximately 80 percent of the combustion air is provided along the rotary combustion chamber length, with most of the air provided in the first half of the chamber. The rest of the combustion air is supplied to the afterburner grate and above the rotary combustor outlet in the boiler. The MB/RC operates at about 50 percent excess air, compared with 80 to 100 percent for typical MB/WW firing systems. Water flowing through the tubes in the rotary chamber recovers heat from combustion. Additional heat recovery occurs in the boiler waterwall, superheater, and economizer. From the economizer, the flue gas is typically routed to APCDs.

2.1.2.3 Mass Burn Refractory Wall Combustors -

Prior to 1970 there were numerous MB/REF MWCs in operation. The purpose of these plants was to achieve waste reduction; energy recovery was generally not incorporated in their design. Most of the roughly 25 MB/REF plants that still operate or that were built in the 1970s and 1980s use electrostatic precipitators (ESPs) to reduce PM emissions, and several have heat recovery boilers. Most MB/REF combustors have unit sizes of 90 to 270 Mg/day (100 to 300 tpd). It is not expected that additional plants of this design will be built in the United States.

The MB/REF combustors comprise several designs. One design involves a batch-fed upright combustor, which may be cylindrical or rectangular in shape. A second design is based on a rectangular combustion chamber with a traveling, rocking, or reciprocating grate. This type of combustor is continuously fed and operates in an excess air mode. If the waste is moved on a traveling grate, it is not sufficiently aerated as it advances through the combustor. As a result, waste burnout or complete combustion is inhibited by fuel bed thickness, and there is considerable potential for unburned waste to be discharged into the bottom ash pit. Rocking and reciprocating grate systems stir and aerate the waste bed as it advances through the combustion chamber, thereby improving contact between the waste and combustion air and increasing the burnout of combustibles. The system generally discharges the ash at the end of the grate to a water quench pit for collection and disposal in a landfill.

Because MB/REF combustors do not contain a heat transfer medium (such as the waterwalls that are present in modern energy recovery units), they typically operate at higher excess air rates (150 to 300 percent) than MB/WW combustors (80 to 100 percent). The higher excess air levels are required to prevent excessive temperatures, which can result in refractory damage, slagging, fouling, and corrosion problems. One adverse effect of higher excess air levels is the potential for increased carryover of PM from the combustion chamber and, ultimately, increased stack emission rates. High PM carryover may also contribute to increased CDD/CDF emissions by providing increased surface area for downstream catalytic formation to take place. A second problem is the potential for high excess air levels to quench (cool) the combustion reactions, preventing thermal destruction of organic species.

An alternate, newer MB/REF combustor is the Volund design (Figure 2.1-3 presents this MB/REF design). This design minimizes some of the problems of other MB/REF systems. A refractory arch is installed above the combustion zone to reduce radiant heat losses and improve solids burnout. The refractory arch also routes part of the rising gases from the drying and combustion grates through a gas by-pass duct to the mixing chamber. There the gas is mixed with gas from the burnout grate or kiln. Bottom ash is conveyed to an ash quench pit. Volund MB/REF combustors operate with 80 to 120 percent excess air, which is more in line with excess air levels in the MB/WW designs. As a result, lower CO levels and better organics destruction are achievable, as compared to other MB/REF combustors.

2.1.2.4 Refuse-derived Fuel Combustors -

Refuse-derived fuel combustors burn MSW that has been processed to varying degrees, from simple removal of bulky and noncombustible items accompanied by shredding, to extensive processing to produce a finely divided fuel suitable for co-firing in pulverized coal-fired boilers. Processing MSW to RDF generally raises the heating value of the waste because many of the noncombustible items are removed.

A set of standards for classifying RDF types has been established by the American Society for Testing and Materials. The type of RDF used is dependent on the boiler design. Boilers that are designed to burn RDF as the primary fuel usually utilize spreader stokers and fire fluff RDF in a semi-suspension mode. This mode of feeding is accomplished by using an air swept distributor, which allows a portion of the RDF to burn in suspension and the remainder to be burned out after falling on a horizontal traveling grate. The number of RDF distributors in a single unit varies directly with unit capacity. The distributors are normally adjustable so that the trajectory of the waste feed can be varied. Because the traveling grate moves from the rear to the front of the furnace, distributor settings are adjusted so that most of the waste lands on the rear two-thirds of the grate. This allows more time for combustion to be completed on the grate. Bottom ash drops into a water-filled quench chamber. Some traveling grates operate at a single speed, but most can be manually adjusted to accommodate variations in burning conditions. Underfire air is normally preheated and introduced beneath the grate by a single plenum. Overfire air is injected through rows of high-pressure nozzles, providing a zone for mixing and completion of the combustion process. These combustors typically operate at 80 to 100 percent excess air.

Due to the basic design of the semi-suspension feeding systems, PM levels at the inlet to the pollution control device are typically double those of mass burn systems and more than an order of magnitude higher than MOD/SA combustors. The higher particulate loadings may contribute to the catalytic formation of CDD/CDF. However, controlled Hg emissions from these plants are considerably lower than from mass burn plants as a result of the higher levels of carbon present in the PM carryover, as Hg adsorbs onto the carbon and can be subsequently captured by the PM control device.

Pulverized coal (PC)-fired boilers can co-fire fluff RDF or powdered RDF. In a PC-fired boiler that co-fires fluff with pulverized coal, the RDF is introduced into the combustor by air transport injectors that are located above or even with the coal nozzles. Due to its high moisture content and large particle size, RDF requires a longer burnout time than coal. A significant portion of the larger, partially burned particles disengage from the gas flow and fall onto stationary drop grates at the bottom of the furnace where combustion is completed. Ash that accumulates on the grate is periodically dumped into the ash hopper below the grate. Refuse-derived fuel can also be co-fired with coal in stoker-fired boilers.

2.1.2.5 Fluidized Bed Combustors -

In an FBC, fluff or pelletized RDF is combusted on a turbulent bed of noncombustible material such as limestone, sand, or silica. In its simplest form, an FBC consists of a combustor vessel equipped with a gas distribution plate and underfire air windbox at the bottom. The combustion bed overlies the gas distribution plate. The combustion bed is suspended or "fluidized" through the introduction of underfire air at a high flow rate. The RDF may be injected into or above the bed through ports in the combustor wall. Other wastes and supplemental fuel may be blended with the RDF outside the combustor or added into the combustor through separate openings. Overfire air is used to complete the combustion process.

There are 2 basic types of FBC systems: bubbling bed and circulating bed. With bubbling bed combustors, most of the fluidized solids are maintained near the bottom of the combustor by using relatively low air fluidization velocities. This helps reduce the entrainment of solids from the bed into the flue gas, minimizing recirculation or reinjection of bed particles. In contrast, circulating bed combustors operate at relatively high fluidization velocities to promote carryover of solids into the upper section of the combustor. Combustion occurs in both the bed and upper section of the combustor. By design, a fraction of the bed material is entrained in the combustion gas and enters a cyclone separator which recycles unburned waste and inert particles to the lower bed. Some of the ash is removed from the cyclone with the solids from the bed.

Good mixing is inherent in the FBC design. Fluidized bed combustors have very uniform gas temperatures and mass compositions in both the bed and in the upper region of the combustor. This allows the FBCs to operate at lower excess air and temperature levels than conventional combustion systems. Waste-fired FBCs typically operate at excess air levels between 30 and 100 percent and at bed temperatures around 815°C (1,500°F). Low temperatures are necessary for waste-firing FBCs because higher temperatures lead to bed agglomeration.

2.1.2.6 Modular Starved-air (Controlled-air) Combustors -

In terms of number of facilities, MOD/SA combustors represent a large segment of the existing MWC population. However, because of their small sizes, they account for only a small percent of the total capacity. The basic design of a MOD/SA combustor consists of 2 separate combustion chambers, referred to as the "primary" and "secondary" chambers. Waste is batch-fed to the primary chamber by a hydraulically activated ram. The charging bin is filled by a front end loader or other means. Waste is fed automatically on a set frequency, with generally 6 to 10 minutes between charges.

Waste is moved through the primary combustion chamber by either hydraulic transfer rams or reciprocating grates. Combustors using transfer rams have individual hearths upon which combustion takes place. Grate systems generally include 2 separate grate sections. In either case, waste retention times in the primary chamber are long, lasting up to 12 hours. Bottom ash is usually discharged to a wet quench pit.

The quantity of air introduced into the primary chamber defines the rate at which waste burns. Combustion air is introduced in the primary chamber at sub-stoichiometric levels, resulting in a flue gas rich in unburned hydrocarbons. The combustion air flow rate to the primary chamber is controlled to maintain an exhaust gas temperature set point, generally 650 to 980°C (1,200 to 1,800°F), which corresponds to about 40 to 60 percent theoretical air.

As the hot, fuel-rich flue gases flow to the secondary chamber, they are mixed with additional air to complete the burning process. Because the temperature of the exhaust gases from the primary chamber is above the autoignition point, completing combustion is simply a matter of introducing air into the fuel-rich gases. The amount of air added to the secondary chamber is controlled to maintain a desired flue gas exit temperature, typically 980 to 1,200°C (1,800 to 2,200°F). Approximately 80 percent of the total combustion air is introduced as secondary air. Typical excess air levels vary from 80 to 150 percent.

The walls of both combustion chambers are refractory lined. Early MOD/SA combustors did not include energy recovery, but a waste heat boiler is common in newer installations, with 2 or more combustion modules manifolded to a single boiler. Combustors with energy recovery capabilities also maintain dump stacks for use in an emergency, or when the boiler and/or air pollution control equipment are not in operation.

Most MOD/SA MWCs are equipped with auxiliary fuel burners located in both the primary and secondary combustion chambers. Auxiliary fuel can be used during startup (many modular units do not operate continuously) or when problems are experienced maintaining desired combustion temperatures. In general, the combustion process is self-sustaining through control of air flow and feed rate, so that continuous co-firing of auxiliary fuel is normally not necessary.

The high combustion temperatures and proper mixing of flue gas with air in the secondary combustion chamber provide good combustion, resulting in relatively low CO and trace organic emissions. Because of the limited amount of combustion air introduced through the primary chamber, gas velocities in the primary chamber and the amount of entrained PM are low. As a result, PM emissions of air pollutants from MOD/SA MWCs are relatively low. Many existing modular systems do not have air pollution controls. This is especially true of the smaller starved-air facilities. A few of the newer MOD/SA MWCs have acid gas/PM controls.

2.1.2.7 Modular Excess Air Combustors -

There are fewer MOD/EA MWCs than MOD/SA MWCs. The design of MOD/EA units is similar to that of MOD/SA units, including the presence of primary and secondary combustion chambers. Waste is batch-fed to the primary chamber, which is refractory-lined. The waste is moved through the primary chamber by hydraulic transfer rams, oscillating grates, or a revolving hearth. Bottom ash is discharged to a wet quench pit. Additional flue gas residence time for fuel/carbon burnout is provided in the secondary chamber, which is also refractory-lined. Energy is typically recovered in a waste heat boiler. Facilities with multiple combustors may have a tertiary chamber where flue gases from each combustor are mixed prior to entering the energy recovery boiler.

Unlike the MOD/SA combustors but similar to MB/REF units, a MOD/EA combustor typically operates at about 100 percent excess air in the primary chamber, but may vary between 50 and 250 percent excess air. The MOD/EA combustors also use recirculated flue gas for combustion air to maintain desired temperatures in the primary and secondary chambers. Due to higher air velocities, PM emissions from MOD/EA combustors are higher than those from MOD/SA combustors and are more similar in concentration to PM emissions from mass burn units. However, NO_x emissions from MOD/EA combustors appear to be lower than from either MOD/SA or mass burn units.

2.1.3 Emissions[4-7]

Depending on the characteristics of the MSW and combustion conditions in the MWC, the following pollutants can be emitted:

- PM,
- Metals (in solid form on PM, except for Hg),
- Acid gases (HCl, SO_2),
- CO,
- NO_x, and
- Toxic organics (most notably CDD/CDF).

A brief discussion on each of the pollutants is provided below, along with discussions on controls used to reduce emissions of these pollutants to the atmosphere.

2.1.3.1 Particulate Matter -

The amount of PM exiting the furnace of an MWC depends on the waste characteristics, the physical nature of the combustor design, and the combustor's operation. Under normal combustion conditions, solid fly ash particulates formed from inorganic, noncombustible constituents in MSW are released into the flue gas. Most of this particulate is captured by the facility's APCD and are not emitted to the atmosphere.

Particulate matter can vary greatly in size with diameters ranging from less than 1 micrometer to hundreds of micrometers (μm). Fine particulates, having diameters less than 10μm (known as PM-10), are of increased concern because a greater potential for inhalation and passage into the pulmonary region exists. Further, acid gases, metals, and toxic organics may preferentially adsorb onto particulates in this size range. The NSPS and EG for MWCs regulate total PM, while PM-10 is of interest for State Implementation Plans and when dealing with ambient PM concentrations. In this chapter, "PM" refers to total PM as measured by EPA Reference Method 5.

The level of PM emissions at the inlet of the APCD will vary according the combustor design, air distribution, and waste characteristics. For example, facilities that operate with high underfire/overfire air ratios or relatively high excess air levels may entrain greater quantities of PM and have high PM levels at the APCD inlet. For combustors with multiple-pass boilers that change the direction of the flue gas flow, part of the PM may be removed prior to the APCD. Lastly, the physical properties of the waste being fed and the method of feeding influences PM levels in the flue gas. Typically, RDF units have higher PM carryover from the furnace due to the suspension-feeding of the RDF. However, controlled PM emissions from RDF plants do not vary substantially from other MWCs (i. e., MB/WW), because the PM is efficiently collected in the APCD.

2.1.3.2 Metals -

Metals are present in a variety of MSW streams, including paper, newsprint, yard wastes, wood, batteries, and metal cans. The metals present in MSW are emitted from MWCs in association with PM (e. g., arsenic [As], Cd, chromium [Cr], and Pb) and as vapors, such as Hg. Due to the variability in MSW composition, metal concentrations are highly variable and are essentially independent of combustor type. If the vapor pressure of a metal is such that condensation onto particulates in the flue gas is possible, the metal can be effectively removed by the PM control device. With the exception of Hg, most metals have sufficiently low vapor pressures to result in almost all of the metals being condensed. Therefore, removal in the PM control device for these metals is generally greater than 98 percent. Mercury, on the other hand, has a high vapor pressure at typical APCD operating temperatures, and capture by the PM control device is highly variable. The level of carbon in the fly ash appears to affect the level of Hg control. A high level of carbon in the fly ash can enhance Hg adsorption onto particles removed by the PM control device.

2.1.3.3 Acid Gases -

The chief acid gases of concern from the combustion of MSW are HCl and SO_2. Hydrogen fluoride (HF), hydrogen bromide (HBr), and sulfur trioxide (SO_3) are also generally present, but at much lower concentrations. Concentrations of HCl and SO_2 in MWC flue gases directly relate to the chlorine and sulfur content in the waste. The chlorine and sulfur content vary considerably based on seasonal and local waste variations. Emissions of SO_2 and HCl from MWCs depend on the chemical form of sulfur and chlorine in the waste, the availability of alkali materials in combustion-generated fly ash that act as sorbents, and the type of emission control system used. Acid gas concentrations are considered to be independent of combustion conditions. The major sources of chlorine in MSW are paper and plastics. Sulfur is contained in many constituents of MSW, such as asphalt shingles, gypsum wallboard, and tires. Because RDF processing does not generally impact the distribution of combustible materials in the waste fuel, HCl and SO_2 concentrations for mass burn and RDF units are similar.

2.1.3.4 Carbon Monoxide -

Carbon monoxide emissions result when all of the carbon in the waste is not oxidized to carbon dioxide (CO_2). High levels of CO indicate that the combustion gases were not held at a sufficiently high temperature in the presence of oxygen (O_2) for a long enough time to convert CO to CO_2. As waste burns in a fuel bed, it releases CO, hydrogen (H_2), and unburned hydrocarbons. Additional air then reacts with the gases escaping from the fuel bed to convert CO and H_2 to CO_2 and H_2O. Adding too much air to the combustion zone will lower the local gas temperature and quench (retard) the oxidation reactions. If too little air is added, the probability of incomplete mixing increases, allowing greater quantities of unburned hydrocarbons to escape the furnace. Both of the conditions would result in increased emissions of CO.

Because O_2 levels and air distributions vary among combustor types, CO levels also vary among combustor types. For example, semi-suspension-fired RDF units generally have higher CO levels than mass burn units, due to the effects of carryover of incompletely combusted materials into low temperature portions of the combustor, and, in some cases, due to instabilities that result from fuel feed characteristics.

Carbon monoxide concentration is a good indicator of combustion efficiency, and is an important criterion for indicating instabilities and nonuniformities in the combustion process. It is during unstable combustion conditions that more carbonaceous material is available and higher CDD/CDF and organic hazardous air pollutant levels occur. The relationship between emissions of CDD/CDF and CO indicates that high levels of CO (several hundred parts per million by volume [ppmv]), corresponding to poor combustion conditions, frequently correlate with high CDD/CDF emissions. When CO levels are low, however, correlations between CO and CDDs/CDFs are not well defined (due to the fact that many mechanisms may contribute to CDD/CDF formation), but CDD/CDF emissions are generally lower.

2.1.3.5 Nitrogen Oxides -

Nitrogen oxides are products of all fuel/air combustion processes. Nitric oxide (NO) is the primary component of NO_x; however, nitrogen dioxide (NO_2) and nitrous oxide (N_2O) are also formed in smaller amounts. The combination of the compounds is referred to as NO_x. Nitrogen oxides are formed during combustion through (1) oxidation of nitrogen in the waste, and (2) fixation of atmospheric nitrogen. Conversion of nitrogen in the waste occurs at relatively low temperatures (less than 1,090°C [2,000°F]), while fixation of atmospheric nitrogen occurs at higher temperatures. Because of the relatively low temperatures at which MWC furnaces operate, 70 to 80 percent of NO_x formed in MWCs is associated with nitrogen in the waste.

2.1.3.6 Organic Compounds -

A variety of organic compounds, including CDDs/CDFs, chlorobenzene (CB), polychlorinated biphenyls (PCBs), chlorophenols (CPs), and polyaromatic hydrocarbons (PAHs), are present in MSW or can be formed during the combustion and post-combination processes. Organics in the flue gas can exist in the vapor phase or can be condensed or absorbed on fine particulates. Control of organics is accomplished through proper design and operation of both the combustor and the APCDs.

Based on potential health effects, CDD/CDF has been a focus of many research and regulatory activities. Due to toxicity levels, attention is most often placed on levels of CDDs/CDFs in the tetra- through octa- homolog groups and specific isomers within those groups that have chlorine substituted in the 2, 3, 7, and 8 positions. As noted earlier, the NSPS and EG for MWCs regulate the total tetra- through octa-CDDs/CDFs.

2.1.4 Controls[8-10]

A wide variety of control technologies are used to control emissions from MWCs. The control of PM, along with metals that have adsorbed onto the PM, is most frequently accomplished through the use of an ESP or fabric filter (FF). Although other PM control technologies (e. g., cyclones, electrified gravel beds, and venturi scrubbers) are available, they are seldom used on existing systems, and it is anticipated that they will not be frequently used in future MWC systems. The control of acid gas emissions (i. e., SO_2 and HCl) is most frequently accomplished through the application of acid gas control technologies such as spray drying or dry sorbent injection, followed by a high-efficiency PM control device. Some facilities use a wet scrubber to control acid gases. It is anticipated that dry systems (spray drying and dry sorbent injection) will be more widely used than wet scrubbers on future U. S. MWC systems. Each of these technologies is discussed in more detail below.

2.1.4.1 Electrostatic Precipitators -

Electrostatic precipitators consist of a series of high-voltage (20 to 100 kilojoules per coulomb [20 to 100 kilovolts]) discharge electrodes and grounded metal plates through which PM-laden flue gas flows. Negatively charged ions formed by this high-voltage field (known as a "corona") attach to PM in the flue gas, causing the charged particles to migrate toward, and be collected on, the grounded plates. The most common types of ESPs used by MWCs are (1) plate wire units in which the discharge electrode is a bottom weighted or rigid wire, and (2) flat plate units which use flat plates rather than wires as the discharge electrode.

As a general rule, the greater the amount of collection plate area, the greater the ESP's PM collection efficiency. Once the charged particles are collected on the grounded plates, the resulting dust layer is removed from the plates by rapping, washing, or some other method and collected in a hopper. When the dust layer is removed, some of the collected PM becomes re-entrained in the flue gas. To ensure good PM collection efficiency during plate cleaning and electrical upsets, ESPs have several fields located in series along the direction of flue gas flow that can be energized and cleaned independently. Particles re-entrained when the dust layer is removed from one field can be recollected in a downstream field. Because of this phenomena, increasing the number of fields generally improves PM removal efficiency.

Small particles generally have lower migration velocities than large particles and are therefore more difficult to collect. This factor is especially important to MWCs because of the large amount of total fly ash smaller than 1 μm. As compared to pulverized coal fired combustors, in which only 1 to 3 percent of the fly ash is generally smaller than 1 μm, 20 to 70 percent of the fly ash at the inlet of the PM control device for MWCs is reported to be smaller than 1 μm. As a result, effective collection of PM from MWCs requires greater collection areas and lower flue gas velocities than many other combustion types.

As an approximate indicator of collection efficiency, the specific collection area (SCA) of an ESP is frequently used. The SCA is calculated by dividing the collecting electrode plate area by the flue gas flow rate and is expressed as square meters per 304.8 cubic meters per minute (square feet per 1000 cubic feet per minute) of flue gas. In general, the higher the SCA, the higher the collection efficiency. Most ESPs at newer MWCs have SCAs in the range of 400 to 600. When estimating emissions from ESP-equipped MWCs, the SCA of the ESP should be taken into consideration. Not all ESPs are designed equally and performance of different ESPs will vary.

2.1.4.2 Fabric Filters -

Fabric filters are also used for PM and metals control, particularly in combination with acid gas control and flue gas cooling. Fabric filters (also known as "baghouses") remove PM by passing flue gas through a porous fabric that has been sewn into a cylindrical bag. Multiple individual filter bags are mounted in an arranged compartment. A complete FF, in turn, consists of 4 to 16 individual compartments that can be independently operated.

As the flue gas flows through the filter bags, particulate is collected on the filter surface, mainly through inertial impaction. The collected particulate builds up on the bag, forming a filter cake. As the thickness of the filter cake increases, the pressure drop across the bag also increases. Once pressure drop across the bags in a given compartment becomes excessive, that compartment is generally taken off-line, mechanically cleaned, and then placed back on-line.

Fabric filters are generally differentiated by cleaning mechanisms. Two main filter cleaning mechanisms are used: reverse-air and pulse-jet. In a reverse-air FF, flue gas flows through unsupported filter bags, leaving the particulate on the inside of the bags. The particulate builds up to form a particulate filter cake. Once excessive pressure drop across the filter cake is reached, air is blown through the filter in the opposite direction, the filter bag collapses, and the filter cake falls off and is collected. In a pulse-jet FF, flue gas flows through supported filter bags leaving particulate on the outside of the bags. To remove the particulate filter cake, compressed air is pulsed through the inside of the filter bag, the filter bag expands and collapses to its pre-pulsed shape, and the filter cake falls off and is collected.

2.1.4.3 Spray Drying -

Spray dryers (SD) are the most frequently used acid gas control technology for MWCs in the United States. When used in combination with an ESP or FF, the system can control CDD/CDF, PM (and metals), SO_2, and HCl emissions from MWCs. Spray dryer/fabric filter systems are more common than SD/ESP systems and are used mostly on new, large MWCs. In the spray drying process, lime slurry is injected into the SD through either a rotary atomizer or dual-fluid nozzles. The water in the slurry evaporates to cool the flue gas, and the lime reacts with acid gases to form calcium salts that can be removed by a PM control device. The SD is designed to provide sufficient contact and residence time to produce a dry product before leaving the SD adsorber vessel. The residence time in the adsorber vessel is typically 10 to 15 seconds. The particulate leaving the SD contains fly ash plus calcium salts, water, and unreacted hydrated lime.

The key design and operating parameters that significantly affect SD performance are SD outlet temperature and lime-to-acid gas stoichiometric ratio. The SD outlet approach to saturation temperature is controlled by the amount of water in the slurry. More effective acid gas removal occurs at lower approach to saturation temperatures, but the temperature must be high enough to ensure the slurry and reaction products are adequately dried prior to collection in the PM control device. For MWC flue gas containing significant chlorine, a minimum SD outlet temperature of around 115°C (240°F) is required to control agglomeration of PM and sorbent by calcium chloride. Outlet gas temperature from the SD is usually around 140°C (285°F).

The stoichiometric ratio is the molar ratio of calcium in the lime slurry fed to the SD divided by the theoretical amount of calcium required to completely react with the inlet HCl and SO_2 in the flue gas. At a ratio of 1.0, the moles of calcium are equal to the moles of incoming HCl and SO_2. However, because of mass transfer limitations, incomplete mixing, and differing rates of reaction (SO_2 reacts more slowly than HCl), more than the theoretical amount of lime is generally fed to the SD. The stoichiometric ratio used in SD systems varies depending on the level of acid gas reduction required, the temperature of the flue gas at the SD exit, and the type of PM control device used.

Lime is fed in quantities sufficient to react with the peak acid gas concentrations expected without severely decreasing performance. The lime content in the slurry is generally about 10 percent by weight, but cannot exceed approximately 30 percent by weight without clogging of the lime slurry feed system and spray nozzles.

2.1.4.4 Dry Sorbent Injection -

This type of technology has been developed primarily to control acid gas emissions. However, when combined with flue gas cooling and either an ESP or FF, sorbent injection processes may also control CDD/CDF and PM emissions from MWCs. Two primary subsets of dry sorbent injection technologies exist. The more widely used of these approaches, referred to as duct sorbent injection (DSI), involves injecting dry alkali sorbents into flue gas downstream of the combustor outlet and upstream of the PM control device. The second approach, referred to as furnace sorbent injection (FSI), injects sorbent directly into the combustor.

In DSI, powdered sorbent is pneumatically injected into either a separate reaction vessel or a section of flue gas duct located downstream of the combustor economizer or quench tower. Alkali in the sorbent (generally calcium or sodium) reacts with HCl, HF, and SO_2 to form alkali salts (e. g., calcium chloride [$CaCl_2$], calcium fluoride [CaF_2], and calcium sulfite [$CaSO_3$]). By lowering the acid content of the flue gas, downstream equipment can be operated at reduced temperatures while minimizing the potential for acid corrosion of equipment. Solid reaction products, fly ash, and unreacted sorbent are collected with either an ESP or FF.

Acid gas removal efficiency with DSI depends on the method of sorbent injection, flue gas temperature, sorbent type and feed rate, and the extent of sorbent mixing with the flue gas. Not all DSI systems are of the same design, and performance of the systems will vary. Flue gas temperature at the point of sorbent injection can range from about 150 to 320°C (300 to 600°F) depending on the sorbent being used and the design of the process. Sorbents that have been successfully tested include hydrated lime ($Ca[OH]_2$), soda ash (Na_2CO_3), and sodium bicarbonate ($NaHCO_3$). Based on published data for hydrated lime, some DSI systems can achieve removal efficiencies comparable to SD systems; however, performance is generally lower.

By combining flue gas cooling with DSI, it may be possible to increase CDD/CDF removal through a combination of vapor condensation and adsorption onto the sorbent surface. Cooling may also benefit PM control by decreasing the effective flue gas flow rate (i. e., cubic meters per minute) and reducing the resistivity of individual particles.

Furnace sorbent injection involves the injection of powdered alkali sorbent (either lime or limestone) into the furnace section of a combustor. This can be accomplished by addition of sorbent to the overfire air, injection through separate ports, or mixing with the waste prior to feeding to the combustor. As with DSI, reaction products, fly ash, and unreacted sorbent are collected using an ESP or FF.

The basic chemistry of FSI is similar to DSI. Both use a reaction of sorbent with acid gases to form alkali salts. However, several key differences exist in these 2 approaches. First, by injecting sorbent directly into the furnace (at temperatures of 870 to 1,200°C [1,600 to 2,200°F]) limestone can be calcined in the combustor to form more reactive lime, thereby allowing use of less expensive limestone as a sorbent. Second, at these temperatures, SO_2 and lime react in the combustor, thus providing a mechanism for effective removal of SO_2 at relatively low sorbent feed rates. Third, by injecting sorbent into the furnace rather than into a downstream duct, additional time is available for mixing and reaction between the sorbent and acid gases. Fourth, if a significant portion of the HCl is removed before the flue gas exits the combustor, it may be possible to reduce the formation of

CDD/CDF in latter sections of the flue gas ducting. However, HCl and lime do not react with each other at temperatures above 760°C (1,400°F). This is the flue gas temperature that exists in the convective sections of the combustor. Therefore, HCl removal may be lower than with DSI. Potential disadvantages of FSI include fouling and erosion of convective heat transfer surfaces by the injected sorbent.

2.1.4.5 Wet Scrubbers -

Many types of wet scrubbers have been used for controlling acid gas emissions from MWCs. These include spray towers, centrifugal scrubbers, and venturi scrubbers. Wet scrubbing technology has primarily been used in Japan and Europe. Currently, it is not anticipated that many new MWCs being built in the United States will use this type of acid gas control system. Wet scrubbing normally involves passing the flue gas through an ESP to reduce PM, followed by a 1- or 2-stage absorber system. With single-stage scrubbers, the flue gas reacts with an alkaline scrubber liquid to simultaneously remove HCl and SO_2. With two-stage scrubbers, a low-pH water scrubber for HCl removal is installed upstream of the alkaline SO_2 scrubber. The alkaline solution, typically containing calcium hydroxide ($Ca[OH]_2$), reacts with the acid gas to form salts, which are generally insoluble and may be removed by sequential clarifying, thickening, and vacuum filtering. The dewatered salts or sludges are then disposed.

2.1.4.6 Nitrogen Oxides Control Techniques -

The control of NO_x emissions can be accomplished through either combustion controls or add-on controls. Combustion controls include staged combustion, low excess air (LEA), and flue gas recirculation (FGR). Add-on controls which have been tested on MWCs include selective noncatalytic reduction (SNCR), selective catalytic reduction (SCR), and natural gas reburning.

Combustion controls involve the control of temperature or O_2 to reduce NO_x formation. With LEA, less air is supplied, which lowers the supply of O_2 that is available to react with N_2 in the combustion air. In staged combustion, the amount of underfire air is reduced, which generates a starved-air region. In FGR, cooled flue gas and ambient air are mixed to become the combustion air. This mixing reduces the O_2 content of the combustion air supply and lowers combustion temperatures. Due to the lower combustion temperatures present in MWCs, most NO_x is produced from the oxidation of nitrogen present in the fuel. As a result, combustion modifications at MWCs have generally shown small to moderate reductions in NO_x emissions as compared to higher temperature combustion devices (i. e., fossil fuel-fired boilers).

With SNCR, ammonia (NH_3) or urea is injected into the furnace along with chemical additives to reduce NO_x to N_2 without the use of catalysts. Based on analyses of data from U. S. MWCs equipped with SNCR, NO_x reductions of 45 percent are achievable.

With SCR, NH_3 is injected into the flue gas downstream of the boiler where it mixes with NO_x in the flue gas and passes through a catalyst bed, where NO_x is reduced to N_2 by a reaction with NH_3. This technique has not been applied to U. S. MWCs, but has been used on MWCs in Japan and Germany. Reductions of up to 80 percent have been observed, but problems with catalyst poisoning and deactivation may reduce performance over time.

Natural gas reburning involves limiting combustion air to produce an LEA zone. Recirculated flue gas and natural gas are then added to this LEA zone to produce a fuel-rich zone that inhibits NO_x formation and promotes reduction of NO_x to N_2. Natural gas reburning has been evaluated on both pilot- and full-scale applications and achieved NO_x reductions of 50 to 60 percent.

2.1.5 Mercury Controls[11-14]

Unlike other metals, Hg exists in vapor form at typical APCD operating temperatures. As a result, collection of Hg in the APCD is highly variable. Factors that affect Hg control are good PM control, low temperatures in the APCD system, and a sufficient level of carbon in the fly ash. Higher levels of carbon in the fly ash enhance Hg adsorption onto the PM, which is removed by the PM control device. To keep the Hg from volatilizing, it is important to operate the control systems at low temperatures, generally less than about 300 to 400°F.

Several mercury control technologies have been used on waste combustors in the United States, Canada, Europe, and Japan. These control technologies include the injection of activated carbon or sodium sulfide (Na_2S) into the flue gas prior to the DSI- or SD-based acid gas control system, or the use of activated carbon filters.

With activated carbon injection, Hg is adsorbed onto the carbon particle, which is then captured in the PM control device. Test programs using activated carbon injection on MWCs in the United States have shown Hg removal efficiencies of 50 to over 95 percent, depending on the carbon feed rate.

Sodium sulfide injection involves spraying Na_2S solution into cooled flue gas prior to the acid gas control device. Solid mercuric sulfide is precipitated from the reaction of Na_2S and Hg and can be collected in the PM control device. Results from tests on European and Canadian MWCs have shown removal efficiencies of 50 to over 90 percent. Testings on a U. S. MWC, however, raised questions on the effectiveness of this technology due to possible oversights in the analytical procedure used in Europe and Canada.

Fixed bed activated carbon filters are another Hg control technology being used in Europe. With this technology, the flue gas is passed through a fixed bed of granular activated carbon where the Hg is adsorbed. Segments of the bed are periodically replaced as system pressure drop increases.

2.1.6 Emissions[15-121]

Tables 2.1-1, 2.1-2, 2.1-3, 2.1-4, 2.1-5, 2.1-6, 2.1-7, 2.1-8, and 2.1-9 present emission factors for MWCs. The tables are for distinct combustor types (i. e., MB/WW, RDF), and include emission factors for uncontrolled (prior to any pollution control device) levels and for controlled levels based on various APCD types (i. e., ESP, SD/FF). There is a large amount of data available for this source category and, as a result of this, many of the emission factors have high quality ratings. However, for some categories there were only limited data, and the ratings are low. In these cases, one should refer to the EPA Background Information Documents (BIDs) developed for the NSPS and EG, which more thoroughly analyze the data than does AP-42, as well as discuss performance capabilities of the control technologies and expected emission levels. Also, when using the MWC emission factors, it should be kept in mind that these are average values, and emissions from MWCs are greatly affected by the composition of the waste and may vary for different facilities due to seasonal and regional differences. The AP-42 background report for this section includes data for individual facilities that represent the range for a combustor/control technology category.

Table 2.1-1 (Metric Units). PARTICULATE MATTER, METALS, AND ACID GAS EMISSION FACTORS FOR MASS BURN AND MODULAR EXCESS AIR COMBUSTORS[a,b]

Pollutant	Uncontrolled		ESP[c]		DSI/ESP[d]		SD/ESP[e]		DSI/FF[f]		SD/FF[g]	
	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
PM[h]	1.26 E+01	A	1.05 E-01	A	2.95 E-02	E	3.52 E-02	A	8.95 E-02	A	3.11 E-02	A
As[i]	2.14 E-03	A	1.09 E-05	A	ND[j]	E	6.85 E-06	A	5.15 E-06	C	2.12 E-05	A
Cd[i]	5.45 E-03	A	3.23 E-04	B	4.44 E-05	E	3.76 E-06	A	1.17 E-05	C	1.36 E-05	A
Cr[i]	4.49 E-03	A	5.65 E-05	B	1.55 E-05	E	1.30 E-04	A	1.00 E-04	C	1.50 E-05	A
Hg[i]	2.8 E-03	A	2.8 E-03	A	1.98 E-03	E	1.63 E-03	A	1.10 E-03	C	1.10 E-03	A
Ni[i]	3.93 E-03	A	5.60 E-05	B	1.61 E-03	E	1.35 E-04	A	7.15 E-05	C	2.58 E-05	A
Pb[i]	1.07 E-01	A	1.50 E-03	A	1.45 E-03	E	4.58 E-04	A	1.49 E-04	C	1.31 E-04	A
SO_2	1.73 E+00	A	ND	NA	4.76 E-01	C	3.27 E-01[k]	A	7.15 E-01	C	2.77 E-01[k]	A
HCl[i]	3.20 E+00	A	ND	NA	1.39 E-01	C	7.90 E-02[k]	A	3.19 E-01	C	1.06 E-01[k]	A

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[a] All factors in kg/Mg refuse combusted. Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/joule (J) and a heating value of 10,466 J/g. Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 10,466 J/g. Source Classification Codes 5-01-001-04, 5-01-001-05, 5-01-001-06, 5-01-001-07, 5-03-001-11, 5-03-001-12, 5-03-001-13, 5-03-001-15. ND = no data. NA = not applicable.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., SO_2).

[c] ESP = Electrostatic Precipitator

[d] DSI/ESP = Duct Sorbent Injection/Electrostatic Precipitator

[e] SD/ESP = Spray Dryer/Electrostatic Precipitator

[f] DSI/FF = Duct Sorbent Injection/Fabric Filter

[g] SD/FF = Spray Dryer/Fabric Filter

[h] PM = total particulate matter, as measured with EPA Reference Method 5.

[i] Hazardous air pollutants listed in the *Clean Air Act*.

[j] No data available at levels greater than detection limits.

[k] Acid gas emissions from SD/ESP- and SD/FF-equipped MWCs are essentially the same. Any differences are due to scatter in the data.

Table 2.1-2 (English Units). PARTICULATE MATTER, METALS, AND ACID GAS EMISSION FACTORS FOR MASS BURN AND MODULAR EXCESS AIR COMBUSTORS[a,b]

	Uncontrolled		ESP[c]		DSI/ESP[d]		SD/ESP[e]		DSI/FF[f]		SD/FF[g]	
Pollutant	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
PM[h]	2.51 E+01	A	2.10 E-01	A	5.90 E-02	E	7.03 E-02	A	1.79 E-01	A	6.20 E-02	A
As[i]	4.37 E-03	A	2.17 E-05	A	ND[j]	E	1.37 E-05	A	1.03 E-05	C	4.23 E-06	A
Cd[i]	1.09 E-02	A	6.46 E-04	B	8.87 E-05	E	7.51 E-05	A	2.34 E-05	C	2.71 E-05	A
Cr[i]	8.97 E-03	A	1.13 E-04	B	3.09 E-05	E	2.59 E-04	A	2.00 E-04	C	3.00 E-05	A
Hg[i]	5.6 E-03	A	5.6 E-03	A	3.96 E-03	E	3.26 E-03	A	2.20 E-03	C	2.20 E-03	A
Ni[i]	7.85 E-03	A	1.12 E-04	B	3.22 E-05	E	2.70 E-04	A	1.43 E-04	C	5.16 E-05	A
Pb[i]	2.13 E-01	A	3.00 E-03	A	2.90 E-03	E	9.15 E-04	A	2.97 E-04	C	2.61 E-04	A
SO_2	3.46 E+00	A	ND	NA	9.51 E-01	C	6.53 E-01[k]	A	1.43 E-00	C	5.54 E-01[k]	A
HCl[i]	6.40 E+00	A	ND	NA	2.78 E-01	C	4.58 E-01[k]	A	6.36 E-01	C	2.11 E-01[k]	A

[a] All factors in lb/ton refuse combusted. Emission factors were calculated from concentrations using an F-factor of 9,570 dscf/MBtu and a heating value of 4,500 Btu/lb. Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 4,500 Btu/lb. Source Classification Codes 5-01-001-04, 5-01-001-05, 5-01-001-06, 5-01-001-07, 5-03-001-11, 5-03-001-12, 5-03-001-13, 5-03-001-15. ND = no data. NA = not applicable.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., SO_2).

[c] ESP = Electrostatic Precipitator

[d] DSI/ESP = Duct Sorbent Injection/Electrostatic Precipitator

[e] SD/ESP = Spray Dryer/Electrostatic Precipitator

[f] DSI/FF = Duct Sorbent Injection/Fabric Filter

[g] SD/FF = Spray Dryer/Fabric Filter

[h] PM = total particulate matter, as measured with EPA Reference Method 5.

[i] Hazardous air pollutants listed in the *Clean Air Act*.

[j] No data available at levels greater than detection limits.

[k] Acid gas emissions from SD/ESP- and SD/FF-equipped MWCs are essentially the same. Any differences are due to scatter in the data.

Table 2.1-3 (Metric Units). ORGANIC, NITROGEN OXIDES, AND CARBON MONOXIDE EMISSION FACTORS FOR MASS BURN WATERWALL COMBUSTORS[a,b]

	Uncontrolled		ESP[c]		SD/ESP[d]		DSI/FF[d]		SD/FF[e]	
Pollutant	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING	kg/Mg	EMISSION FACTOR RATING
CDD/CDF[g]	8.35 E-07	A	5.85 E-07	A	3.11 E-07	A	8.0 E-08	C	3.31 E-08	A
NO_x[h]	1.83 E+00	A	*		*		*		*	
CO[h]	2.32 E-01	A	*		*		*		*	

[a] All factors in kg/Mg refuse combusted. Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/J and a heating value of 10,466 J/g. Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 10,466 J/g. Source Classification Codes 5-01-001-05, 5-03-001-12. * = Same as "uncontrolled" for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., CO, NO_x).

[c] ESP = Electrostatic Precipitator

[d] SD/ESP = Spray Dryer/Electrostatic Precipitator

[e] DSI/FF = Duct Sorbent Injection/Fabric Filter

[f] SD/FF = Spray Dryer/Fabric Filter

[g] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in 1990 *Clean Air Act*.

[h] Control of NO_x and CO is not tied to traditional acid gas/PM control devices.

Table 2.1-4 (English Units). ORGANIC, NITROGEN OXIDES, AND CARBON MONOXIDE EMISSION FACTORS FOR MASS BURN WATERWALL COMBUSTORS[a,b]

Pollutant	Uncontrolled		ESP[c]		SD/ESP[d]		DSI/FF[e]		SD/FF[f]	
	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING	lb/ton	EMISSION FACTOR RATING
CDD/CDF[g]	1.67 E-06	A	1.17 E-06	A	6.21 E-07	A	1.60 E-07	C	6.61 E-08	A
NO_x[h]	3.56 E+00	A	*		*		*		*	
CO[h]	4.63 E-01	A	*		*		*		*	

[a] All factors in lb/ton refuse combusted. Emission factors were calculated from concentrations using an F-factor of 9,570 dscf/MBtu and a heating value of 4,500 Btu/lb. Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 4,500 Btu/lb. Source Classification Codes 5-01-001-05, 5-03-001-12. * = Same as "uncontrolled" for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., CO, NO_x).

[c] ESP = Electrostatic Precipitator

[d] SD/ESP = Spray Dryer/Electrostatic Precipitator

[e] DSI/FF = Duct Sorbent Injection/Fabric Filter

[f] SD/FF = Spray Dryer/Fabric Filter

[g] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in the 1990 *Clean Air Act*.

[h] Control of NO_x and CO is not tied to traditional acid gas/PM control devices.

Table 2.1-5 (Metric And English Units). ORGANIC, NITROGEN OXIDES, AND CARBON MONOXIDE EMISSION FACTORS FOR MASS BURN ROTARY WATERWALL COMBUSTORS[a,b]

	Uncontrolled			ESP[c]			DSI/FF[d]			SD/FF[e]		
Pollutant	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
CDD/CDF[f]	ND	ND	NA	ND	ND	NA	4.58 E-08	9.16 E-08	D	2.66 E-08	5.31E-08	B
NO_x[g]	1.13 E+00	2.25 E+00	E	*	*		*	*		*	*	
CO[g]	3.83 E-01	7.66 E-01	C	*	*		*	*		*	*	

[a] Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/J (9,570 dscf/MBtu) and a heating value of 10,466 J/g (4,500 Btu/lb). Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 10,466 J/g (4,500 Btu/lb). Source Classification Codes 5-01-001-06, 5-03-001-13. ND = no data. NA = not applicable. * = Same as "uncontrolled" for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., CO, NO_X).

[c] ESP = Electrostatic Precipitator

[d] DSI/FF = Duct Sorbent Injection/Fabric Filter

[e] SD/FF = Spray Dryer/Fabric Filter

[f] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in the *Clean Air Act*.

[g] Control of NO_X and CO is not tied to traditional acid gas/PM control devices.

Table 2.1-6 (Metric And English Units). ORGANIC, NITROGEN OXIDES, AND CARBON MONOXIDE EMISSION FACTORS FOR MASS BURN REFRACTORY WALL COMBUSTORS[a,b]

	Uncontrolled			ESP[c]			DSI/ESP[d]		
Pollutant	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
CDD/CDF[e]	7.50 E-06	1.50 E-05	D	3.63 E-05	7.25 E-05	D	2.31 E-07	4.61 E-07	E
NO_x[f]	1.23 E+00	2.46 E+00	A	*	*		*	*	
CO[f]	6.85 E-01	1.37 E+00	C	*	*		*	*	

[a] Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/J (9,570 dscf/MBtu) and a heating value of 10,466 J/g (4,500 Btu/lb). Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 10,466 J/g (4,500 Btu/lb). Source Classification Codes 5-01-001-04, 5-03-001-11. * = Same as "uncontrolled" for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., CO, NO_X).

[c] ESP = Electrostatic Precipitator

[d] DSI/ESP = Duct Sorbent Injection/Electrostatic Precipitator

[e] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in the *Clean Air Act*.

[f] Control of NO_X and CO is not tied to traditional acid gas/PM control devices.

Table 2.1-7 (Metric And English Units). ORGANIC, NITROGEN OXIDES, AND CARBON MONOXIDE EMISSION FACTORS FOR MODULAR EXCESS AIR COMBUSTORS[a,b]

Pollutant	Uncontrolled			ESP[c]			DSI/FF[d]		
	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
CDD/CDF[e]	ND	ND	NA	1.11 E-06	2.22 E-06	C	3.12 E-08	6.23 E-08	E
NO_x[f]	1.24 E+00	2.47 E+00	A	*	*		*	*	
CO[f]	ND	ND	NA	*	*		*	*	

[a] Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/J (9,570 dscf/MBtu) and a heating value of 10,466 J/g (4,500 Btu/lb). Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 10,466 J/g (4,500 Btu/lb). Source Classification Codes 5-01-001-07, 5-03-001-15. ND = no data. NA = not applicable. * = Same as "uncontrolled" for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., CO, NO_x).

[c] ESP = Electrostatic Precipitator

[d] DSI/FF = Duct Sorbent Injection/Fabric Filter

[e] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in the *Clean Air Act*.

[f] Control of NO_x and CO is not tied to traditional acid gas/PM control devices.

Table 2.1-8 (Metric And English Units). EMISSION FACTORS FOR REFUSE-DERIVED FUEL-FIRED COMBUSTORS[a,b]

Pollutant	Uncontrolled			ESP[c]			SD/ESP[d]			SD/FF[e]		
	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
PM[f]	3.48 E+01	6.96 E+01	A	5.17 E-01	1.04 E+00	A	4.82 E-02	9.65 E-02	B	6.64 E-02	1.33 E-01	B
As[g]	2.97 E-03	5.94 E-03	B	6.70 E-05	1.34 E-04	D	5.41 E-06	1.08 E-05	D	2.59 E-06[h]	5.17 E-06[h]	A
Cd[g]	4.37 E-03	8.75 E-03	C	1.10 E-04	2.20 E-04	C	4.18 E-05	8.37 E-05	D	1.66 E-05[h]	3.32 E-05[h]	A
Cr[g]	6.99 E-03	1.40 E-02	B	2.34 E-04	4.68 E-04	D	5.44 E-05	1.09 E-04	D	2.04 E-05	4.07 E-05	D
Hg[g]	2.8 E-03	5.5 E-03	D	2.8 E-03	5.5 E-03	D	2.10 E-04	4.20 E-04	B	1.46 E-04	2.92 E-04	D
Ni[g]	2.18 E-03	4.36 E-03	C	9.05 E-03	1.81 E-02	D	9.64 E-05	1.93 E-04	D	3.15 E-05[i]	6.30 E-05[i]	A
Pb[g]	1.00 E-01	2.01 E-01	C	1.84 E-03[h]	3.66 E-03[h]	A	5.77 E-04	1.16 E-03	B	5.19 E-04	1.04 E-03	D
SO_2	1.95 E+00	3.90 E+00	C	ND	ND	NA	7.99 E-01	1.60E+00	D	2.21 E-01	4.41 E-01	D
HCl[g]	3.49 E+00	6.97 E+00	E	*	*		ND	ND	NA	2.64 E-02	5.28 E-02	C
NO_x[j]	2.51 E+00	5.02 E+00	A	*	*		*	*		*	*	
CO[j]	9.60 E-01	1.92 E+00	A	*	*		*	*		*	*	
CDD/CDF[k]	4.73 E-06	9.47 E-06	D	8.46 E-06	1.69 E-05	B	5.31 E-08	1.06 E-07	D	1.22 E-08	2.44 E-08	E

[a] Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/J (9,570 dscf/MBtu) and a heating value of 12,792 J/g (5,500 Btu/lb). Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 12,792 J/g (5,500 Btu/lb). Source Classification Code 5-01-001-03. ND = no data. NA = not applicable. * = Same as uncontrolled for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (SO_2, NO_x, CO).

[c] ESP = Electrostatic Precipitator

[d] SD/ESP = Spray Dryer/Electrostatic Precipitator

[e] SD/FF = Spray Dryer/Fabric Filter

[f] PM = total particulate matter, as measured with EPA Reference Method 5.

[g] Hazardous air pollutants listed in the *Clean Air Act*.

[h] Levels were measured at non-detect levels, where the detection limit was higher than levels measured at other similarly equipped MWCs. Emission factors shown are based on emission levels from similarly equipped mass burn and MOD/EA combustors.

[i] No data available. Values shown are based on emission levels from SD/FF-equipped mass burn combustors.

[j] Control of NO_x and CO is not tied to traditional acid gas/PM control devices.

[k] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in the *Clean Air Act*.

Table 2.1-9 (Metric And English Units). EMISSION FACTORS FOR MODULAR STARVED-AIR COMBUSTORS[a,b]

	Uncontrolled			ESP[c]		
Pollutant	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
PM[d]	1.72 E+00	3.43 E+00	B	1.74 E-01	3.48 E-01	B
As[e]	3.34 E-04	6.69 E-04	C	5.25 E-05	1.05 E-04	D
Cd[e]	1.20 E-03	2.41 E-03	D	2.30 E-04	4.59 E-04	D
Cr[e]	1.65 E-03	3.31 E-03	C	3.08 E-04	6.16 E-04	D
Hg[e,f]	2.8 E-03	5.6 E-03	A	2.8 E-03	5.6 E-03	A
Ni[e]	2.76 E-03	5.52 E-03	D	5.04 E-04	1.01 E-03	E
Pb[e]	ND	ND	NA	1.41 E-03	2.82 E-03	C
SO_2	1.61 E+00	3.23 E+00	E	*	*	
HCl[e]	1.08 E+00	2.15 E+00	D	*	*	
NO_x[g]	1.58 E+00	3.16 E+00	B	*	*	
CO[g]	1.50 E-01	2.99 E-01	B	*	*	
CDD/CDF[h]	1.47 E-06	2.94 E-06	D	1.88 E-06	3.76 E-06	C

[a] Emission factors were calculated from concentrations using an F-factor of 0.26 dscm/J (9,570 dscf/MBtu) and a heating value of 10,466 J/g (4,500 Btu/lb). Other heating values can be substituted by multiplying the emission factor by the new heating value and dividing by 10,466 J/g (4,500 Btu/lb). Source Classification Codes 5-01-001-01, 5-03-001-14. ND = no data. NA = not applicable. * = Same as "uncontrolled" for these pollutants.

[b] Emission factors should be used for estimating long-term, not short-term, emission levels. This particularly applies to pollutants measured with a continuous emission monitoring system (e. g., CO, NO_x).

[c] ESP = Electrostatic Precipitator

[d] PM = total particulate matter, as measured with EPA Reference Method 5.

[e] Hazardous air pollutants listed in the *Clean Air Act*.

[f] Mercury levels based on emission levels measured at mass burn, MOD/EA, and MOD/SA combustors.

[g] Control of NO_x and CO is not tied to traditional acid gas/PM control devices.

[h] CDD/CDF = total tetra- through octa- chlorinated dibenzo-p-dioxin/chlorinated dibenzofurans, 2,3,7,8-tetrachlorodibenzo-p-dioxin, and dibenzofurans are hazardous air pollutants listed in the *Clean Air Act*.

Another point to keep in mind when using emission factors is that certain control technologies, specifically ESPs and DSI systems, are not all designed with equal performance capabilities. The ESP and DSI-based emission factors are based on data from a variety of facilities and represent average emission levels for MWCs equipped with these control technologies. To estimate emissions for a specific ESP or DSI system, refer to either the AP-42 background report for this section or the NSPS and EG BIDs to obtain actual emissions data for these facilities. These documents should also be used when conducting risk assessments, as well as for determining removal efficiencies. Since the AP-42 emission factors represent averages from numerous facilities, the uncontrolled and controlled levels frequently do not correspond to simultaneous testing and should not be used to calculate removal efficiencies.

Emission factors for MWCs were calculated from flue gas concentrations using an F-factor of 0.26 dry standard cubic meters per joule (dscm/J) (9,570 dry standard cubic feet per million British thermal units [Btu]) and an assumed heating value of the waste of 10,466 J/g (4,500 Btu per pound [Btu/lb]) for all combustors except RDF, for which a 12,792 J/g (5,500 Btu/lb) heating value was assumed. These are average values for MWCs; however, a particular facility may have a different heating value for the waste. In such a case, the emission factors shown in the tables can be adjusted by multiplying the emission factor by the actual facility heating value and dividing by the assumed heating value (4,500 or 5,500 Btu/lb, depending on the combustor type). Also, conversion factors to obtain concentrations, which can be used for developing more specific emission factors or making comparisons to regulatory limits, are provided in Tables 2.1-10 and 2.1-11 for all combustor types (except RDF) and RDF combustors, respectively.

Also note that the values shown in the tables for PM are for total PM, and the CDD/CDF data represent total tetra- through octa-CDD/CDF. For SO_2, NO_x, and CO, the data presented in the tables represent long-term averages, and should not be used to estimate short-term emissions. Refer to the EPA BIDs which discuss achievable emission levels of SO_2, NO_x, and CO for different averaging times based on analysis of continuous emission monitoring data. Lastly, for PM and metals, levels for MB/WW, MB/RC, MB/REF, and MOD/EA were combined to determine the emission factors, since these emissions should be the same for these types of combustors. For controlled levels, data were combined within each control technology type (e. g., SD/FF data, ESP data). For Hg, MOD/SA data were also combined with the mass burn and MOD/EA data.

2.1.7 Other Types Of Combustors[122-134]

2.1.7.1 Industrial/Commercial Combustors -

The capacities of these units cover a wide range, generally between 23 and 1,800 kilograms (50 and 4,000 pounds) per hour. Of either single- or multiple-chamber design, these units are often manually charged and intermittently operated. Some industrial combustors are similar to municipal combustors in size and design. Emission control systems include gas-fired afterburners, scrubbers, or both. Under Section 129 of the CAAA, these types of combustors will be required to meet emission limits for the same list of pollutants as for MWCs. The EPA has not yet established these limits.

2.1.7.2 Trench Combustors -

Trench combustors, also called air curtain incinerators, forcefully project a curtain of air across a pit in which open burning occurs. The air curtain is intended to increase combustion efficiency and reduce smoke and PM emissions. Underfire air is also used to increase combustion efficiency.

Table 2.1-10. CONVERSION FACTORS FOR ALL COMBUSTOR TYPES EXCEPT RDF

Divide	By	To Obtain[a]
For As, Cd, Cr, Hg, Ni, Pb, and CDD/CDF:		
kg/Mg refuse	4.03×10^{-6}	µg/dscm
lb/ton refuse	8.06×10^{-6}	
For PM:		
kg/Mg refuse	4.03×10^{-3}	mg/dscm
lb/ton refuse	8.06×10^{-3}	
For HCl:		
kg/Mg refuse	6.15×10^{-3}	ppmv
lb/ton refuse	1.23×10^{-2}	
For SO^2:		
kg/Mg refuse	1.07×10^{-2}	ppmv
lb/ton refuse	2.15×10^{-2}	
For NO_X:		
kg/Mg refuse	7.70×10^{-3}	ppmv
lb/ton refuse	1.54×10^{-2}	
For CO:		
kg/Mg refuse	4.69×10^{-3}	ppmv
lb/ton refuse	9.4×10^{-3}	

[a] At 7% O_2.

Table 2.1-11. CONVERSION FACTORS FOR REFUSE-DERIVED FUEL COMBUSTORS

Divide	By	To Obtain[a]
For As, Cd, Cr, Hg, Ni, Pb, and CDD/CDF:		
kg/Mg refuse	4.92×10^{-6}	μg/dscm
lb/ton refuse	9.85×10^{-6}	
For PM:		
kg/Mg refuse	4.92×10^{-3}	mg/dscm
lb/ton refuse	9.85×10^{-3}	
For HCl:		
kg/Mg refuse	7.5×10^{-3}	ppmv
lb/ton refuse	1.5×10^{-2}	
For SO_2:		
kg/Mg refuse	1.31×10^{-2}	ppmv
lb/ton refuse	2.62×10^{-2}	
For NO_x:		
kg/Mg refuse	9.45×10^{-3}	ppmv
lb/ton refuse	1.89×10^{-2}	
For CO:		
kg/Mg refuse	5.75×10^{-3}	ppmv
lb/ton refuse	1.15×10^{-2}	

[a] At 7% O_2.

Trench combustors can be built either above- or below-ground. They have refractory walls and floors and are normally 8-feet wide and 10-feet deep. Length varies from 8 to 16 feet. Some units have mesh screens to contain larger particles of fly ash, but other add-on pollution controls are normally not used.

Trench combustors burning wood wastes, yard wastes, and clean lumber are exempt from Section 129, provided they comply with opacity limitations established by the Administrator. The primary use of air curtain incinerators is the disposal of these types of wastes; however, some of these combustors are used to burn MSW or construction and demolition debris.

In some states, trench combustors are often viewed as a version of open burning and the use of these types of units has been discontinued in some States.

2.1.7.3 Domestic Combustors -

This category includes combustors marketed for residential use. These types of units are typically located at apartment complexes, residential buildings, or other multiple family dwellings, and are generally found in urban areas. Fairly simple in design, they may have single or multiple refractory-lined chambers and usually are equipped with an auxiliary burner to aid combustion. Due to their small size, these types of units are not currently covered by the MWC regulations.

2.1.7.4 Flue-fed Combustors -

These units, commonly found in large apartment houses or other multiple family dwellings, are characterized by the charging method of dropping refuse down the combustor flue and into the combustion chamber. Modified flue-fed incinerators utilize afterburners and draft controls to improve combustion efficiency and reduce emissions. Due to their small size, these types of units are not currently covered by the MWC regulations.

Emission factors for industrial/commercial, trench, domestic, and flue-fed combustors are presented in Table 2.1-12.

Table 2.1-12 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR REFUSE COMBUSTORS OTHER THAN MUNICIPAL WASTE[a]

EMISSION FACTOR RATING: D

Combustor Type	PM		SO_2		CO		Total Organic Compounds[b]		NO_x	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Industrial/commercial										
Multiple chamber	3.50 E+00	7.00 E+00	1.25 E+00	2.50 E+00	5.00 E+00	1.00 E+01	1.50 E+00	3.00 E+00	1.50 E+00	3.00 E+00
Single chamber	7.50 E+00	1.50 E+01	1.25 E+00	2.50 E+00	1.00 E+01	2.00 E+01	7.50 E+01	1.50 E+01	1.00 E+00	2.00 E+00
Trench										
Wood (SCC 5-01-005-10, 5-03-001-06)	6.50 E+00	1.30 E+01	5.00 E-02	1.00 E-01	ND	ND	ND	ND	2.00 E+00	4.00 E+00
Rubber tires (SCC 5-01-005-11, 5-03-001-07)	6.90 E+01	1.38 E+02	ND	ND	ND	ND	ND	ND	ND	ND
Municipal refuse (SCC 5-01-005-12, 5-03-001-09)	1.85 E+01	3.70 E+01	1.25 E+00	2.50 E+00	ND	ND	ND	ND	ND	ND
Flue-fed single chamber	1.50 E+01	3.00 E+01	2.50 E-01	5.00 E-01	1.00 E+01	2.00 E+01	7.50 E+00	1.50 E+01	1.50 E+00	3.00 E+00
Flue-fed (modified)	3.00 E+00	6.00 E+00	2.50 E-01	5.00 E-01	5.00 E+00	1.00 E+01	1.50 E+00	3.00 E+00	5.00 E+00	1.00 E+01
Domestic single chamber (no SCC)										
Without primary burner	1.75 E+01	3.50 E+01	2.50 E-01	5.00 E-01	1.50 E+02	3.00 E+02	5.00 E+01	1.00 E+02	5.00 E-01	1.00 E+00
With primary burner	3.50 E+00	7.00 E+00	2.50 E-01	5.00 E-01	Neg	Neg	1.00 E+00	2.00 E+00	1.00 E+00	2.00 E+00

[a] References 116-123. ND = no data. SCC = Source Classification Code. Neg = negligible.
[b] Expressed as methane.

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2.2 Sewage Sludge Incineration

There are approximately 170 sewage sludge incineration (SSI) plants in operation in the United States. Three main types of incinerators are used: multiple hearth, fluidized bed, and electric infrared. Some sludge is co-fired with municipal solid waste in combustors based on refuse combustion technology (see Section 2.1). Refuse co-fired with sludge in combustors based on sludge incinerating technology is limited to multiple hearth incinerators only.

Over 80 percent of the identified operating sludge incinerators are of the multiple hearth design. About 15 percent are fluidized bed combustors and 3 percent are electric. The remaining combustors co-fire refuse with sludge. Most sludge incinerators are located in the Eastern United States, though there are a significant number on the West Coast. New York has the largest number of facilities with 33. Pennsylvania and Michigan have the next-largest numbers of facilities with 21 and 19 sites, respectively.

Sewage sludge incinerator emissions are currently regulated under 40 CFR Part 60, Subpart O and 40 CFR Part 61, Subparts C and E. Subpart O in Part 60 establishes a New Source Performance Standard for particulate matter. Subparts C and E of Part 61--National Emission Standards for Hazardous Air Pollutants (NESHAP)--establish emission limits for beryllium and mercury, respectively.

In 1989, technical standards for the use and disposal of sewage sludge were proposed as 40 CFR Part 503, under authority of Section 405 of the Clean Water Act. Subpart G of this proposed Part 503 proposes to establish national emission limits for arsenic, beryllium, cadmium, chromium, lead, mercury, nickel, and total hydrocarbons from sewage sludge incinerators. The proposed limits for mercury and beryllium are based on the assumptions used in developing the NESHAPs for these pollutants, and no additional controls were proposed to be required. Carbon monoxide emissions were examined, but no limit was proposed.

2.2.1 Process Description[1,2]

Types of incineration described in this section include:

- Multiple hearth,
- Fluidized bed, and
- Electric.

Single hearth cyclone, rotary kiln, and wet air oxidation are also briefly discussed.

2.2.1.1 Multiple Hearth Furnaces -

The multiple hearth furnace was originally developed for mineral ore roasting nearly a century ago. The air-cooled variation has been used to incinerate sewage sludge since the 1930s. A cross-sectional diagram of a typical multiple hearth furnace is shown in Figure 2.2-1. The basic multiple hearth furnace (MHF) is a vertically oriented cylinder. The outer shell is constructed of steel, lined with refractory, and surrounds a series of horizontal refractory hearths. A hollow cast iron rotating shaft runs through the center of the hearths. Cooling air is introduced into the shaft

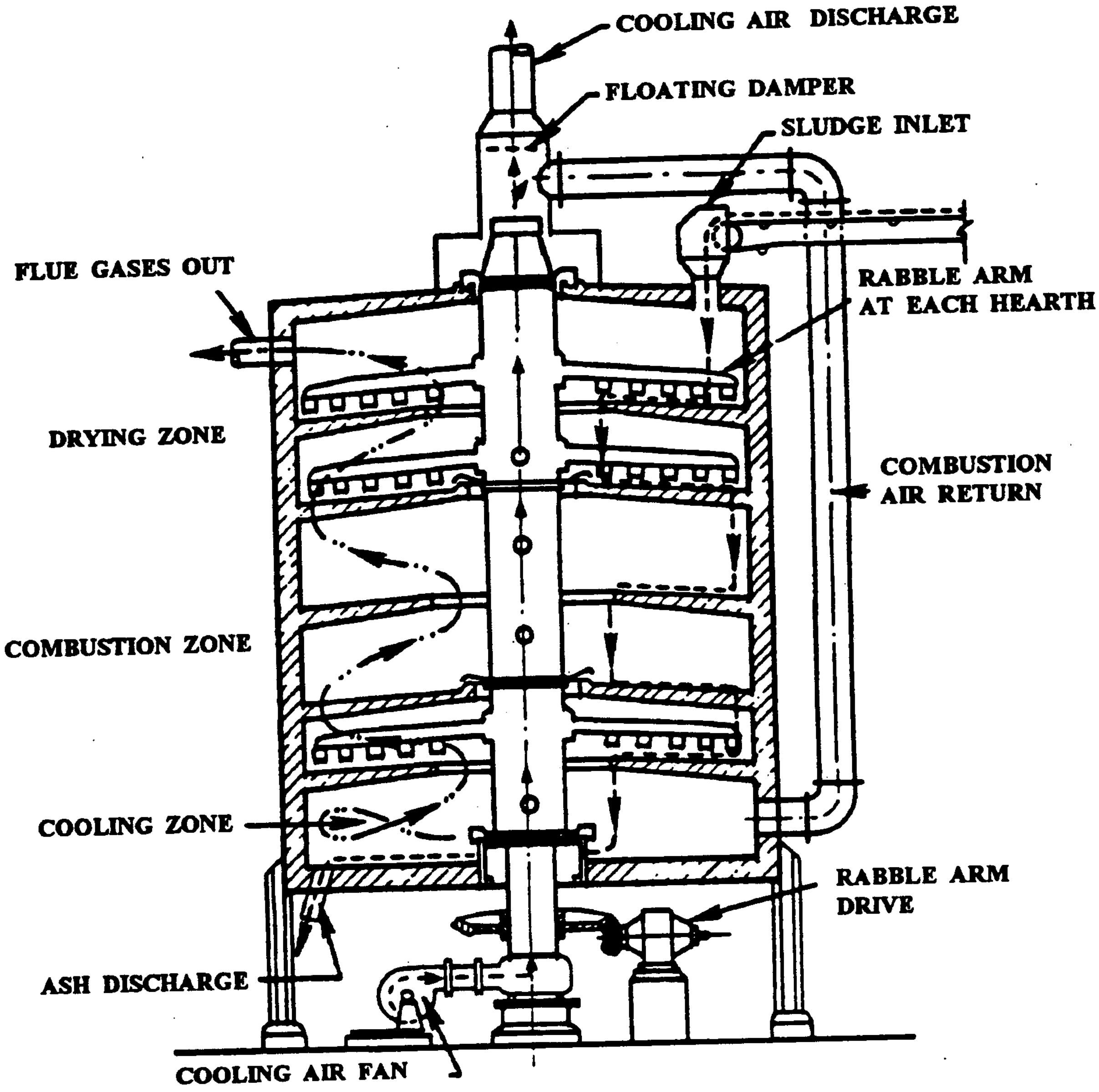

Figure 2.2-1. Cross Section of a Multiple Hearth Furnace

which extend above the hearths. Each rabble arm is equipped with a number of teeth, approximately 6 inches in length, and spaced about 10 inches apart. The teeth are shaped to rake the sludge in a spiral motion, alternating in direction from the outside in, to the inside out, between hearths. Typically, the upper and lower hearths are fitted with four rabble arms, and the middle hearths are fitted with two. Burners, providing auxiliary heat, are located in the sidewalls of the hearths.

In most multiple hearth furnaces, partially dewatered sludge is fed onto the perimeter of the top hearth. The rabble arms move the sludge through the incinerator by raking the sludge toward the center shaft where it drops through holes located at the center of the hearth. In the next hearth the sludge is raked in the opposite direction. This process is repeated in all of the subsequent hearths. The effect of the rabble motion is to break up solid material to allow better surface contact with heat and oxygen. A sludge depth of about 1 inch is maintained in each hearth at the design sludge flow rate.

Scum may also be fed to one or more hearths of the incinerator. Scum is the material that floats on wastewater. It is generally composed of vegetable and mineral oils, grease, hair, waxes, fats, and other materials that will float. Scum may be removed from many treatment units including preaeration tanks, skimming tanks, and sedimentation tanks. Quantities of scum are generally small compared to those of other wastewater solids.

Ambient air is first ducted through the central shaft and its associated rabble arms. A portion, or all, of this air is then taken from the top of the shaft and recirculated into the lowermost hearth as preheated combustion air. Shaft cooling air which is not circulated back into the furnace is ducted into the stack downstream of the air pollution control devices. The combustion air flows upward through the drop holes in the hearths, countercurrent to the flow of the sludge, before being exhausted from the top hearth. Air enters the bottom to cool the ash. Provisions are usually made to inject ambient air directly into the middle hearths as well.

From the standpoint of the overall incineration process, multiple hearth furnaces can be divided into three zones. The upper hearths comprise the drying zone where most of the moisture in the sludge is evaporated. The temperature in the drying zone is typically between 425 and 760°C (800 and 1400°F). Sludge combustion occurs in the middle hearths (second zone) as the temperature is increased to about 925°C (1700°F). The combustion zone can be further subdivided into the upper-middle hearths where the volatile gases and solids are burned, and the lower-middle hearths where most of the fixed carbon is combusted. The third zone, made up of the lowermost hearth(s), is the cooling zone. In this zone the ash is cooled as its heat is transferred to the incoming combustion air.

Multiple hearth furnaces are sometimes operated with afterburners to further reduce odors and concentrations of unburned hydrocarbons. In afterburning, furnace exhaust gases are ducted to a chamber where they are mixed with supplemental fuel and air and completely combusted. Some incinerators have the flexibility to allow sludge to be fed to a lower hearth, thus allowing the upper hearth(s) to function essentially as an afterburner.

Under normal operating condition, 50 to 100 percent excess air must be added to an MHF in order to ensure complete combustion of the sludge. Besides enhancing contact between fuel and oxygen in the furnace, these relatively high rates of excess air are necessary to compensate for normal variations in both the organic characteristics of the sludge feed and the rate at which it enters the incinerator. When an inadequate amount of excess air is available, only partial oxidation of the carbon will occur, with a resultant increase in emissions of carbon monoxide, soot, and hydrocarbons.

Too much excess air, on the other hand, can cause increased entrainment of particulate and unnecessarily high auxiliary fuel consumption.

Multiple hearth furnace emissions are usually controlled by a venturi scrubber, an impingement tray scrubber, or a combination of both. Wet cyclones and dry cyclones are also used. Wet electrostatic precipitators (Wet ESPs) are being installed as retrofits where tighter limits on particulate matter and metals are required by State regulations.

2.2.1.2 Fluidized Bed Incinerators -

Fluidized bed technology was first developed by the petroleum industry to be used for catalyst regeneration. Figure 2.2-2 shows the cross section diagram of a fluidized bed furnace. Fluidized bed combustors (FBCs) consist of a vertically oriented outer shell constructed of steel and lined with refractory. Tuyeres (nozzles designed to deliver blasts of air) are located at the base of the furnace within a refractory-lined grid. A bed of sand, approximately 0.75 meters (2.5 feet) thick, rests upon the grid. Two general configurations can be distinguished on the basis of how the fluidizing air is injected into the furnace. In the "hot windbox" design the combustion air is first preheated by passing through a heat exchanger where heat is recovered from the hot flue gases. Alternatively, ambient air can be injected directly into the furnace from a cold windbox.

Partially dewatered sludge is fed into the lower portion of the furnace. Air injected through the tuyeres, at pressures of from 20 to 35 kilopascals (3 to 5 pounds per square inch gauge), simultaneously fluidizes the bed of hot sand and the incoming sludge. Temperatures of 750 to 925°C (1400 to 1700°F) are maintained in the bed. Residence times are typically 2 to 5 seconds. As the sludge burns, fine ash particles are carried out the top of the furnace. Some sand is also removed in the air stream; sand make-up requirements are on the order of 5 percent for every 300 hours of operation.

Combustion of the sludge occurs in two zones. Within the bed itself (Zone 1), evaporation of the water and pyrolysis of the organic materials occur nearly simultaneously as the temperature of the sludge is rapidly raised. In the second zone (freeboard area), the remaining free carbon and combustible gases are burned. The second zone functions essentially as an afterburner.

Fluidization achieves nearly ideal mixing between the sludge and the combustion air and the turbulence facilitates the transfer of heat from the hot sand to the sludge. The most noticeable impact of the better burning atmosphere provided by a fluidized bed incinerator is seen in the limited amount of excess air required for complete combustion of the sludge. Typically, FBCs can achieve complete combustion with 20 to 50 percent excess air, about half the excess air required by multiple hearth furnaces. As a consequence, FBC incinerators have generally lower fuel requirements compared to MHF incinerators.

Fluidized bed incinerators most often have venturi scrubbers or venturi/impingement tray scrubber combinations for emissions control.

2.2.1.3 Electric Infrared Incinerators -

The first electric infrared furnace was installed in 1975, and their use is not common. Electric infrared incinerators consist of a horizontally oriented, insulated furnace. A woven wire belt conveyor extends the length of the furnace and infrared heating elements are located in the roof above the conveyor belt. Combustion air is preheated by the flue gases and is injected into the discharge end of the furnace. Electric infrared incinerators consist of a number of prefabricated modules, which can be linked together to provide the necessary furnace length. A cross section of an electric furnace is shown in Figure 2.2-3.

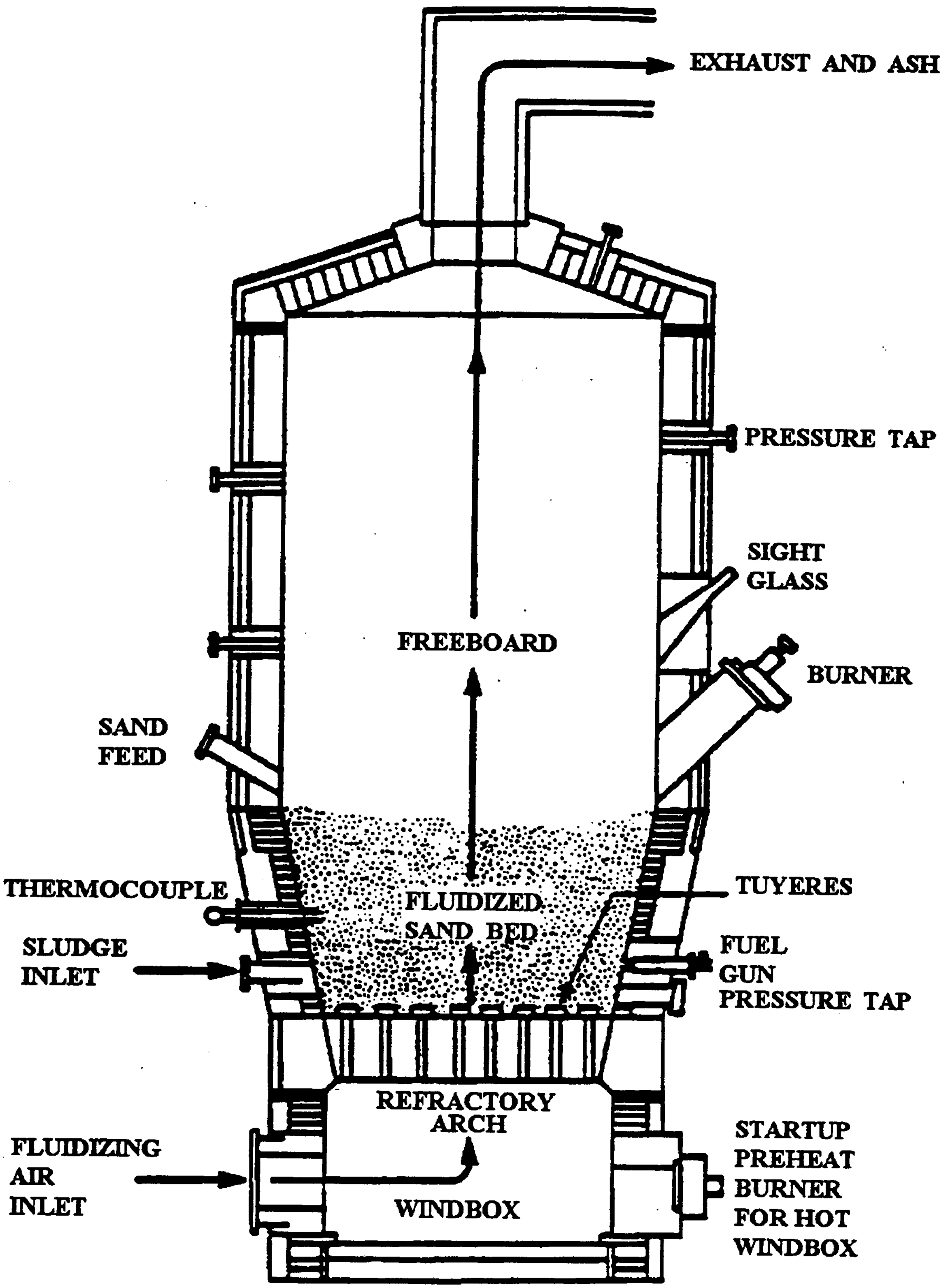

Figure 2.2-2. Cross Section of a Fluidized Bed Furnace

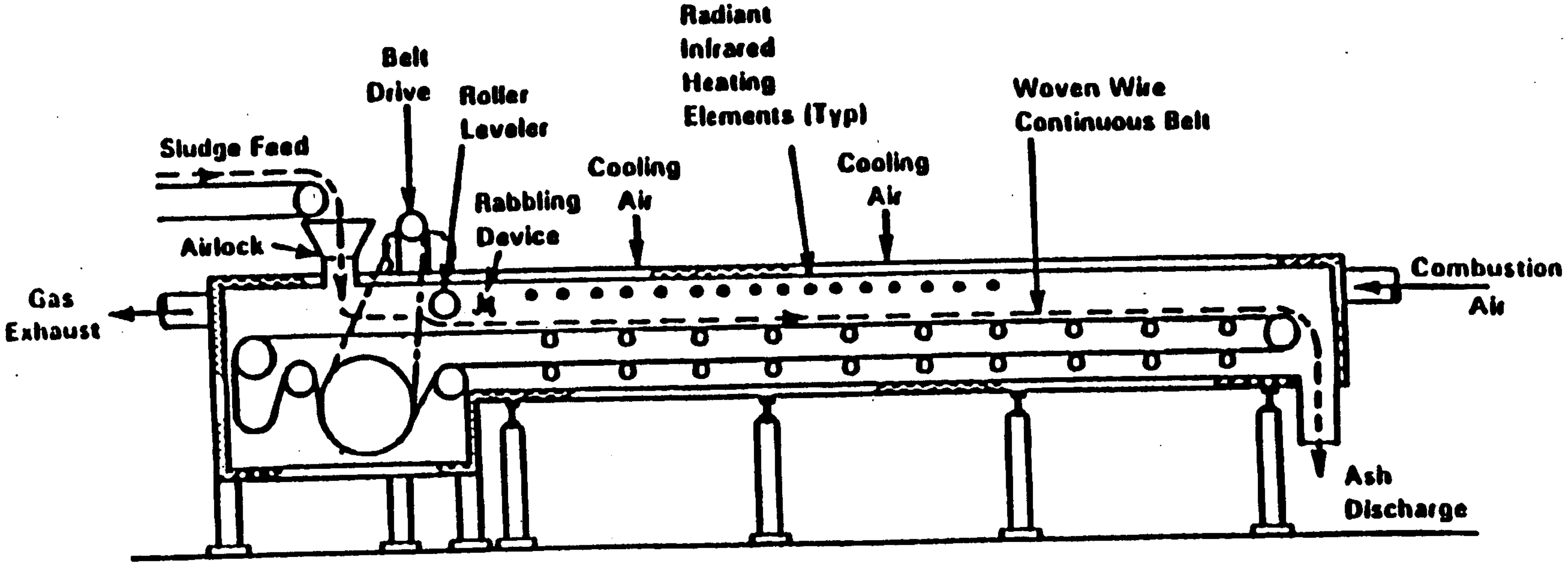

Figure 2.2-3. Cross Section of an Electric Infrared Furnace.

The dewatered sludge cake is conveyed into one end of the incinerator. An internal roller mechanism levels the sludge into a continuous layer approximately one inch thick across the width of the belt. The sludge is sequentially dried and then burned as it moves beneath the infrared heating elements. Ash is discharged into a hopper at the opposite end of the furnace. The preheated combustion air enters the furnace above the ash hopper and is further heated by the outgoing ash. The direction of air flow is countercurrent to the movement of the sludge along the conveyor. Exhaust gases leave the furnace at the feed end. Excess air rates vary from 20 to 70 percent.

Compared to MHF and FBC technologies, the electric infrared furnace offers the advantage of lower capital cost, especially for smaller systems. However, electricity costs in some areas may make an electric furnace infeasible. One other concern is replacement of various components such as the woven wire belt and infrared heaters, which have 3- to 5-year lifetimes.

Electric infrared incinerator emissions are usually controlled with a venturi scrubber or some other wet scrubber.

2.2.1.4 Other Technologies -

A number of other technologies have been used for incineration of sewage sludge, including cyclonic reactors, rotary kilns, and wet oxidation reactors. These processes are not in widespread use in the United States and will be discussed only briefly.

The cyclonic reactor is designed for small capacity applications. It is constructed of a vertical cylindrical chamber that is lined with refractory. Preheated combustion air is introduced into the chamber tangentially at high velocities. The sludge is sprayed radially toward the hot refractory walls. Combustion is rapid: The residence time of the sludge in the chamber is on the order of 10 seconds. The ash is removed with the flue gases.

Rotary kilns are also generally used for small capacity applications. The kiln is inclined slightly from the horizontal plane, with the upper end receiving both the sludge feed and the combustion air. A burner is located at the lower end of the kiln. The circumference of the kiln rotates at a speed of about 15 centimeters (cm) per second (6 inches per second). Ash is deposited into a hopper located below the burner.

The wet oxidation process is not strictly one of incineration; it instead utilizes oxidation at elevated temperature and pressure in the presence of water (flameless combustion). Thickened sludge, at about 6 percent solids, is first ground and mixed with a stoichiometric amount of compressed air. The slurry is then pressurized. The mixture is then circulated through a series of heat exchangers before entering a pressurized reactor. The temperature of the reactor is held between 175 and 315°C (350 and 600°F). The pressure is normally 7,000 to 12,500 kilopascals (1,000 to 1,800 pounds per square inch grade). Steam is usually used for auxiliary heat. The water and remaining ash are circulated out the reactor and are finally separated in a tank or lagoon. The liquid phase is recycled to the treatment plant. Offgases must be treated to eliminate odors: wet scrubbing, afterburning, or carbon absorption may be used.

2.2.1.5 Co-incineration and Co-firing -

Wastewater treatment plant sludge generally has a high water content and in some cases, fairly high levels of inert materials. As a result, its net fuel value is often low. If sludge is combined with other combustible materials in a co-incineration scheme, a furnace feed can be created that has both a low water concentration and a heat value high enough to sustain combustion with little or no supplemental fuel.

Virtually any material that can be burned can be combined with sludge in a co-incineration process. Common materials for co-combustion are coal, municipal solid waste (MSW), wood waste and agriculture waste. Thus, a municipal or industrial waste can be disposed of while providing an autogenous (self-sustaining) sludge feed, thereby solving two disposal problems.

There are two basic approaches to combusting sludge with MSW: (1) use of MSW combustion technology by adding dewatered or dried sludge to the MSW combustion unit, and (2) use of sludge combustion technology by adding processed MSW as a supplemental fuel to the sludge furnace. With the latter, MSW is processed by removing noncombustibles, shredding, air classifying, and screening. Waste that is more finely processed is less likely to cause problems such as severe erosion of the hearths, poor temperature control, and refractory failures.

2.2.2 Emissions And Controls[1-3]

Sewage sludge incinerators potentially emit significant quantities of pollutants. The major pollutants emitted are: (1) particulate matter, (2) metals, (3) carbon monoxide (CO), (4) nitrogen oxides (NO_x), (5) sulfur dioxide (SO_2), and (6) unburned hydrocarbons. Partial combustion of sludge can result in emissions of intermediate products of incomplete combustion (PIC), including toxic organic compounds.

Uncontrolled particulate emission rates vary widely depending on the type of incinerator, the volatiles and moisture content of the sludge, and the operating practices employed. Generally, uncontrolled particulate emissions are highest from fluidized bed incinerators because suspension burning results in much of the ash being carried out of the incinerator with the flue gas. Uncontrolled emissions from multiple hearth and fluidized bed incinerators are extremely variable, however. Electric incinerators appear to have the lowest rates of uncontrolled particulate release of the three major furnace types, possibly because the sludge is not disturbed during firing. In general, higher airflow rates increase the opportunity for particulate matter to be entrained in the exhaust gases. Sludge with low volatile content or high moisture content may compound this situation by requiring more supplemental fuel to burn. As more fuel is consumed, the amount of air flowing through the incinerator is also increased. However, no direct correlation has been established between airflow and particulate emissions.

Metal emissions are affected by metal content of the sludge, fuel bed temperature, and the level of particulate matter control. Since metals which are volatilized in the combustion zone condense in the exhaust gas stream, most metals (except mercury) are associated with fine particulate and are removed as the fine particulates are removed.

Carbon monoxide is formed when available oxygen is insufficient for complete combustion or when excess air levels are too high, resulting in lower combustion temperatures.

Emissions of nitrogen and sulfur oxides are primarily the result of oxidation of nitrogen and sulfur in the sludge. Therefore, these emissions can vary greatly based on local and seasonal sewage characteristics.

Emissions of volatile organic compounds (VOC) also vary greatly with incinerator type and operation. Incinerators with countercurrent airflow such as multiple hearth designs provide the greatest opportunity for unburned hydrocarbons to be emitted. In the MHF, hot air and wet sludge feed are contacted at the top of the furnace. Any compounds distilled from the solids are immediately vented from the furnace at temperatures too low to completely destruct them.

Particulate emissions from sewage sludge incinerators have historically been controlled by wet scrubbers, since the associated sewage treatment plant provides both a convenient source and a good disposal option for the scrubber water. The types of existing sewage sludge incinerator controls range from low pressure drop spray towers and wet cyclones to higher pressure drop venturi scrubbers and venturi/impingement tray scrubber combinations. Electrostatic precipitators and baghouses are employed primarily where sludge is co-fired with municipal solid waste. The most widely used control device applied to a multiple hearth incinerator is the impingement tray scrubber. Older units use the tray scrubber alone while combination venturi/impingement tray scrubbers are widely applied to newer multiple hearth incinerators and to fluidized bed incinerators. Most electric incinerators and many fluidized bed incinerators use venturi scrubbers only.

In a typical combination venturi/impingement tray scrubber, hot gas exits the incinerator and enters the precooling or quench section of the scrubber. Spray nozzles in the quench section cool the incoming gas and the quenched gas then enters the venturi section of the control device. Venturi water is usually pumped into an inlet weir above the quencher. The venturi water enters the scrubber above the throat and floods the throat completely. This eliminates build-up of solids and reduces abrasion. Turbulence created by high gas velocity in the converging throat section deflects some of the water traveling down the throat into the gas stream. Particulate matter carried along with the gas stream impacts on these water particles and on the water wall. As the scrubber water and flue gas leave the venturi section, they pass into a flooded elbow where the stream velocity decreases, allowing the water and gas to separate. Most venturi sections come equipped with variable throats. By restricting the throat area within the venturi, the linear gas velocity is increased and the pressure drop is subsequently increased. Up to a certain point, increasing the venturi pressure drop increases the removal efficiency. Venturi scrubbers typically maintain 60 to 99 percent removal efficiency for particulate matter, depending on pressure drop and particle size distribution.

At the base of the flooded elbow, the gas stream passes through a connecting duct to the base of the impingement tray tower. Gas velocity is further reduced upon entry to the tower as the gas stream passes upward through the perforated impingement trays. Water usually enters the trays from inlet ports on opposite sides and flows across the tray. As gas passes through each perforation in the tray, it creates a jet which bubbles up the water and further entrains solid particles. At the top of the tower is a mist eliminator to reduce the carryover of water droplets in the stack effluent gas. The impingement section can contain from one to four trays, but most systems for which data are available have two or three trays.

Emission factors and emission factor ratings for multiple hearth sewage sludge incinerators are shown in Tables 2.2-1, 2.2-2, 2.2-3, 2.2-4, and 2.2-5. Tables 2.2-6, 2.2-7, and 2.2-8 present emission factors for fluidized bed sewage sludge incinerators. Table 2.2-9 presents the available emission factors for electric infrared incinerators. Tables 2.2-10 and 2.2-11 present the cumulative particle size distribution and size-specific emission factors for sewage sludge incinerators. Figure 2.2-4, Figure 2.2-5, and Figure 2.2-6 present cumulative particle size distribution and size-specific emission factors for multiple-hearth, fluidized-bed, and electric infrared incinerators, respectively.

Table 2.2-1 (Metric And English Units). CRITERIA POLLUTANT EMISSION FACTORS FOR MULTIPLE HEARTH SEWAGE SLUDGE INCINERATORS[a]

Source Category[b]	Filterable Particulate Matter (PM)			Sulfur Dioxide (SO_2)			Nitrogen Oxides (NO_x)[c]		
	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	5.2 E+01	1.0 E+02	B	1.4 E+01	2.8 E+01	B	2.5 E+00	5.0 E+00	C
Controlled									
Cyclone	2.0 E+00	4.0 E+00	E	2.8 E+00	5.6 E+00	E			
Cyclone/impingement	4.0 E-01	8.0 E-01	E						
Cyclone/venturi	2.5 E-01	5.0 E-01	D						
Cyclone/venturi/impingement	3.1 E-01	6.2 E-01	E						
Electrostatic precipitator									
Fabric filter	2.0 E-03	4.0 E-03	E						
Impingement	7.0 E-01	1.4 E+00	B	3.2 E-01	6.4 E-01	D			
Venturi	1.6 E+00	3.2 E+00	B	2.3 E+00	4.6 E+00	E			
Venturi/impingement/afterburner									
Venturi/impingement	1.1 E+00	2.2 E+00	A	1.0 E-01	2.0 E-01	E			
Venturi/impingement/Wet ESP	2.0 E-01	4.0 E-01	E						
Venturi/Wet ESP									

Table 2.2-8 (Metric And English Units). METAL EMISSION FACTORS FOR FLUIDIZED BED SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Pollutant	Uncontrolled		Impingement		Venturi/Impingement		Venturi/Impingement/ Wet ESP[b]	
	g/Mg	lb/ton	g/Mg	lb/ton	g/Mg	lb/ton	g/Mg	lb/ton
Aluminum					1.9 E+00	3.8 E-03		
Arsenic[c]	2.2 E+00	4.4 E-03			1.5 E-02	3.0 E-05	5.0 E-03	1.0 E-05
Barium					2.4 E-01	4.8 E-04		
Beryllium[c]					2.0 E-04	4.0 E-07	2.0 E-04	4.0 E-07
Cadmium[c]	2.2 E+00	4.4 E-03	4.0 E-01	8.0 E-04	5.7 E-01	1.1 E-03	1.0 E-03	2.0 E-06
Calcium[c]					5.2 E+00	1.0 E-02		
Chromium[c]			3.2 E-01	6.4 E-04	2.5 E-01	5.0 E-04	3.0 E-02	6.0 E-05
Copper					3.0 E-01	6.0 E-04		
Manganese[c]					3.0 E-01	6.0 E-04		
Magnesium					6.0 E-01	1.2 E-03		
Mercury[c]					3.0 E-02	6.0 E-05		
Nickel[c]	1.78 E+01	3.5 E-02			1.7 E+00	3.4 E-03	5.0E-03	1.0E-05
Potassium					6.0 E-01	1.2 E-03		
Selenium[c]					2.0 E-01	4.0 E-04		
Silicon					3.2 E+00	6.4 E-03		
Sulfur					8.6 E+00	1.7 E-02		
Tin					3.5 E-01	7.0 E-04		
Titanium					4.0 E-01	8.0 E-04		
Zinc					1.0 E+00	2.0 E-03		

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-16.

[b] Wet ESP = wet electrostatic precipitator.

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-7 (cont.).

Pollutant	Uncontrolled		Impingement		Venturi/Impingement		Cyclone/Impingement	
	g/Mg	lb/ton	g/Mg	lb/ton	g/Mg	lb/ton	g/Mg	lb/ton
Chloroform[b]					2.0 E+00	4.0 E-03		
Ethylbenzene[b]					2.5 E-02	5.0 E-05		
Methylene Chloride[b]					7.0 E-01	1.4 E-03		
Naphthalene[b]					9.7 E+01	1.9 E-01		
Perchloroethylene[b]					1.2 E-01	2.4 E-04		
Toluene[b]							3.5 E-01	7.0 E-04
Trichloroethene[b]					3.0 E-02	6.0 E-05		

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-16. Blanks indicate no data.

[b] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-7 (Metric And English Units). ACID GAS AND ORGANIC COMPOUND EMISSION FACTORS FOR FLUIDIZED BED SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Pollutant	Uncontrolled		Impingement		Venturi/Impingement		Cyclone/Impingement	
	g/Mg	lb/ton	g/Mg	lb/ton	g/Mg	lb/ton	g/Mg	lb/ton
Sulfuric Acid (H_2SO_4)			3.0 E+01	6.0 E-02	6.0 E+01	1.2 E-01		
Hydrogen Chloride (HCl)[b]					5.0 E+01	1.0 E-01		
2,3,7,8-TCDD[b]					3.0 E-07	6.0 E-10		
Total TCDD					2.2 E-06	4.4 E-09		
Total PCDD	1.1 E-06	2.2 E-09						
Total HxCDD					9.0 E-07	1.8 E-09		
Total HpCDD					9.0 E-07	1.8 E-09		
Total OCDD					4.3 E-06	8.6 E-09		
2,3,7,8-TCDF[b]					2.0 E-07	4.0 E-10		
Total TCDF[b]					6.2 E-06	1.2 E-08		
Total PCDF[b]					5.2 E-06	1.0 E-08		
Total HxCDF[b]					4.1 E-06	8.2 E-09		
Total HpCDF[b]					1.6 E-06	3.2 E-09		
Total OCDF[b]					1.3 E-06	2.6 E-09		
1,1,1-Trichloroethane[b]					2.6 E-01	5.2 E-04		
1,2-Dichlorobenzene					6.4 E+01	1.3 E-01		
1,4-Dichlorobenzene[b]					2.4 E+02	4.8 E-01		
Benzene[b]					2.0 E-01	4.0 E-04		
Bis(2-ethylhexyl)phthalate[b]					4.1 E+01	8.2 E-02		
Carbon Tetrachloride[b]					1.2 E-02	2.4 E-05		
Chlorobenzene[b]					5.0 E-03	1.0 E-05		

Table 2.2-6 (cont.).

Source Category[b]	Carbon Monoxide[c] (CO)		Lead[d]		Methane VOC	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Uncontrolled	1.1 E+00	2.1 E+00	2.0 E-02	4.0 E-02		
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi						
Cyclone/venturi/impingement						
Electrostatic precipitator						
Fabric filter			5.0 E-06	1.0 E-05		
Impingement			3.0 E-03	6.0 E-03		
Venturi					1.6 E+00	3.2 E+00
Venturi/impingement/afterburner						
Venturi/impingement			8.0 E-02	1.6 E-01	4.0 E-01	8.0 E-01
Venturi/impingement/Wet ESP			1.0 E-06	2.0 E-06		
Venturi/Wet ESP						

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-16.

[b] Wet ESP = wet electrostatic precipitator.

[c] Uncontrolled Emission Factors for NO_x and CO apply to all Air Pollution Control Device Types.

[d] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-6 (Metric And English Units). CRITERIA POLLUTANT EMISSION FACTORS FOR FLUIDIZED BED SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Source Category[b]	Particulate Matter		Sulfur Dioxide		Nitrogen Oxides[c]	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Uncontrolled	2.3 E+02	4.6 E+02	1.5 E-01	3.0 E-01	8.8 E-01	1.7 E+00
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi						
Cyclone/venturi/impingement	5.0 E-01	1.0 E+00				
Electrostatic precipitator						
Fabric filter						
Impingement	1.3 E-01	2.6 E-01	3.0 E-01	6.0 E-01		
Venturi	5.7 E-01		9.2 E+00	1.8 E+01		
Venturi/impingement/afterburner						
Venturi/impingement	2.7 E-01	1.1 E+00	4.0 E-01	8.0 E-01		
Venturi/impingement/Wet ESP	1.0 E-01	2.0 E-01				
Venturi/Wet ESP						

Table 2.2-5 (cont.).

Source Category[b]	Titanium			Vanadium			Zinc		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	5.1 E+01	1.0 E-01	C	3.3 E+00	6.6 E-03	C	6.6 E+01	1.3 E-01	C
Controlled							1.1 E+01	2.2 E-02	E
Cyclone	1.0 E-01	2.0 E-04	E	3.0 E-01	6.0 E-04	E			
Cyclone/impingement									
Cyclone/venturi							3.8 E+01	7.6 E-02	E
Cyclone/venturi/impingement									
Electrostatic precipitator	9.0 E-01	1.8 E-03	E	9.9 E-01	2.0 E-03	E	3.9 E-01	7.8 E-04	E
Fabric filter	6.0 E-03	1.2 E-05	E	2.0 E-03	4.0 E-06	E	4.0 E-02	8.0 E-05	E
Impingement									
Venturi							4.4 E+00	8.8 E-03	E
Venturi/impingement/ afterburner							3.3 E+01	6.6 E-02	E
Venturi/impingement	3.1 E+00	6.2 E-03	D	8.0 E-01	1.6 E-03	E	2.4 E+01	4.8 E-02	C
Venturi/impingement/Wet ESP									
Venturi/Wet ESP							2.0 E-01	4.0 E-04	E

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-15. Blanks indicate no data.

[b] Wet ESP = wet electrostatic precipitator.

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-5 (cont.).

Source Category[b]	Sodium			Sulfur			Tin		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	4.7 E+01	9.4 E-02	C	3.6 E+03	7.2 E-00	D	1.3 E+01	2.6 E-02	C
Controlled									
Cyclone	1.8 E+00	3.6 E-03	E	1.9 E+01	3.9 E-02	E	5.9 E+00	1.2 E-02	E
Cyclone/impingement									
Cyclone/venturi									
Cyclone/venturi/impingement									
Electrostatic precipitator	5.5 E-01	1.1 E-03	E				2.0 E-01	4.0 E-04	E
Fabric filter	1.0 E-02	2.0 E-05	E	6.0 E+01	1.2 E-01	E	2.0 E-02	4.0 E-05	E
Impingement									
Venturi									
Venturi/impingement/afterburner									
Venturi/impingement	1.4 E+01	2.8 E-02	D	1.1 E+02	2.2 E-01	E	7.9 E+00	1.6 E-02	D
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-5 (cont.).

Source Category[b]	Selenium[c]			Silicon			Silver		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	1.5 E-01	3.0 E-04	D	3.4 E+02	6.8 E-01	E	6.5 E-01	1.3 E-03	E
Controlled									
Cyclone				4.6 E+00	9.2 E-03	E			
Cyclone/impingement									
Cyclone/venturi									
Cyclone/venturi/impingement									
Electrostatic precipitator							6.0 E-03	1.2 E-05	E
Fabric filter	1.2 E-01	2.4 E-04	E				1.0 E-04	2.0 E-07	E
Impingement									
Venturi	6.0 E-02	1.2 E-04	E				4.0 E-01	8.0 E-04	E
Venturi/impingement/afterburner									
Venturi/impingement				4.4 E+01	8.8 E-02	E	9.0 E-02	1.8 E-04	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-5 (cont.).

Source Category[b]	Nickel[c]			Phosphorus[c]			Potassium		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	8.0 E+00	1.6 E-02	B	3.8 E+02	7.6 E-01	D	5.3 E+01	1.1 E-01	E
Controlled									
Cyclone	8.0 E-02	1.6 E-04	E	8.9 E+00	1.8 E-02	E	9.0 E-01	1.8 E-03	E
Cyclone/impingement	1.3 E+00	2.6 E-03	D						
Cyclone/venturi	3.5 E-01	7.0 E-04	E						
Cyclone/venturi/impingement	4.5 E+00	9.0 E-03	E						
Electrostatic precipitator	2.0 E+00	4.0 E-03	E	6.9 E+00	1.4 E-02	E			
Fabric filter	1.4 E-02	2.8 E-05	E	2.0 E-01		E			
Impingement	4.1 E+00	8.2 E-03	E						
Venturi	6.0 E-02	1.2 E-04	E	9.6 E-01	1.9 E-03	E			
Venturi/impingement/afterburner	9.0 E-01	1.8 E-03	E						
Venturi/impingement	9.0 E-01	1.8 E-03	A	1.2 E+01	2.4 E-02	D	7.3 E+00	1.4 E-02	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP	3.0 E-03	6.0 E-06	E						

Table 2.2-5 (cont.).

Source Category[b]	Manganese[c]			Magnesium			Mercury[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	9.4 E+00	1.9 E-02	C	1.4 E+02	2.8 E-01	C			
Controlled									
Cyclone	3.3 E-01	6.6 E-04	E	1.4 E+00	2.8 E-03	E	2.3 E+00	4.6E-03	E
Cyclone/impingement									
Cyclone/venturi							1.6 E+00	3.2E-03	E
Cyclone/venturi/impingement									
Electrostatic precipitator	3.2 E-01	6.4 E-04	E	8.8 E+00	1.8 E-02	E			
Fabric filter	5.0 E-03	1.0 E-05	E	3.0 E-02	6.0 E-05	E			
Impingement							9.7 E-01	1.9E-03	E
Venturi									
Venturi/impingement/afterburner									
Venturi/impingement	8.5 E-01	1.7 E-03	D	4.2 E+00	8.4 E-03	D	5.0 E-03	1.0E-05	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-5 (cont.).

Source Category^b	Copper			Gold			Iron		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	4.0 E+01	8.0 E-02	B	3.0 E-02	6.0 E-05	E	5.6 E+02	1.1 E+00	C
Controlled									
Cyclone	2.7 E+00	5.4 E-03	E				1.7 E+00	3.4 E-03	E
Cyclone/impingement									
Cyclone/venturi	1.0 E+00	2.0 E-03	E						
Cyclone/venturi/impingement									
Electrostatic precipitator	2.0 E-01	4.0 E-04	E	9.0 E-03	1.8 E-05	E	2.5 E+01	5.0 E-02	E
Fabric filter	2.0 E-03	4.0 E-06	E	2.0 E-03	4.0 E-06	E	2.3 E-01	4.6 E-04	E
Impingement									
Venturi	4.0 E-01	8.0 E-04	E						
Venturi/impingement/afterburner	5.8 E+00	1.2 E-02	E						
Venturi/impingement	5.5 E+00	1.1 E-02	D	1.0 E-02	2.0 E-05	E	4.8 E+01	9.6 E-02	D
Venturi/impingement/Wet ESP									
Venturi/Wet ESP	1.0 E-02	2.0 E-05	E						

Table 2.2-5 (cont.).

Source Category[b]	Calcium			Chromium[c]			Cobalt[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	7.0 E+02	1.4 E+00	C	1.4 E+01	2.9 E-02	B	9.0 E-01	1.8 E-03	C
Controlled									
Cyclone	1.2 E+00	2.4 E-03	E	1.9 E+00	3.8 E-03	D	2.0 E-01	4.0 E-04	E
Cyclone/impingement				4.0 E-02	8.0 E-05	E			
Cyclone/venturi				5.0 E-01	1.0 E-03	E			
Cyclone/venturi/impingement				1.1 E+01	2.7 E-02	E			
Electrostatic precipitator	3.5 E+02	7.0 E-01	E	1.4 E+00	2.8 E-03	E	3.8 E-01	7.6 E-04	E
Fabric filter	8.0 E-02	1.6 E-04	E	4.0 E-02	8.0 E-05	E	6.0 E-03	1.2 E-05	E
Impingement				9.8 E+00	1.9 E-02	E			
Venturi				5.0 E-01	1.0 E-03	E			
Venturi/impingement/afterburner				4.9 E+00	9.8 E-03	E			
Venturi/impingement	2.6 E+02	5.2 E-01	D	2.1 E+00	4.2 E-03	E	4.5 E-01	9.0 E-04	D
Venturi/impingement/Wet ESP				1.1 E-01	2.2 E-04	E			
Venturi/Wet ESP				1.0 E-02	2.0 E-05	E			

Table 2.2-5. (cont.).

Source Category[b]	Barium			Beryllium[c]			Cadmium[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	1.5 E+01	3.0 E-02	D	1.5 E-01	3.0 E-04	E	1.6 E+01	3.7 E-02	B
Controlled									
Cyclone	1.0 E-01	2.0 E-04	E	9.0 E-03	1.8 E-05	D	1.7 E+01	3.4 E-02	D
Cyclone/impingement									
Cyclone/venturi							1.3 E+01	2.6 E-02	C
Cyclone/venturi/impingement							8.1 E+00	1.6 E-02	E
Electrostatic precipitator	7.4 E+00	1.5 E-02	E				1.7 E-01	3.4 E-04	E
Fabric filter	4.0 E-03	8.0 E-06	E				1.0 E-02	2.0 E-05	E
Impingement							1.2 E+00	2.4 E-03	E
Venturi							1.1 E-01	2.2 E-04	E
Venturi/impingement/ afterburner							3.0 E+00	6.0 E-03	E
Venturi/impingement	3.2 E+00	6.4 E-03	D	5.0 E-03	1.0 E-05	E	3.3 E+00	6.6 E-03	E
Venturi/impingement/ Wet ESP							1.0 E-01	2.0 E-04	E
Venturi/Wet ESP							4.0 E-02	8.0 E-05	E

Table 2.2-5 (Metric And English Units). SUMMARY OF METAL EMISSIONS FROM MULTIPLE HEARTH SEWAGE SLUDGE INCINERATORS[a]

	Aluminum			Antimony[c]			Arsenic[c]		
Source Category[b]	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	2.4 E+02	4.8E-01	D	1.5 E+00	3.0 E-03	E	4.7 E+00	9.4 E-03	B
Controlled									
Cyclone	3.0 E-01	6.0E-04	E	3.2 E-01	6.4 E-04	E			
Cyclone/impingement									
Cyclone/venturi							1.0 E-01	2.0 E-04	E
Cyclone/venturi/impingement							8.5 E-01	1.7 E-03	E
Electrostatic precipitator	3.8 E+02	7.6 E-02	E	4.0 E-02	8.0 E-05	E	1.2 E+00	2.4 E-03	E
Fabric filter	6.8 E-01		E	4.0 E-03	8.0 E-06	E	3.0 E-03	6.0 E-06	E
Impingement									
Venturi							5.0 E-02	1.0 E-04	E
Venturi/impingement/ afterburner							4.0 E-02	8.0 E-05	E
Venturi/impingement	9.2 E+01	1.8E-01	E	2.4 E-01	4.8 E-04	E	6.1 E-01	1.2 E-03	B
Venturi/impingement/ Wet ESP									
Venturi/Wet ESP							6.0 E-01	1.2 E-03	E

Table 2.2-4. (cont.).

Source Category[b]	Vinyl Chloride[c]			Xylene, m,p[c]			Xylene (total)[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	6.6 E+00	1.3 E-02	E				9.5 E-01	1.9 E-03	E
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi	1.0 E+00	2.0 E-03	E						
Cyclone/venturi/impingement									
Electrostatic precipitator	8.0 E-01	1.6 E-03	E						
Fabric filter									
Impingement									
Venturi				2.0 E+00	4.0 E-03	E			
Venturi/impingement/ afterburner									
Venturi/impingement	3.7 E+00	7.4 E-03	D						
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-15. Blanks indicate no data.
[b] Wet ESP = wet electrostatic precipitator.
[c] Hazardous air pollutants in the *Clean Air Act*.

Table 2.2-4 (cont.).

Source Category[b]	Toluene[c] g/Mg	Toluene[c] lb/ton	Toluene[c] EMISSION FACTOR RATING	Trans-1,2-Dichloroethene[c] g/Mg	Trans-1,2-Dichloroethene[c] lb/ton	Trans-1,2-Dichloroethene[c] EMISSION FACTOR RATING	Trichloroethene[c] g/Mg	Trichloroethene[c] lb/ton	Trichloroethene[c] EMISSION FACTOR RATING
Uncontrolled	7.8 E+00	1.5 E-02	D	9.0 E-02	1.8 E-04	E	4.0 E-01	8.0 E-04	E
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi	3.3 E+00	6.6 E-03	E						
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi	1.6 E+01	3.0 E-02	E						
Venturi/impingement/ afterburner	6.6 E-01	1.3 E-03	E	4.0 E-02	8.0 E-05	D			
Venturi/impingement	6.5 E+00	1.3 E-02	D	5.0 E-02	1.0 E-04	E	4.5 E-01	9.0 E-04	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	Perchloroethylene[c]			Phenol[c]			Tetrachloroethane[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	4.0 E-01	8.0 E-04	E	2.2 E+01	4.4 E-02	E			
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi	3.0 E-01	6.0 E-04	E						
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi	2.0 E-01	4.0 E-04	E				1.2 E+01	2.4 E-02	E
Venturi/impingement/ afterburner									
Venturi/impingement				1.8 E+00	3.6 E-03	E			
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	Methyl Isobutyl Ketone[c]			Methylene Chloride[c]			Naphthalene[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled				4.0 E-01	8.0 E-04	D	9.2 E+00	1.8 E-02	E
Controlled									
Cyclone									
Cyclone/impingement	1.0 E-02	2.0 E-05	E						
Cyclone/venturi				3.0 E-01	6.0 E-04	E	9.7 E-01	1.9 E-03	D
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi									
Venturi/impingement/ afterburner				4.0 E-01	8.0 E-04	E			
Venturi/impingement				9.0 E-01	1.8 E-03	D			
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	Ethylbenzene[c]			Formaldehyde[c]			Methyl Ethyl Ketone[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	8.0 E-01	1.6 E-03	E				6.1 E+00	1.2 E-02	E
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi	3.0 E-03	6.0 E-06	E	1.3 E+00	2.6 E-03	E			
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi	6.0 E+00	1.2 E-02	E	4.0 E-01	8.0 E-04	E	6.1 E+00	1.2 E-02	E
Venturi/impingement/ afterburner	2.0 E-02	4.0 E-05	E				5.0 E-02	1.0 E-04	E
Venturi/impingement	1.0 E+00	2.0 E-03	D				8.9 E+00	1.8 E-02	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	Chlorobenzene[c]			Chloroform[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	7.5 E-01	1.5 E-03	E	3.0 E-02	6.0 E-05	E
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi	6.0 E-03	1.2 E-05	E	2.0 E-02	4.0 E-05	E
Cyclone/venturi/impingement						
Electrostatic precipitator						
Fabric filter						
Impingement						
Venturi	4.2 E+00	8.4 E-03	E	3.3 E+00	6.6 E-03	E
Venturi/impingement/afterburner	2.6 E-01	5.2 E-04	E	4.9 E-01	9.8 E-04	E
Venturi/impingement	6.0 E-01	1.2 E-03	E	1.3 E+00	2.6 E-03	D
Venturi/impingement/Wet ESP						
Venturi/Wet ESP						

Table 2.2-4. (cont.).

Source Category[b]	Bis(2-ethylhexyl)phthalate[c]			Bromodichloromethane			Carbon Tetrachloride[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	9.3 E-01	1.9 E-03	E	4.0 E-03	8.0 E-06	E	1.0 E-02	2.0 E-05	E
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi	4.0 E-02	8.0 E-05	E				7.0 E-03	1.4 E-05	E
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi				1.5 E+00	3.0 E-03	E			
Venturi/impingement/ afterburner							1.0 E-03	2.0 E-06	E
Venturi/impingement	3.2 E-01	6.4 E-04	E				3.0 E-02	6.0 E-05	D
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	Acetonitrile[c]			Acrylonitrile[c]			Benzene[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	2.5 E+01	5.0 E-02	E	2.5 E+01	5.0 E-02	E	5.8 E+00	1.2 E-02	D
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi				1.5 E-01	3.0 E-04	E	3.5 E-01	7.0 E-04	E
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi							1.4 E+01	2.8 E-02	E
Venturi/impingement/ afterburner	7.4 E-01	1.5 E-03	E	4.9 E-01	9.8 E-04	E	1.7 E-01	3.4 E-04	E
Venturi/impingement	9.7 E+00	2.0 E-02	E	1.7 E+01	3.4 E-02	E	6.3 E+00	1.3 E-02	D
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	2-Nitrophenol			Acetaldehyde[c]			Acetone		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	6.0 E+00	1.2 E-02	E						
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi	3.8 E-01	7.6 E-04	E						
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement				1.6 E-01	3.2 E-04	E			
Venturi							3.2 E+00	6.4 E-03	E
Venturi/impingement/afterburner									
Venturi/impingement	1.2 E+00	2.4 E-03	E						
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (cont.).

Source Category[b]	1,2-Dichlorobenzene g/Mg	1,2-Dichlorobenzene lb/ton	1,2-Dichlorobenzene EMISSION FACTOR RATING	1,3-Dichlorobenzene g/Mg	1,3-Dichlorobenzene lb/ton	1,3-Dichlorobenzene EMISSION FACTOR RATING	1,4-Dichlorobenzene[c] g/Mg	1,4-Dichlorobenzene[c] lb/ton	1,4-Dichlorobenzene[c] EMISSION FACTOR RATING
Uncontrolled	3.7 E-01	7.4 E-04	E				4.1 E-01	8.2 E-04	E
Controlled									
Cyclone									
Cyclone/impingement									
Cyclone/venturi				5.0 E-02	1.0 E-04	E	7.0 E-03	1.4 E-05	E
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi									
Venturi/impingement/ afterburner									
Venturi/impingement	1.9 E-01	3.8 E-04	E	2.0 E-02	4.0 E-05	E	2.4 E-01	4.8 E-04	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-4 (Metric And English Units). SUMMARY OF ORGANIC COMPOUND EMISSIONS FROM MULTIPLE HEARTH SEWAGE SLUDGE INCINERATORS[a]

Source Category[b]	1,1,1-Trichloroethane[c]			1,1-Dichloroethane[c]			1,2-Dichloroethane[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING	g/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	6.0 E-02	1.2 E-04	D						
Controlled									
Cyclone									
Cyclone/impingement	1.9 E+00	3.8 E-03	E	2.3 E-01	4.6 E-04	E			
Cyclone/venturi	7.0 E-02	1.4 E-04	E				4.0 E-03	8.0 E-06	E
Cyclone/venturi/impingement									
Electrostatic precipitator									
Fabric filter									
Impingement									
Venturi									
Venturi/impingement/afterburner	1.4 E+00	2.8 E-03	E				3.0 E-02	6.0 E-05	E
Venturi/impingement	6.1 E-01	1.2 E-03	D				1.0 E-02	2.0 E-05	E
Venturi/impingement/Wet ESP									
Venturi/Wet ESP									

Table 2.2-3 (cont.).

Source Category[b]	Total Tetra- through Octa- CDD		Total Tetra- through Octa- CDF	
	µg/Mg	lb/ton	µg/Mg	lb/ton
Uncontrolled	8.5 E+02	1.7 E-06	3.8 E+03	7.6 E-06
Controlled				
Cyclone				
Cyclone/impingement				
Cyclone/venturi	5.6 E+00	1.1 E-08	6.6 E+01	1.3 E-07
Cyclone/venturi/impingement	1.1 E+02	2.2 E-07	2.5 E+02	5.0 E-07
Electrostatic precipitator				
Fabric filter				
Impingement	1.8 E+02	3.6 E-07	1.5 E+03	3.0 E-06
Venturi				
Venturi/impingement/afterburner	3.1 E+02	6.2 E-07	4.6 E+02	9.2 E-07
Venturi/impingement	2.7 E+02	5.4 E-07	9.3 E+02	1.9 E-06
Venturi/impingement/Wet ESP				
Venturi/Wet ESP				

[a] Units are pollutant emitted of dry sludge burned. Source Classification Code 5-01-005-15. Blanks indicate no data.

[b] Wet ESP = wet electrostatic precipitator.

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-3 (cont.).

Source Category[b]	Total HxCDF[c]		Total HpCDF[c]		Total OCDF[c]	
	μg/Mg	lb/ton	μg/Mg	lb/ton	μg/Mg	lb/ton
Uncontrolled	9.9 E+01	2.0 E-07	4.8 E+02	9.6 E-07	4.9 E+02	9.8 E-07
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi	3.4 E+00	6.8 E-09	9.0 E-01	1.8 E-09	7.0 E-01	1.4 E-09
Cyclone/venturi/impingement	1.8 E+00	3.6 E-09	2.9 E+00	5.8 E-09	1.8 E+00	3.6 E-09
Electrostatic precipitator						
Fabric filter						
Impingement	1.1 E+02	2.2 E-07	2.0 E+02	4.0 E-07	1.5 E+02	3.0 E-07
Venturi						
Venturi/impingement/afterburner	7.8 E+01	1.5 E-07	4.8 E+01	9.6 E-08	7.7 E+00	1.5 E-08
Venturi/impingement	5.7 E+01	1.1 E-07	4.1 E+01	8.2 E-08	6.3 E+00	1.3 E-08
Venturi/impingement/Wet ESP						
Venturi/Wet ESP						

Table 2.2-3 (cont.).

Source Category[b]	2,3,7,8-TCDF[c]		Total TCDF[c]		Total PCDF[c]	
	μg/Mg	lb/ton	μg/Mg	lb/ton	μg/Mg	lb/ton
Uncontrolled	6.2 E+02	1.2 E-06	1.7 E+03	3.4 E-06	9.8 E+02	2.0 E-06
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi	5.6 E+00	1.1 E-08	5.0 E+01	1.0 E-07	1.1 E+01	2.2 E-08
Cyclone/venturi/impingement			1.8 E+02	3.8 E-07	5.7 E+01	1.1 E-07
Electrostatic precipitator						
Fabric filter						
Impingement	1.8 E+02	3.6 E-07	7.0 E+02	1.4 E-06	3.6 E+02	7.2 E-07
Venturi						
Venturi/impingement/afterburner	5.4 E+01	1.1 E-07	3.5 E+02	7.0 E-07	1.3 E+02	2.6 E-07
Venturi/impingement	4.6 E+01	9.2 E-08	6.0 E+02	1.2 E-06	1.3 E+00	2.6 E-09
Venturi/impingement/Wet ESP						
Venturi/Wet ESP						

Table 2.2-3 (cont.).

Source Category[b]	Total HxCDD		Total HpCDD		Total OCDD	
	µg/Mg	lb/ton	µg/Mg	lb/ton	µg/Mg	lb/ton
Uncontrolled	6.8 E+01	1.4 E-07	3.4 E+02	6.8 E-07	3.7 E+02	7.4 E-07
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi			8.0 E-01	1.6 E-09	3.4 E+00	6.8 E-09
Cyclone/venturi/impingement	4.4 E+00	8.8 E-09	1.4 E+01	2.8 E-08	3.1 E+01	6.7 E-08
Electrostatic precipitator						
Fabric filter						
Impingement	2.4 E+01	4.8 E-08	7.3 E+01	1.5 E-07	5.3 E+01	1.1 E-07
Venturi						
Venturi/impingement/afterburner	6.0 E+01	1.2 E-07	2.3 E+01	4.6 E-08	1.2 E+01	2.4 E-08
Venturi/impingement	3.8 E+01	7.6 E-08	1.5 E+01	3.0 E-08	1.9 E+01	3.8 E-08
Venturi/impingement/Wet ESP						
Venturi/Wet ESP						

Table 2.2-3 (Metric And English Units). CHLORINATED DIBENZO-P-DIOXIN (CDD) AND CHLORINATED DIBENZOFURAN (CDF) EMISSION FACTORS FOR MULTIPLE HEARTH SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Source Category[b]	2,3,7,8-TCDD[c]		Total TCDD		Total PCDD	
	µg/Mg	lb/ton	µg/Mg	lb/ton	µg/Mg	lb/ton
Uncontrolled			6.3 E+01	1.3 E-07	2.7 E+00	5.4 E-09
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi			1.4 E+00	2.8 E-09		
Cyclone/venturi/impingement	3.0 E-01	6.0 E-10				
Electrostatic precipitator						
Fabric filter						
Impingement	5.0 E-01	1.0 E-09	2.8 E+01	5.6 E-08	3.7 E+00	7.4 E-09
Venturi						
Venturi/impingement/afterburner	9.0 E-01	1.8 E-09				
Venturi/impingement	2.0 E+00	4.0 E-09				
Venturi/impingement/Wet ESP						
Venturi/Wet ESP						

Table 2.2-2 (Metric And English Units). ACID GAS EMISSION FACTORS FOR MULTIPLE HEARTH SEWAGE SLUDGE INCINERATORS[a]

Source Category[b]	Sulfuric Acid (H_2SO_4)			Hydrogen Chloride (HCl)[c]		
	g/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	6.0 E-01	1.2 E+00	D			
Controlled						
Cyclone	3.3 E-01	6.6 E-01	E			
Cyclone/impingement				1.0 E-02	2.0 E-02	E
Cyclone/venturi				1.0 E-02	2.0 E-02	E
Cyclone/venturi/impingement						
Electrostatic precipitator						
Fabric filter						
Impingement	5.0 E-02	1.0 E-01	E	1.0 E-02	2.0 E-02	E
Venturi				1.0 E-02	2.0 E-02	E
Venturi/impingement/afterburner						
Venturi/impingement	2.0 E-01	4.0 E-01	E			
Venturi/impingement/Wet ESP						
Venturi/Wet ESP						

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-15. Blanks indicate no data.

[b] Wet ESP = wet electrostatic precipitator.

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-1 (cont.).

Source Category	Carbon Monoxide (CO)[c]			Lead[d]			Methane			Total Nonmethane Organic Compounds		
	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING	kg/Mg	lb/ton	EMISSION FACTOR RATING
Uncontrolled	1.55 E+01	3.1 E+01	C	5.0 E-02	1.0 E-01	B				8.4 E-01	1.7 E+00	D
Controlled												
Cyclone				3.0 E-02	6.0 E-02	E				1.5 E+00	3.0 E+00	E
Cyclone/impingement												
Cyclone/venturi				3.0 E-03	6.0 E-03	E				2.2 E-01	4.4 E-01	E
Cyclone/venturi/ impingement				1.1 E-02	2.2 E-02	E						
Electrostatic precipitator				1.0 E-03	2.0 E-03	E						
Fabric filter												
Impingement				2.0 E-02	4.0 E-02	E	3.9 E-01	7.8 E-01	E	7.8 E-01	1.6 E+00	E
Venturi				9.0 E-04	1.8 E-03	E	3.2 E+00	6.4 E+00	E			
Venturi/impingement/ afterburner				5.0 E-02	1.0 E-01	E						
Venturi/impingement				3.0 E-02	6.0 E-02	B						
Venturi/impingement/ Wet ESP												
Venturi/Wet ESP				9.0 E-05	1.8 E-04	E						

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-15. Blanks indicate no data.

[b] Wet ESP = wet electrostatic precipitator.

[c] Uncontrolled emission factors for NO_x and CO apply to all air pollution control device types.

[d] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.2-9 (Metric And English Units). SUMMARY OF EMISSION FACTORS FOR ELECTRIC INFRARED SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Source Category[b]	Particulate Matter		Sulfur Dioxide		Nitrogen Oxides	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Uncontrolled	3.7 E+00	7.4 E+00	9.2 E+00	1.8 E+01	4.3 E+00	8.6 E+00
Controlled						
Cyclone						
Cyclone/impingement						
Cyclone/venturi	1.9 E+00	3.8 E+00				
Cyclone/venturi/impingement						
Electrostatic precipitator						
Fabric filter						
Impingement	8.2 E-01	1.6 E+00				
Venturi						
Venturi/impingement/ afterburner						
Venturi/impingement	9.5 E-01	1.9 E+00	2.3 E+00	4.6 E+00	2.9 E+00	5.8 E+00
Venturi/impingement/ Wet ESP						
Venturi/Wet ESP						

[a] Units are pollutants emitted of dry sludge burned. Source Classification Code 5-01-005-17.

[b] Wet ESP = wet electrostatic precipitator.

Table 2.2-10 (Metric And English Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION FOR SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Particle Size (μm)	Cumulative Mass % Stated Size				
	Uncontrolled		Controlled (Scrubber)		
	MH[b]	EI[c]	MH	FB[d]	EI
15	15	43	30	7.7	60
10	10	30	27	7.3	50
5.0	5.3	17	25	6.7	35
2.5	2.8	10	22	6.0	25
1.0	1.2	6.0	20	5.0	18
0.625	0.75	5.0	17	2.7	15

[a] Reference 5.

[b] MH = multiple hearth incinerator. Source Classification Code (SCC) 5-01-005-15.

[c] EI = electric infrared incinerator. SCC 5-01-005-17.

[d] FB = fluidized bed incinerator. SCC 5-01-005-16.

Table 2.2-11 (Metric And English Units). CUMULATIVE PARTICLE SIZE-SPECIFIC EMISSION FACTORS FOR SEWAGE SLUDGE INCINERATORS[a]

EMISSION FACTOR RATING: E

Particle Size (µm)	Cumulative Emission Factor									
	Uncontrolled				Controlled (Scrubber)					
	MH[b]		EI[c]		MH		FB[d]		EI	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
15	6.0 E+00	1.2 E+01	4.3 E+00	8.6 E+00	1.2 E-01	2.4 E-01	2.3 E-01	4.6 E-01	1.2 E+00	2.4 E+00
10	4.1 E+00	8.2 E+00	3.0 E+00	6.0 E+00	1.1 E-01	2.2 E-01	2.2 E-01	4.4 E-01	1.0 E+00	2.0 E+00
5.0	2.1 E+00	4.2 E+00	1.7 E+00	3.4 E+00	1.0 E-01	2.0 E-01	2.0 E-01	4.0 E-01	7.0 E-01	1.4 E+00
2.5	1.1 E+00	2.2 E+00	1.0 E+00	2.0 E+00	9.0 E-02	1.8 E-01	1.8 E-01	3.6 E-01	5.0 E-01	1.0 E+00
1.0	4.7 E-01	9.4 E-01	6.0 E-01	1.2 E+00	8.0 E-02	1.6 E-01	1.5 E-01	3.0 E-01	3.5 E-01	7.0 E-01
0.625	3.0 E-01	6.0 E-01	5.0 E-01	1.0 E+00	7.0 E-02	1.4 E-01	8.0 E-02	1.6 E-01	3.0 E-01	6.0 E-01

[a] Reference 5.

[b] MH = multiple hearth incinerator. Source Classification Code (SCC) 5-01-005-15.

[c] EI = electric infrared incinerator. SCC 5-01-005-17.

[d] FB = fluidized bed incinerator. SCC 5-01-005-16.

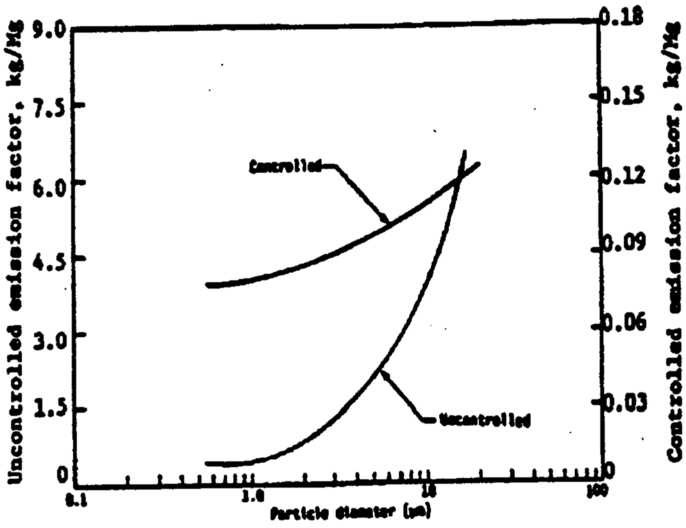

Figure 2.2-4. Cumulative Particle Size Distribution and Size-Specific Emission Factors for Multiple-Health Incinerators

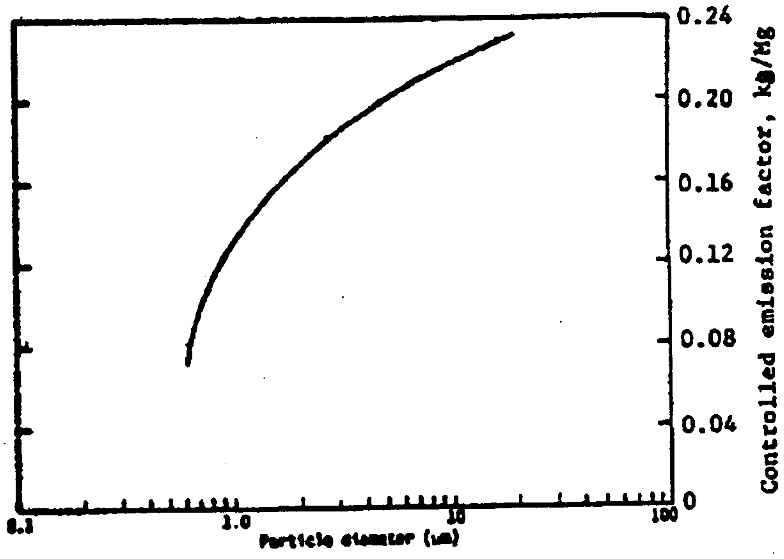

Figure 2.2-5. Cumulative Particle Size Distribution and Size-Specific Emission Factors for Fluidized-Bed Incinerators

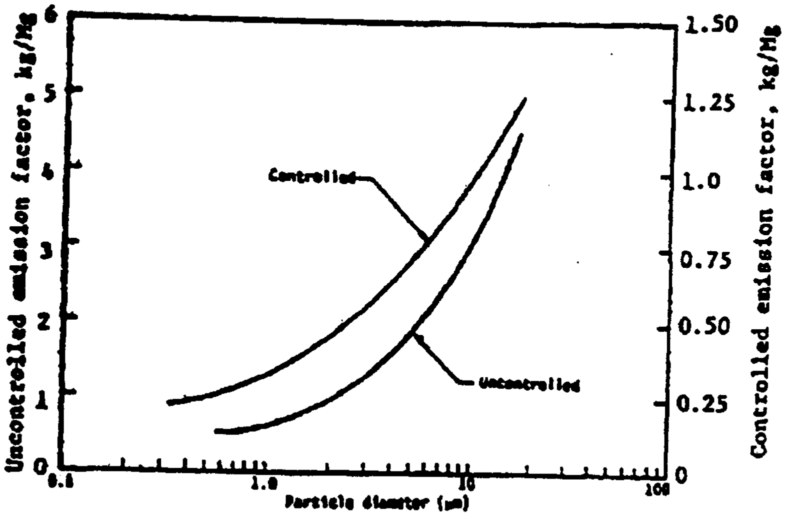

Figure 2.2-6. Cumulative Particle Size Distribution and Size-Specific Emission Factors for Electric (infrared) Incinerators

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2.3 Medical Waste Incineration

Medical waste incineration involves the burning of wastes produced by hospitals, veterinary facilities, and medical research facilities. These wastes include both infectious ("red bag") medical wastes as well as non-infectious, general housekeeping wastes. The emission factors presented here represent emissions when both types of these wastes are combusted rather than just infectious wastes.

Three main types of incinerators are used: controlled air, excess air, and rotary kiln. Of the incinerators identified in this study, the majority (>95 percent) are controlled air units. A small percentage (<2 percent) are excess air. Less than 1 percent were identified as rotary kiln. The rotary kiln units tend to be larger, and typically are equipped with air pollution control devices. Approximately 2 percent of the total population identified in this study were found to be equipped with air pollution control devices.

2.3.1 Process Description[1-6]

Types of incineration described in this section include:

- Controlled air,

- Excess air, and

- Rotary kiln.

2.3.1.1 Controlled-Air Incinerators -

Controlled-air incineration is the most widely used medical waste incinerator (MWI) technology, and now dominates the market for new systems at hospitals and similar medical facilities. This technology is also known as starved-air incineration, two-stage incineration, or modular combustion. Figure 2.3-1 presents a typical schematic diagram of a controlled air unit.

Combustion of waste in controlled air incinerators occurs in two stages. In the first stage, waste is fed into the primary, or lower, combustion chamber, which is operated with less than the stoichiometric amount of air required for combustion. Combustion air enters the primary chamber from beneath the incinerator hearth (below the burning bed of waste). This air is called primary or underfire air. In the primary (starved-air) chamber, the low air-to-fuel ratio dries and facilitates volatilization of the waste, and most of the residual carbon in the ash burns. At these conditions, combustion gas temperatures are relatively low (760 to 980°C [1,400 to 1,800°F]).

In the second stage, excess air is added to the volatile gases formed in the primary chamber to complete combustion. Secondary chamber temperatures are higher than primary chamber temperatures--typically 980 to 1,095°C (1,800 to 2,000°F). Depending on the heating value and moisture content of the waste, additional heat may be needed. This can be provided by auxiliary burners located at the entrance to the secondary (upper) chamber to maintain desired temperatures.

Waste feed capacities for controlled air incinerators range from about 0.6 to 50 kg/min (75 to 6,500 lb/hr) (at an assumed fuel heating value of 19,700 kJ/kg [8,500 Btu/lb]). Waste feed and ash removal can be manual or automatic, depending on the unit size and options purchased. Throughput capacities for lower heating value wastes may be higher, since feed capacities are limited by primary

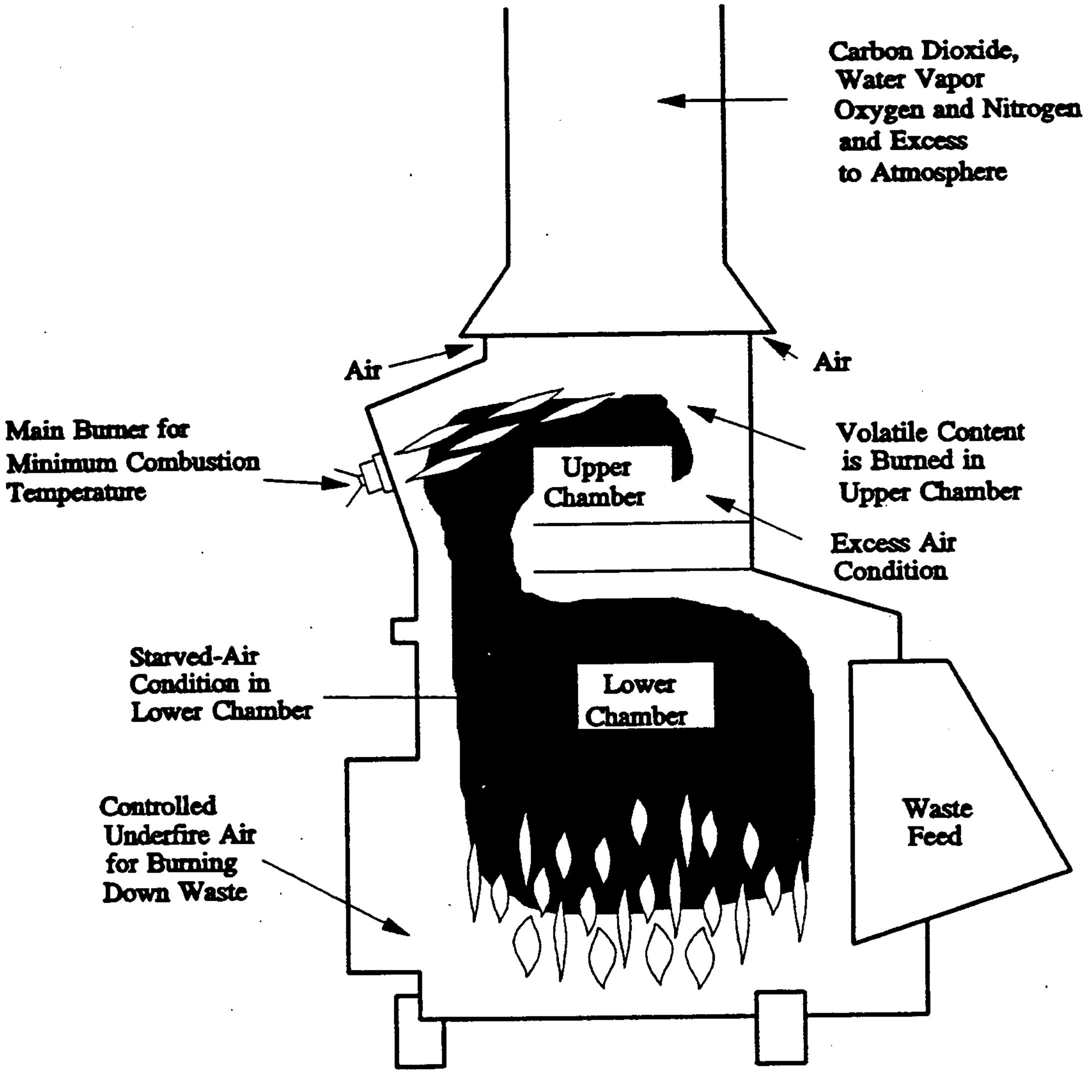

Figure 2.3-1. Controlled Air Incinerator

chamber heat release rates. Heat release rates for controlled air incinerators typically range from about 430,000 to 710,000 kJ/hr-m^3 (15,000 to 25,000 Btu/hr-ft^3).

Because of the low air addition rates in the primary chamber, and corresponding low flue gas velocities (and turbulence), the amount of solids entrained in the gases leaving the primary chamber is low. Therefore, the majority of controlled air incinerators do not have add-on gas cleaning devices.

2.3.1.2 Excess Air Incinerators -

Excess air incinerators are typically small modular units. They are also referred to as batch incinerators, multiple chamber incinerators, or "retort" incinerators. Excess air incinerators are typically a compact cube with a series of internal chambers and baffles. Although they can be operated continuously, they are usually operated in a batch mode.

Figure 2.3-2 presents a schematic for an excess air unit. Typically, waste is manually fed into the combustion chamber. The charging door is then closed, and an afterburner is ignited to bring the secondary chamber to a target temperature (typically 870 to 980°C [1600 to 1800°F]). When the target temperature is reached, the primary chamber burner ignites. The waste is dried, ignited, and combusted by heat provided by the primary chamber burner, as well as by radiant heat from the chamber walls. Moisture and volatile components in the waste are vaporized, and pass (along with combustion gases) out of the primary chamber and through a flame port which connects the primary chamber to the secondary or mixing chamber. Secondary air is added through the flame port and is mixed with the volatile components in the secondary chamber. Burners are also installed in the secondary chamber to maintain adequate temperatures for combustion of volatile gases. Gases exiting the secondary chamber are directed to the incinerator stack or to an air pollution control device. When the waste is consumed, the primary burner shuts off. Typically, the afterburner shuts off after a set time. Once the chamber cools, ash is manually removed from the primary chamber floor and a new charge of waste can be added.

Incinerators designed to burn general hospital waste operate at excess air levels of up to 300 percent. If only pathological wastes are combusted, excess air levels near 100 percent are more common. The lower excess air helps maintain higher chamber temperature when burning high-moisture waste. Waste feed capacities for excess air incinerators are usually 3.8 kg/min (500 lb/hr) or less.

2.3.1.3 Rotary Kiln Incinerators -

Rotary kiln incinerators, like the other types, are designed with a primary chamber, where the waste is heated and volatilized, and a secondary chamber, where combustion of the volatile fraction is completed. The primary chamber consists of a slightly inclined, rotating kiln in which waste materials migrate from the feed end to the ash discharge end. The waste throughput rate is controlled by adjusting the rate of kiln rotation and the angle of inclination. Combustion air enters the primary chamber through a port. An auxiliary burner is generally used to start combustion and maintain desired combustion temperatures. Both the primary and secondary chambers are usually lined with acid-resistant refractory brick, as shown in the schematic drawing, Figure 2.3-3.

Volatiles and combustion gases pass from the primary chamber to the secondary chamber. The secondary chamber operates at excess air. Combustion of the volatiles is completed in the secondary chamber. Due to the turbulent motion of the waste in the primary chamber, solids burnout rates and particulate entrainment in the flue gas are higher for rotary kiln incinerators than for other incinerator designs. As a result, rotary kiln incinerators generally have add-on gas cleaning devices.

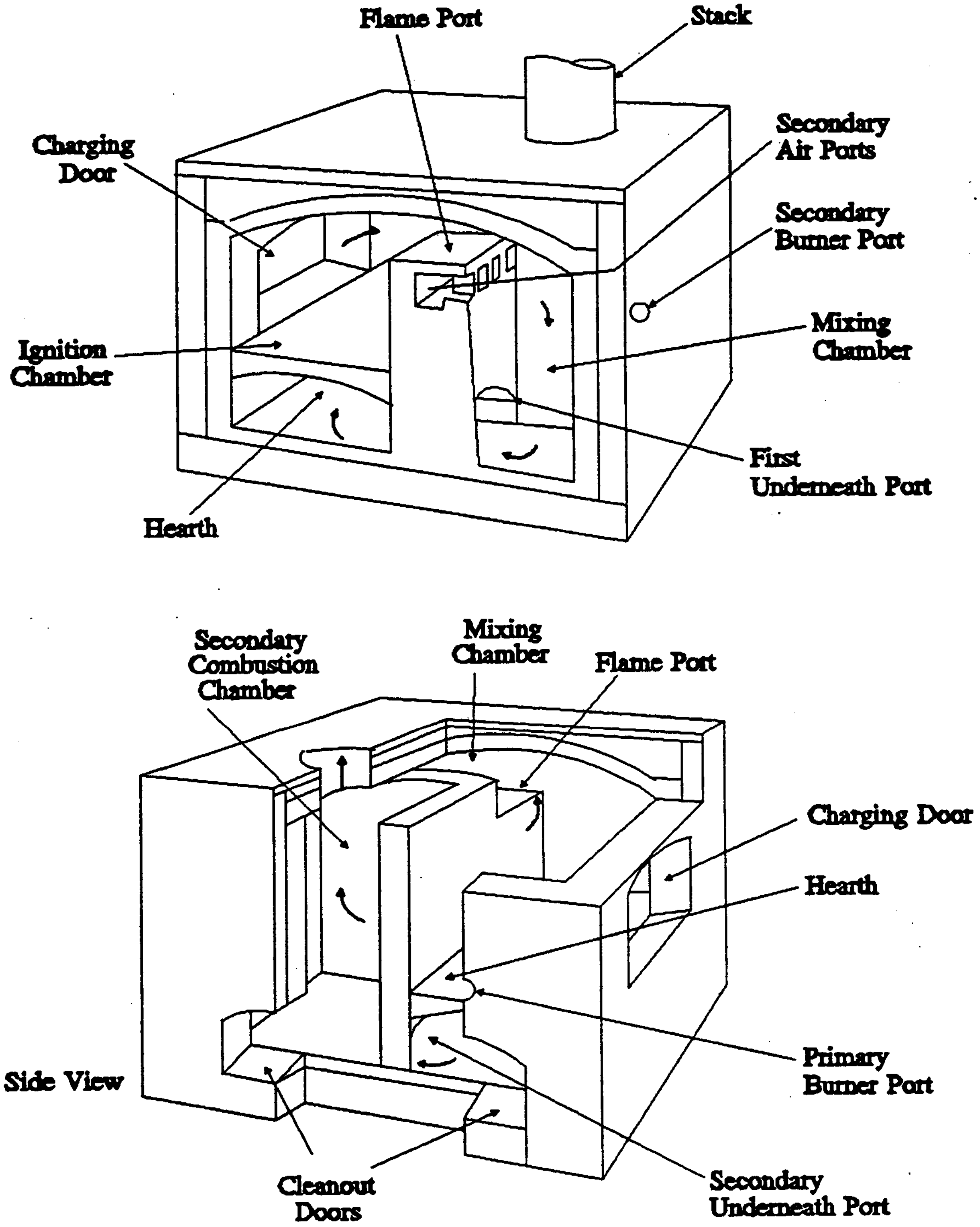

Figure 2.3-2. Excess Air Incinerator

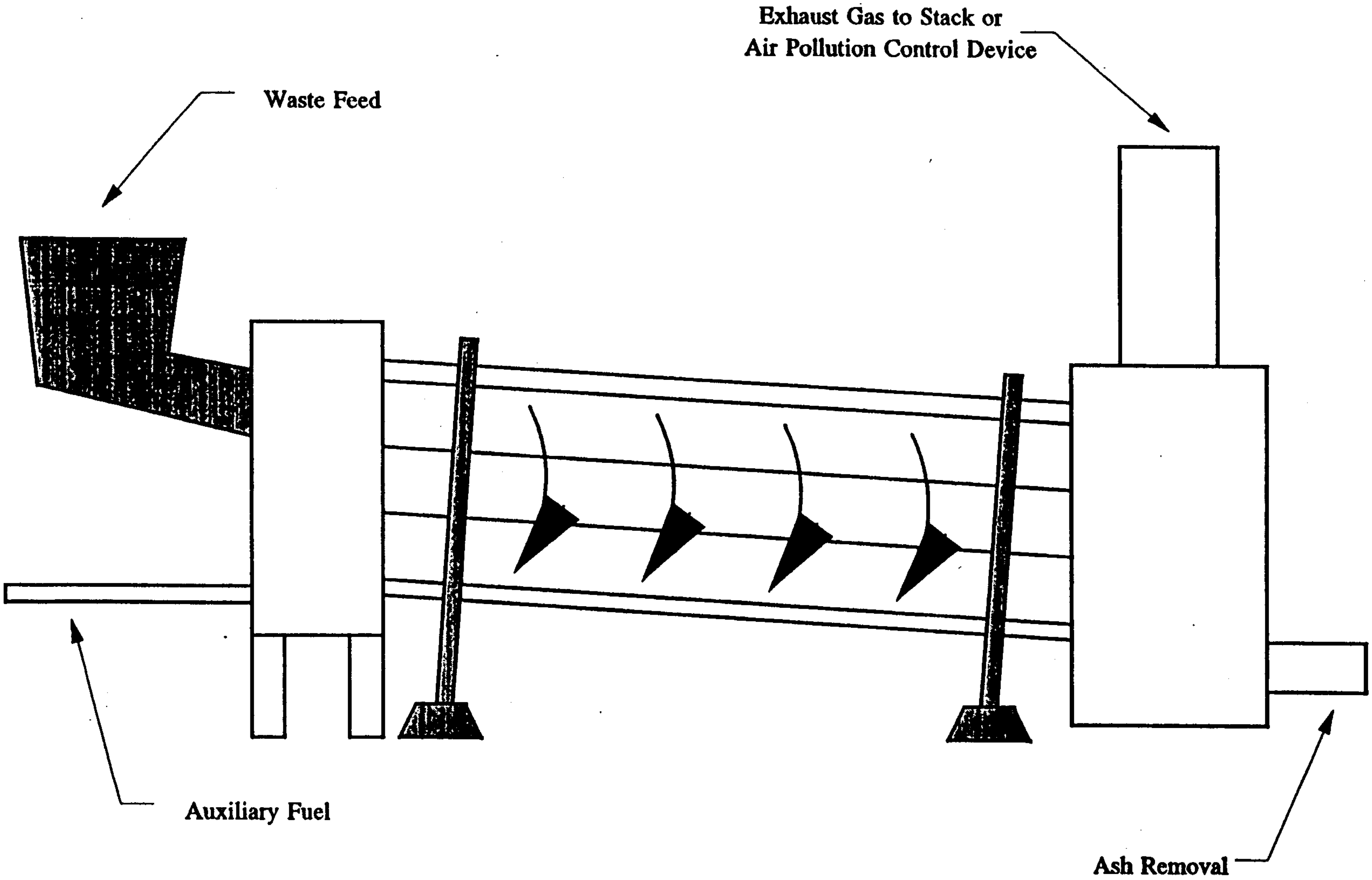

Figure 2.3-3. Rotary Kiln Incinerator

2.3.2 Emissions And Controls[2,4,7-43]

Medical waste incinerators can emit significant quantities of pollutants to the atmosphere. These pollutants include: (1) particulate matter (PM), (2) metals, (3) acid gases, (4) oxides of nitrogen (NO_x), (5) carbon monoxide (CO), (6) organics, and (7) various other materials present in medical wastes, such as pathogens, cytotoxins, and radioactive diagnostic materials.

Particulate matter is emitted as a result of incomplete combustion of organics (i. e., soot) and by the entrainment of noncombustible ash due to the turbulent movement of combustion gases. Particulate matter may exit as a solid or an aerosol, and may contain heavy metals, acids, and/or trace organics.

Uncontrolled particulate emission rates vary widely, depending on the type of incinerator, composition of the waste, and the operating practices employed. Entrainment of PM in the incinerator exhaust is primarily a function of the gas velocity within the combustion chamber containing the solid waste. Controlled air incinerators have the lowest turbulence and, consequently, the lowest PM emissions; rotary kiln incinerators have highly turbulent combustion, and thus have the highest PM emissions.

The type and amount of trace metals in the flue gas are directly related to the metals contained in the waste. Metal emissions are affected by the level of PM control and the flue gas temperature. Most metals (except mercury) exhibit fine-particle enrichment and are removed by maximizing small particle collection. Mercury, due to its high vapor pressure, does not show significant particle enrichment, and removal is not a function of small particle collection in gas streams at temperatures greater than 150°C (300°F).

Acid gas concentrations of hydrogen chloride (HCl) and sulfur dioxide (SO_2) in MWI flue gases are directly related to the chlorine and sulfur content of the waste. Most of the chlorine, which is chemically bound within the waste in the form of polyvinyl chloride (PVC) and other chlorinated compounds, will be converted to HCl. Sulfur is also chemically bound within the materials making up medical waste and is oxidized during combustion to form SO_2.

Oxides of nitrogen (NO_x) represent a mixture of mainly nitric oxide (NO) and nitrogen dioxide (NO_2). They are formed during combustion by: (1) oxidation of nitrogen chemically bound in the waste, and (2) reaction between molecular nitrogen and oxygen in the combustion air. The formation of NO_x is dependent on the quantity of fuel-bound nitrogen compounds, flame temperature, and air/fuel ratio.

Carbon monoxide is a product of incomplete combustion. Its presence can be related to insufficient oxygen, combustion (residence) time, temperature, and turbulence (fuel/air mixing) in the combustion zone.

Failure to achieve complete combustion of organic materials evolved from the waste can result in emissions of a variety of organic compounds. The products of incomplete combustion (PICs) range from low molecular weight hydrocarbon (e. g., methane or ethane) to high molecular weight compounds (e. g., polychlorinated dibenzo-p-dioxins and dibenzofurans [CDD/CDF]). In general, combustion conditions required for control of CO (i. e., adequate oxygen, temperature, residence time, and turbulence) will also minimize emissions of most organics.

Emissions of CDDs/CDFs from MWIs may occur as either a vapor or as a fine particulate. Many factors are believed to be involved in the formation of CDDs/CDFs and many theories exist concerning the formation of these compounds. In brief, the best supported theories involve four mechanisms of formation.[2] The first theory states that trace quantities of CDDs/CDFs present in the refuse feed are carried over, unburned, to the exhaust. The second theory involves formation of CDDs/CDFs from chlorinated precursors with similar structures. Conversion of precursor material to CDDs/CDFs can potentially occur either in the combustor at relatively high temperatures or at lower temperatures such as are present in wet scrubbing systems. The third theory involves synthesis of CDDs/CDFs compounds from a variety of organics and a chlorine donor. The fourth mechanism involves catalyzed reactions on fly ash particles at low temperatures.

To date, most MWIs have operated without add-on air pollution control devices (APCDs). A small percentage (approximately 2 percent) of MWIs do use APCDs. The most frequently used control devices are wet scrubbers and fabric filters (FFs). Fabric filters provide mainly PM control. Other PM control technologies include venturi scrubbers and electrostatic precipitators (ESPs). In addition to wet scrubbing, dry sorbent injection (DSI) and spray dryer (SD) absorbers have also been used for acid gas control.

Wet scrubbers use gas-liquid absorption to transfer pollutants from a gas to a liquid stream. Scrubber design and the type of liquid solution used largely determine contaminant removal efficiencies. With plain water, removal efficiencies for acid gases could be as high as 70 percent for HCl and 30 percent for SO_2. Addition of an alkaline reagent to the scrubber liquor for acid neutralization has been shown to result in removal efficiencies of 93 to 96 percent.

Wet scrubbers are generally classified according to the energy required to overcome the pressure drop through the system. Low-energy scrubbers (spray towers) are primarily used for acid gas control only, and are usually circular in cross section. The liquid is sprayed down the tower through the rising gas. Acid gases are absorbed/neutralized by the scrubbing liquid. Low-energy scrubbers mainly remove particles larger than 5-10 micrometers (μm) in diameter.

Medium-energy scrubbers can be used for particulate matter and/or acid gas control. Medium energy devices rely mostly on impingement to facilitate removal of PM. This can be accomplished through a variety of configurations, such as packed columns, baffle plates, and liquid impingement scrubbers.

Venturi scrubbers are high-energy systems that are used primarily for PM control. A typical venturi scrubber consists of a converging and a diverging section connected by a throat section. A liquid (usually water) is introduced into the gas stream upstream of the throat. The flue gas impinges on the liquid stream in the converging section. As the gas passes through the throat, the shearing action atomizes the liquid into fine droplets. The gas then decelerates through the diverging section, resulting in further contact between particles and liquid droplets. The droplets are then removed from the gas stream by a cyclone, demister, or swirl vanes.

A fabric filtration system (baghouse) consists of a number of filtering elements (bags) along with a bag cleaning system contained in a main shell structure with dust hoppers. Particulate-laden gas passes through the bags so that the particles are retained on the upstream side of the fabric, thus cleaning the gas. A FF is typically divided into several compartments or sections. In a FF, both the collection efficiency and the pressure drop across the bag surface increase as the dust layer on the bag builds up. Since the system cannot continue to operate with an increasing pressure drop, the bags are cleaned periodically. The cleaning processes include reverse flow with bag collapse, pulse jet cleaning, and mechanical shaking. When reverse flow and mechanical shaking are used, the particulate matter is collected on the inside of the bag; particulate matter is collected on the outside of the bag in pulse jet systems. Generally, reverse flow FFs operate with lower gas flow per unit area of bag surface (air-to-cloth ratio) than pulse jet systems and, thus, are larger and more costly for a given gas flow-rate or application. Fabric filters can achieve very high (>99.9 percent) PM removal efficiencies. These systems are also very effective in controlling fine particulate matter, which results in good control of metals and organics entrained on fine particulate.

Particulate collection in an ESP occurs in 3 steps: (1) suspended particles are given an electrical charge; (2) the charged particles migrate to a collecting electrode of opposite polarity; and (3) the collected PM is dislodged from the collecting electrodes and collected in hoppers for disposal.

Charging of the particles is usually caused by ions produced in a high voltage corona. The electric fields and the corona necessary for particle charging are provided by converting alternating current to direct current using high voltage transformers and rectifiers. Removal of the collected particulate matter is accomplished mechanically by rapping or vibrating the collecting electrode plates. ESPs have been used in many applications due to their high reliability and efficiency in controlling total PM emissions. Except for very large and carefully designed ESPs, however, they are less efficient than FFs at control of fine particulates and metals.

Dry sorbent injection (DSI) is another method for controlling acid gases. In the DSI process, a dry alkaline material is injected into the flue gas into a dry venturi within the ducting or into the duct ahead of a particulate control device. The alkaline material reacts with and neutralizes acids in the flue gas. Fabric filters are employed downstream of DSI to: (1) control the PM generated by the incinerator, (2) capture the DSI reaction products and unreacted sorbent, and (3) increase sorbent/acid gas contact time, thus enhancing acid gas removal efficiency and sorbent utilization. Fabric filters are commonly used with DSI because they provide high sorbent/acid gas contact. Fabric filters are less sensitive to PM loading changes or combustion upsets than other PM control devices since they operate with nearly constant efficiency. A potential disadvantage of ESPs used in conjunction with DSI is that the sorbent increases the electrical resistivity of the PM being collected. This phenomenon makes the PM more difficult to charge and, therefore, to collect. High resistivity can be compensated for by flue gas conditioning or by increasing the plate area and size of the ESP.

The major factors affecting DSI performance are flue gas temperature, acid gas dew point (temperature at which the acid gases condense), and sorbent-to-acid gas ratio. DSI performance improves as the difference between flue gas and acid dew point temperatures decreases and the sorbent-to-acid gas ratio increases. Acid gas removal efficiency with DSI also depends on sorbent type and the extent of sorbent mixing with the flue gas. Sorbents that have been successfully applied include hydrated lime ($Ca[OH]_2$), sodium hydroxide ($NaOH$), and sodium bicarbonate ($NaHCO_3$). For hydrated lime, DSI can achieve 80 to 95 percent of HCl removal and 40 to 70 percent removal of SO_2 under proper operating conditions.

The primary advantage of DSI compared to wet scrubbers is the relative simplicity of the sorbent preparation, handling, and injection systems as well as the easier handling and disposal of dry solid process wastes. The primary disadvantages are its lower sorbent utilization rate and correspondingly higher sorbent and waste disposal rates.

In the spray drying process, lime slurry is injected into the SD through either a rotary atomizer or dual-fluid nozzles. The water in the slurry evaporates to cool the flue gas, and the lime reacts with acid gases to form calcium salts that can be removed by a PM control device. The SD is designed to provide sufficient contact and residence time to produce a dry product before leaving the SD adsorber vessel. The residence time in the adsorber vessel is typically 10 to 15 seconds. The particulates leaving the SD (fly ash, calcium salts, and unreacted hydrated lime) are collected by an FF or ESP.

Emission factors and emission factor ratings for controlled air incinerators are presented in Tables 2.3-1, 2.3-2, 2.3-3, 2.3-4, 2.3-5, 2.3-6, 2.3-7, 2.3-8, 2.3-9, 2.3-10, 2.3-11, 2.3-12, 2.3-13, 2.13-14, and 2.3-15. For emissions controlled with wet scrubbers, emission factors are presented separately for low-, medium-, and high-energy wet scrubbers. Particle size distribution data for controlled air incinerators are presented in Table 2.3-15 for uncontrolled emissions and controlled emissions following a medium-energy wet scrubber/FF and a low-energy wet scrubber. Emission factors and emission factor ratings for rotary kiln incinerators are presented in Tables 2.3-16, 2.3-17, and 2.3-18. Emissions data are not available for pathogens because there is not an accepted methodology for measurement of these emissions. Refer to References 8, 9, 11, 12, and 19 for more information.

Table 2.3-1 (English And Metric Units). EMISSION FACTORS FOR NITROGEN OXIDES (NO_x), CARBON MONOXIDE (CO), AND SULFUR DIOXIDE (SO_2) FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	NO_x[c]			CO[c]			SO_2[c]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	3.56 E+00	1.78 E+00	A	2.95 E+00	1.48 E+00	A	2.17 E+00	1.09 E+00	B
Low Energy Scrubber/FF									
Medium Energy Scrubber/FF							3.75 E-01	1.88 E-01	E
FF							8.45 E-01	4.22 E-01	E
Low Energy Scrubber							2.09 E+00	1.04 E+00	E
High Energy Scrubber							2.57 E-02	1.29 E-02	E
DSI/FF							3.83 E-01	1.92 E-01	E
DSI/Carbon Injection/FF							7.14 E-01	3.57 E-01	E
DSI/FF/Scrubber							1.51 E-02	7.57 E-03	E
DSI/ESP									

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter

DSI = Dry Sorbent Injection

ESP = Electrostatic Precipitator

[c] NO_x and CO emission factors for uncontrolled facilities are applicable for all add-on control devices shown.

Table 2.3-2 (English And Metric Units). EMISSION FACTORS FOR TOTAL PARTICULATE MATTER, LEAD, AND TOTAL ORGANIC COMPOUNDS (TOC) FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	Total Particulate Matter			Lead[c]			TOC		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	4.67 E+00	2.33 E+00	B	7.28 E-02	3.64 E-02	B	2.99 E-01	1.50 E-01	B
Low Energy Scrubber/FF	9.09 E-01	4.55 E-01	E						
Medium Energy Scrubber/FF	1.61 E-01	8.03 E-02	E	1.60 E-03	7.99 E-04	E			
FF	1.75 E-01	8.76 E-02	E	9.92 E-05	4.96 E-05	E	6.86 E-02	3.43 E-01	E
Low Energy Scrubber	2.90 E+00	1.45 E+00	E	7.94 E-02	3.97 E-02	E	1.40 E-01	7.01 E-02	E
High Energy Scrubber	1.48 E+00	7.41 E-01	E	6.98 E-02	3.49 E-02	E	1.40 E-01	7.01 E-02	E
DSI/FF	3.37 E-01	1.69 E-01	E	6.25 E-05	3.12 E+01	E	4.71 E-02	2.35 E-02	E
DSI/Carbon Injection/FF	7.23 E-02	3.61 E-02	E	9.27 E-05	4.64 E-05	E			
DSI/FF/Scrubber	2.68 E+00	1.34 E+00	E	5.17 E-05	2.58 E-05	E			
DSI/ESP	7.34 E-01	3.67 E-01	E	4.70 E-03	2.35 E-03	E			

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-3 (English And Metric Units). EMISSION FACTORS FOR HYDROGEN CHLORIDE (HCl) AND POLYCHLORINATED BIPHENYLS (PCBs) FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	HCl[c]			Total PCBs[c]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	3.35 E+01	1.68 E+01	C	4.65 E-05	2.33 E-05	E
Low Energy Scrubber/FF	1.90 E+00	9.48 E-01	E			
Medium Energy Scrubber/FF	2.82 E+00	1.41 E+00	E			
FF	5.65 E+00	2.82 E+00	E			
Low Energy Scrubber	1.00 E+00	5.01 E-01	E			
High Energy Scrubber	1.39 E-01	6.97 E-02	E			
DSI/FF	1.27 E+01	6.37 E+00	D			
DSI/Carbon Injection/FF	9.01 E-01	4.50 E-01	E			
DSI/FF/Scrubber	9.43 E-02	4.71 E-02	E			
DSI/ESP	4.98 E-01	2.49 E-01	E			

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-4 (English And Metric Units). EMISSION FACTORS FOR ALUMINUM, ANTIMONY, AND ARSENIC CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	Aluminum			Antimony[c]			Arsenic[c]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	1.05 E-02	5.24 E-03	E	1.28 E-02	6.39 E-03	D	2.42 E-04	1.21 E-04	B
Low Energy Scrubber/FF									
Medium Energy Scrubber/FF				3.09 E-04	1.55 E-04	E	3.27 E-05	1.53 E-02	E
FF							3.95 E-08	1.97 E-08	E
Low Energy Scrubber							1.42 E-04	7.12 E-05	E
High Energy Scrubber				4.08 E-04	2.04 E-04	E	3.27 E-05	1.64 E-05	E
DSI/FF	3.03 E-03	1.51 E-03	E	2.10 E-04	1.05 E-04	E	1.19 E-05	5.93 E-06	E
DSI/Carbon Injection/FF	2.99 E-03	1.50 E-03	E	1.51 E-04	7.53 E-05	E	1.46 E-05	7.32 E-06	E
DSI/FF/Scrubber									
DSI/ESP							5.01 E-05	2.51 E-05	E

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-5 (English And Metric Units). EMISSION FACTORS FOR BARIUM, BERYLLIUM, AND CADMIUM FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

	Barium			Beryllium[c]			Cadmium[c]		
Control Level[b]	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	3.24 E-03	1.62 E-03	D	6.25 E-06	3.12 E-06	D	5.48 E-03	2.74 E-03	B
Low Energy Scrubber/FF									
Medium Energy Scrubber/FF	2.07 E-04	1.03 E-04	E				1.78 E-04	8.89 E-05	E
FF									
Low Energy Scrubber							6.97 E-03	3.49 E-03	E
High Energy Scrubber							7.43 E-02	3.72 E-02	E
DSI/FF	7.39 E-05	3.70 E-05	E				2.46 E-05	1.23 E-05	E
DSI/Carbon Injection/FF	7.39 E-05	3.69 E-05	E	3.84 E-06	1.92 E-06	E	9.99 E-05	4.99 E-05	E
DSI/FF/Scrubber							1.30 E-05	6.48 E-06	E
DSI/ESP							5.93 E-04	2.97 E-04	E

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-6 (English And English Units). EMISSION FACTORS FOR CHROMIUM, COPPER, AND IRON FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

	Chromium[c]			Copper			Iron		
Control Level[b]	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	7.75 E-04	3.88 E-04	B	1.25 E-02	6.24 E-03	E	1.44 E-02	7.22 E-03	C
Low Energy Scrubber/FF									
Medium Energy Scrubber/FF	2.58 E-04	1.29 E-04	E						
FF	2.15 E-06	1.07 E-06	E						
Low Energy Scrubber	4.13 E-04	2.07 E-04	E				9.47 E-03	4.73E -03	E
High Energy Scrubber	1.03 E-03	5.15 E-04	E						
DSI/FF	3.06 E-04	1.53 E-04	E	1.25 E-03	6.25 E-04	E			
DSI/Carbon Injection/FF	1.92 E-04	9.58 E-05	E	2.75 E-04	1.37 E-04	E			
DSI/FF/Scrubber	3.96 E-05	1.98 E-05	E						
DSI/ESP	6.58 E-04	3.29 E-04	E						

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-7 (English and Metric Units). EMISSION FACTORS FOR MANGANESE, MERCURY, AND NICKEL FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	Manganese[c]			Mercury[c]			Nickel[c]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	5.67 E-04	2.84 E-04	C	1.07 E-01	5.37 E-02	C	5.90 E-04	2.95 E-04	B
Low Energy Scrubber/FF									
Medium Energy Scrubber/FF				3.07 E-02	1.53 E-02	E	5.30 E-04	2.65 E-04	E
FF									
Low Energy Scrubber	4.66 E-04	2.33 E-04	E	1.55 E-02	7.75 E-03	E	3.28 E-04	1.64 E-02	E
High Energy Scrubber	6.12 E-04	3.06 E-04	E	1.73 E-02	8.65 E-03	E	2.54 E-03	1.27 E-03	E
DSI/FF				1.11 E-01	5.55 E-02	E	4.54 E-04	2.27 E-04	E
DSI/Carbon Injection/FF				9.74 E-03	4.87 E-03	E	2.84 E-04	1.42 E-04	E
DSI/FF/Scrubber				3.56 E-04	1.78 E-04	E			
DSI/ESP				1.81 E-02	9.05 E-03	E	4.84 E-04	2.42 E-04	E

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-8 (English And Metric Units). EMISSION FACTORS FOR SILVER AND THALLIUM FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	Silver			Thallium		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	2.26 E-04	1.13 E-04	D	1.10 E-03	5.51 E-04	D
Low Energy Scrubber/FF						
Medium Energy Scrubber/FF	1.71 E-04	8.57 E-05	E			
FF						
Low Energy Scrubber						
High Energy Scrubber	4.33 E-04	2.17 E-04	E			
DSI/FF	6.65 E-05	3.32 E-05	E			
DSI/Carbon Injection/FF	7.19 E-05	3.59 E-05	E			
DSI/FF/Scrubber						
DSI/ESP						

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

Table 2.3-9 (English And Metric Units). EMISSION FACTORS FOR SULFUR TRIOXIDE (SO_3) AND HYDROGEN BROMIDE (HBr) FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Control Level[b]	SO_3			HBr		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled				4.33 E-02	2.16 E-02	D
Low Energy Scrubber/FF						
Medium Energy Scrubber/FF				5.24 E-02	2.62 E-02	E
FF						
Low Energy Scrubber						
High Energy Scrubber						
DSI/FF						
DSI/Carbon Injection/FF				4.42 E-03	2.21 E-03	E
DSI/FF/Scrubber	9.07 E-03	4.53 E-03	E			
DSI/ESP						

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

Table 2.3-10 (English And Metric Units). EMISSION FACTORS FOR HYDROGEN FLUORIDE AND CHLORINE FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

	Hydrogen Fluoride[c]			Chlorine[c]		
Control Level[b]	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
Uncontrolled	1.49 E-01	7.43 E-02	D	1.05 E-01	5.23 E-02	E
Low Energy Scrubber/FF						
Medium Energy Scrubber/FF						
FF						
Low Energy Scrubber						
High Energy Scrubber						
DSI/FF						
DSI/Carbon Injection/FF	1.33 E-02	6.66 E-03	E			
DSI/FF/Scrubber						
DSI/ESP						

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] FF = Fabric Filter
DSI = Dry Sorbent Injection
ESP = Electrostatic Precipitator

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.3-11 (English And Metric Units). CHLORINATED DIBENZO-P-DIOXIN EMISSION FACTORS FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Congener[b]	Uncontrolled			Fabric Filter			Wet Scrubber			DSI/FF[c]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
TCDD												
2,3,7,8-	5.47 E-08	2.73 E-08	E	6.72 E-09	3.36 E-09	E	1.29 E-10	6.45 E-11	E	5.61 E-10	2.81 E-10	E
Total	1.00 E-06	5.01 E-07	B	1.23 E-07	6.17 E-08	E	2.67 E-08	1.34 E-08	E	6.50 E-09	3.25 E-09	E
PeCDD												
1,2,3,7,8-							6.08 E-10	3.04 E-10	E			
Total							5.53 E-10	2.77 E-10	E			
HxCDD												
1,2,3,6,7,8-	3.78 E-10	1.89 E-10	E				1.84 E-09	9.05 E-10	E			
1,2,3,7,8,9-	1.21 E-09	6.07 E-10	E				2.28 E-09	1.14 E-09	E			
1,2,3,4,7,8-							9.22 E-10	4.61 E-10	E			
Total							5.77 E-10	2.89 E-10	E			
HpCDD												
1,2,3,4,6, 7,8-	5.23 E-09	2.62 E-09	E				6.94 E-09	3.47 E-09	E			
Total							1.98 E-09	9.91 E-10	E			
OCDD - total	2.21 E-08	1.11 E-08	E									
Total CDD	2.13 E-05	1.07 E-05	B	2.68 E-06	1.34 E-06	E	1.84 E-06	9.18 E-07	E	3.44 E-07	1.72 E-07	E

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] Hazardous air pollutants listed in *Clean Air Act*.

[c] FF = Fabric Filter
DSI = Dry Sorbent Injection

Table 2.3-12 (English And Metric Units). CHLORINATED DIBENZO-P-DIOXIN EMISSION FACTORS FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Congener[b]	DSI/Carbon Injection/FF[c]			DSI/ESP[d]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
TCDD						
2,3,7,8-	8.23 E-10	4.11 E-10	E	1.73 E-10	8.65 E-11	E
Total						
PeCDD						
1,2,3,7,8-						
Total						
HxCDD						
1,2,3,6,7,8-						
1,2,3,7,8,9-						
1,2,3,4,7,8-						
Total						
HpCDD						
2,3,4,6,7,8-						
1,2,3,4,6,7,8-						
Total						
OCDD - Total						
Total CDD	5.38 E-08	2.69 E-08	E			

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] Hazardous air pollutants listed in the *Clean Air Act*.

[c] FF = Fabric Filter
DSI = Dry Sorbent Injection

[d] ESP = Electrostatic Precipitator

Table 2.3-13 (English And Metric Units). CHLORINATED DIBENZOFURAN EMISSION FACTORS FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

Congener[b]	Uncontrolled			Fabric Filter			Wet Scrubber			DSI/FF[c]		
	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
TCDF												
2,3,7,8-	2.40 E-07	1.20 E-07	E	3.85 E-08	1.97 E-08	E	1.26 E-08	6.30 E-09	E	4.93 E-09	2.47 E-09	E
Total	7.21 E-06	3.61 E-06	B	1.28 E-06	6.39 E-07	E	4.45 E-07	2.22 E-07	E	1.39 E-07	6.96 E-08	E
PeCDF												
1,2,3,7,8-	7.56 E-10	3.78 E-10	E				1.04 E-09	5.22 E-10	E			
2,3,4,7,8-	2.07 E-09	1.04 E-09	E				3.07 E-09	1.53 E-09	E			
Total							6.18 E-09	3.09 E-09	E			
HxCDF												
1,2,3,4,7,8-	7.55 E-09	3.77 E-09	E				8.96 E-09	4.48 E-09	E			
1,2,3,6,7,8-	2.53 E-09	1.26 E-09	E				3.53 E-09	1.76 E-09	E			
2,3,4,6,7,8-	7.18 E-09	3.59 E-09	E				9.59 E-09	4.80 E-09	E			
1,2,3,7,8,9-							3.51 E-10	1.76 E-10	E			
Total							5.10 E-09	2.55 E-09	E			
HpCDF												
1,2,3,4,6,7,8-	1.76 E-08	8.78 E-09	E				1.79 E-08	8.97 E-09	E			
1,2,3,4,7,8,9-	2.72 E-09	1.36 E-09	E				3.50 E-09	1.75 E-09	E			
Total							1.91 E-09	9.56 E-10	E			
OCDF - Total	7.42 E-08	3.71 E-08	E				4.91 E-10	2.45 E-10	E			
Total CDF	7.15 E-05	3.58 E-05	B	8.50 E-06	4.25 E-06	E	4.92 E-06	2.46 E-06	E	1.47 E-06	7.37 E-07	E

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] Hazardous air pollutants listed in the *Clean Air Act*.

[c] FF = Fabric Filter
DSI = Dry Sorbent Injection

Table 2.3-14 (English And Metric Units). CHLORINATED DIBENZOFURANS EMISSION FACTORS FOR CONTROLLED AIR MEDICAL WASTE INCINERATORS[a]

Rating (A-E) Follows Each Factor

	DSI/Carbon Injection/FF[c]			DSI/ESP[d]		
Congener[b]	lb/ton	kg/Mg	EMISSION FACTOR RATING	lb/ton	kg/Mg	EMISSION FACTOR RATING
TCDF						
2,3,7,8-	7.31 E-10	3.65 E-10	E	1.73 E-09	8.66 E-10	E
Total	1.01 E-08	5.07 E-09	E			
PeCDF						
1,2,3,7,8-						
2,3,4,7,8-						
Total						
HxCDF						
1,2,3,4,7,8-						
1,2,3,6,7,8-						
2,3,4,6,7,8-						
1,2,3,7,8,9-						
Total						
HpCDF						
1,2,3,4,6,7,8-						
1,2,3,4,7,8,9-						
Total						
OCDF - Total						
Total CDF	9.47 E-08	4.74 E-08	E			

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.

[b] Hazardous air pollutants listed in the *Clean Air Act*.

[c] FF = Fabric Filter
DSI = Dry Sorbent Injection

[d] ESP = Electrostatic Precipitator

Table 2.3-15. PARTICLE SIZE DISTRIBUTION FOR CONTROLLED AIR MEDICAL WASTE INCINERATOR PARTICULATE MATTER EMISSIONS[a]

EMISSION FACTOR RATING: E

Cut Diameter (μm)	Uncontrolled Cumulative Mass % Less Than Stated Size	Scrubber Cumulative Mass % Less Than Stated Size
0.625	31.1	0.1
1.0	35.4	0.2
2.5	43.3	2.7
5.0	52.0	28.1
10.0	65.0	71.9

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05.

Table 2.3-16 (English And Metric Units). ROTARY KILN MEDICAL WASTE INCINERATOR EMISSION FACTORS FOR CRITERIA POLLUTANTS AND ACID GASES[a]

EMISSION FACTOR RATING: E

Pollutant	Uncontrolled		SD/Fabric Filter[b]		SD/Carbon Injection/FF[c]		High Energy Scrubber	
	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg
Carbon monoxide	3.82 E-01	1.91 E-01	3.89 E-02	1.94 E-02	4.99 E-02	2.50 E-02	5.99 E-02	3.00 E-02
Nitrogen oxides	4.63 E+00	2.31 E+00	5.25 E+00	2.63 E+00	4.91 E+00	2.45 E+00	4.08 E+00	2.04 E+00
Sulfur dioxide	1.09 E+00	5.43 E-01	6.47 E-01	3.24 E-01	3.00 E-01	1.50 E-01		
PM	3.45 E+01	1.73 E+01	3.09 E-01	1.54 E-01	7.56 E-02	3.78 E-02	8.53 E-01	4.27 E-01
TOC	6.66 E-02	3.33 E-02	4.11 E-02	2.05 E-02	5.05 E-02	2.53 E-02	2.17 E-02	1.08 E-02
HCl[d]	4.42 E+01	2.21 E+01	2.68 E-01	1.34 E-01	3.57 E-01	1.79 E-01	2.94 E+01	1.47 E+01
HF[d]	9.31 E-02	4.65 E-02	2.99 E-02	1.50 E-02				
HBr	1.05 E+00	5.25 E-01	6.01 E-02	3.00 E-02	1.90 E-02	9.48 E-03		
H_2SO_4							2.98 E+00	1.49 E+00

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. Blanks indicate no data.
[b] SD = Spray Dryer
[c] FF = Fabric Filter
[d] Hazardous air pollutant listed in the *Clean Air Act*.

Table 2.3-17 (English And Metric Units). ROTARY KILN MEDICAL WASTE INCINERATOR EMISSION FACTORS FOR METALS[a]

EMISSION FACTOR RATING: E

Pollutant	Uncontrolled		SD/Fabric Filter[b]		SD/Carbon Injection/FF[c]	
	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg
Aluminum	6.13 E-01	3.06 E-01	4.18 E-03	2.09 E-03	2.62 E-03	1.31 E-03
Antimony[d]	1.99 E-02	9.96 E-03	2.13 E-04	1.15 E-04	1.41 E-04	7.04 E-05
Arsenic[d]	3.32 E-04	1.66 E-04				
Barium	8.93 E-02	4.46 E-02	2.71 E-04	1.35 E-04	1.25 E-04	6.25 E-05
Beryllium[d]	4.81 E-05	2.41 E-05	5.81 E-06	2.91 E-06		
Cadmium[d]	1.51 E-02	7.53 E-03	5.36 E-05	2.68 E-05	2.42 E-05	1.21 E-05
Chromium[d]	4.43 E-03	2.21 E-03	9.85 E-05	4.92 E-05	7.73 E-05	3.86 E-05
Copper	1.95 E-01	9.77 E-02	6.23 E-04	3.12 E-04	4.11 E-04	2.06 E-04
Lead[d]	1.24 E-01	6.19 E-02	1.89 E-04	9.47 E-05	7.38 E-05	3.69 E-05
Mercury[d]	8.68 E-02	4.34 E-02	6.65 E-02	3.33 E-02	7.86 E-03	3.93 E-03
Nickel[d]	3.53 E-03	1.77 E-03	8.69 E-05	4.34 E-05	3.58 E-05	1.79 E-05
Silver	1.30 E-04	6.51 E-05	9.23 E-05	4.61 E-05	8.05 E-05	4.03 E-05
Thallium	7.58 E-04	3.79 E-04				

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05. ND = no data. Blanks indicate no data.

[b] SD = Spray Dryer.

[c] FF = Fabric Filter.

[d] Hazardous air pollutant listed in the *Clean Air Act*.

Table 2.3-18 (English And Metric Units). ROTARY KILN MEDICAL WASTE INCINERATOR EMISSION FACTORS FOR DIOXINS AND FURANS[a]

EMISSION FACTOR RATING: E

Congener[d]	Uncontrolled		SD/Fabric Filter[b]		SD/Carbon Injection/FF[c]	
	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg
2,3,7,8-TCDD	6.61 E-10	3.30 E-10	4.52 E-10	2.26 E-10	6.42 E-11	3.21 E-11
Total TCDD	7.23 E-09	3.61 E-09	4.16 E-09	2.08 E-09	1.55 E-10	7.77 E-11
Total CDD	7.49 E-07	3.75 E-07	5.79 E-08	2.90 E-08	2.01 E-08	1.01 E-08
2,3,7,8-TCDF	1.67 E-08	8.37 E-09	1.68 E-08	8.42 E-09	4.96 E-10	2.48 E-10
Total TCDF	2.55 E-07	1.27 E-07	1.92 E-07	9.58 E-08	1.15 E-08	5.74 E-09
Total CDF	5.20 E-06	2.60 E-06	7.91 E-07	3.96 E-07	7.57 E-08	3.78 E-08

[a] References 7-43. Source Classification Codes 5-01-005-05, 5-02-005-05.

[b] SD = Spray Dryer.

[c] FF = Fabric Filter.

[d] Hazardous air pollutants listed in the *Clean Air Act*.

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2.4 Landfills

2.4.1 General[1-4]

A municipal solid waste (MSW) landfill unit is a discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile. An MSW landfill unit may also receive other types of wastes, such as commercial solid waste, nonhazardous sludge, and industrial solid waste. The municipal solid waste types potentially accepted by MSW landfills include:

- MSW,
- Household hazardous waste,
- Municipal sludge,
- Municipal waste combustion ash,
- Infectious waste,
- Waste tires,
- Industrial nonhazardous waste,
- Conditionally exempt small quantity generator (CESQG) hazardous waste,
- Construction and demolition waste,
- Agricultural wastes,
- Oil and gas wastes, and
- Mining wastes.

Municipal solid waste management in the United States is dominated by disposal in landfills. Approximately 67 percent of solid waste is landfilled, 16 percent is incinerated, and 17 percent is recycled or composted. There were an estimated 5,345 active MSW landfills in the United States in 1992. In 1990, active landfills were receiving an estimated 118 million megagrams (Mg) (130 million tons) of waste annually, with 55 to 60 percent reported as household waste, and 35 to 45 percent reported as commercial waste.

2.4.2 Process Description[2,5]

There are three major designs for municipal landfills. These are the area, trench, and ramp methods. All of these methods utilize a three step process, which includes spreading the waste, compacting the waste, and covering the waste with soil. The trench and ramp methods are not commonly used, and are not the preferred methods when liners and leachate collection systems are utilized or required by law. The area fill method involves placing waste on the ground surface or landfill liner, spreading it in layers, and compacting with heavy equipment. A daily soil cover is spread over the compacted waste. The trench method entails excavating trenches designed to receive a day's worth of waste. The soil from the excavation is often used for cover material and wind breaks. The ramp method is typically employed on sloping land, where waste is spread and compacted similar to the area method; however, the cover material obtained is generally from the front of the working face of the filling operation.

Modern landfill design often incorporates liners constructed of soil (e. g., recompacted clay), or synthetics (e. g., high density polyethylene), or both to provide an impermeable barrier to leachate (i. e., water that has passed through the landfill) and gas migration from the landfill.

2.4.3 Control Technology[1,2,6]

The Resource Conservation and Recovery Act (RCRA) Subtitle D regulations promulgated on October 9, 1991, require that the concentration of methane generated by MSW landfills not exceed 25 percent of the lower explosive limit (LEL) in on-site structures, such as scale houses, or the LEL at the facility property boundary.

Proposed New Source Performance Standards (NSPS) and emission guidelines for air emissions from MSW landfills for certain new and existing landfills were published in the Federal Register on May 30, 1991. The regulation, if adopted, will require that Best Demonstrated Technology (BDT) be used to reduce MSW landfill emissions from affected new and existing MSW landfills emitting greater than or equal to 150 Mg/yr (165 tons/yr) of non-methanogenic organic compounds (NMOCs). The MSW landfills that would be affected by the proposed NSPS would be each new MSW landfill, and each existing MSW landfill that has accepted waste since November 8, 1987, or that has capacity available for future use. Control systems would require: (1) a well-designed and well-operated gas collection system, and (2) a control device capable of reducing NMOCs in the collected gas by 98 weight-percent.

Landfill gas collection systems are either active or passive systems. Active collection systems provide a pressure gradient in order to extract landfill gas by use of mechanical blowers or compressors. Passive systems allow the natural pressure gradient created by the increase in landfill pressure from landfill gas generation to mobilize the gas for collection.

Landfill gas control and treatment options include (1) combustion of the landfill gas, and (2) purification of the landfill gas. Combustion techniques include techniques that do not recover energy (i. e., flares and thermal incinerators), and techniques that recover energy (i. e., gas turbines and internal combustion engines) and generate electricity from the combustion of the landfill gas. Boilers can also be employed to recover energy from landfill gas in the form of steam. Flares involve an open combustion process that requires oxygen for combustion, and can be open or enclosed. Thermal incinerators heat an organic chemical to a high enough temperature in the presence of sufficient oxygen to oxidize the chemical to carbon dioxide (CO_2) and water. Purification techniques can also be used to process raw landfill gas to pipeline quality natural gas by using adsorption, absorption, and membranes.

2.4.4 Emissions[2,7]

Methane (CH_4) and CO_2 are the primary constituents of landfill gas, and are produced by microorganisms within the landfill under anaerobic conditions. Transformations of CH_4 and CO_2 are mediated by microbial populations that are adapted to the cycling of materials in anaerobic environments. Landfill gas generation, including rate and composition, proceeds through four phases. The first phase is aerobic (e. g., with oxygen [O_2] available) and the primary gas produced is CO_2. The second phase is characterized by O_2 depletion, resulting in an anaerobic environment, where large amounts of CO_2 and some hydrogen (H_2) are produced. In the third phase, CH_4 production begins, with an accompanying reduction in the amount of CO_2 produced. Nitrogen (N_2) content is initially high in landfill gas in the first phase, and declines sharply as the landfill proceeds through the second and third phases. In the fourth phase, gas production of CH_4, CO_2, and N_2 becomes fairly steady. The total time and phase duration of gas generation varies with landfill conditions (e. g., waste composition, design management, and anaerobic state).

The rate of emissions from a landfill is governed by gas production and transport mechanisms. Production mechanisms involve the production of the emission constituent in its vapor phase through vaporization, biological decomposition, or chemical reaction. Transport mechanisms involve the transportation of a volatile constituent in its vapor phase to the surface of the landfill, through the air boundary layer above the landfill, and into the atmosphere. The three major transport mechanisms that enable transport of a volatile constituent in its vapor phase are diffusion, convection, and displacement.

2.4.4.1 Uncontrolled Emissions -

To estimate uncontrolled emissions of the various compounds present in landfill gas, total landfill gas emissions must first be estimated. Uncontrolled CH_4 emissions may be estimated for individual landfills by using a theoretical first-order kinetic model of methane production developed by the EPA.[2] This model is known as the Landfill Air Emissions Estimation model, and can be accessed from the EPA's Control Technology Center bulletin board. The Landfill Air Emissions Estimation model equation is as follows:

$$Q_{CH4} = L_o \; R \, (e^{-kc} - e^{-kt}) \tag{1}$$

where:

Q_{CH4} = Methane generation rate at time t, m^3/yr;
L_o = Methane generation potential, m^3 CH_4/Mg refuse;
R = Average annual refuse acceptance rate during active life, Mg/yr;
e = Base log, unitless;
k = Methane generation rate constant, yr^{-1};
c = Time since landfill closure, yrs (c = 0 for active landfills); and
t = Time since the initial refuse placement, yrs.

Site-specific landfill information is generally available for variables R, c, and t. When refuse acceptance rate information is scant or unknown, R can be determined by dividing the refuse in place by the age of the landfill. Also, nondegradable refuse should be subtracted from the mass of acceptance rate to prevent overestimation of CH_4 generation. The average annual acceptance rate should only be estimated by this method when there is inadequate information available on the actual average acceptance rate.

Values for variables L_o and k must be estimated. Estimation of the potential CH_4 generation capacity of refuse (L_o) is generally treated as a function of the moisture and organic content of the refuse. Estimation of the CH_4 generation constant (k) is a function of a variety of factors, including moisture, pH, temperature, and other environmental factors, and landfill operating conditions. Specific CH_4 generation constants can be computed by use of the EPA Method 2E.

The Landfill Air Emission Estimation model uses the proposed regulatory default values for L_o and k. However, the defaults were developed for regulatory compliance purposes. As a result, it contains conservative L_o and k default values in order to protect human health, to encompass a wide range of landfills, and to encourage the use of site-specific data. Therefore, different L_o and k values may be appropriate in estimating landfill emissions for particular landfills and for use in an emissions inventory.

A k value of 0.04/yr is appropriate for areas with normal or above normal precipitation rather than the default value of 0.02/yr. For landfills with drier waste, a k value of 0.02/yr is more appropriate. An L_o value of 125 m^3/Mg (4,411 ft^3/Mg) refuse is appropriate for most landfills. It should be emphasized that in order to comply with the NSPS, the model defaults for k and L_o must be applied as specified in the final rule.

Landfill gas consists of approximately 50 percent by volume CO_2, 50 percent CH_4, and trace amounts of NMOCs when gas generation reaches steady state conditions. Therefore, the estimate derived for CH_4 generation using the Landfill Air Emissions Estimation model can also be used to represent CO_2 generation. Addition of the CH_4 and CO_2 emissions will yield an estimate of total landfill gas emissions. If site-specific information is available to suggest that the CH_4 content of landfill gas is not 50 percent, then the site-specific information should be used, and the CO_2 emission estimate should be adjusted accordingly.

Emissions of NMOCs result from NMOCs contained in the landfilled waste, and from their creation from biological processes and chemical reactions within the landfill cell. The Landfill Air Emissions Estimation model contains a proposed regulatory default value for total NMOCs of 8000 ppmv, expressed as hexane. However, there is a wide range for total NMOC values from landfills. The proposed regulatory default value for NMOC concentration was developed for regulatory compliance and to provide the most cost-effective default values on a national basis. For emissions inventory purposes, it would be preferable that site-specific information be taken into account when determining the total NMOC concentration. A value of 4,400 ppmv as hexane is preferable for landfills known to have co-disposal of MSW and commercial/industrial organic wastes. If the landfill is known to contain only MSW or have very little organic commercial/industrial wastes, then a total NMOC value of 1,170 ppmv as hexane should be used.

If a site-specific total NMOC concentration is available (i. e., as measured by EPA Reference Method 25C), it must be corrected for air infiltration into the collected landfill gas before it can be combined with the estimated landfill gas emissions to estimate total NMOC emissions. The total NMOC concentration is adjusted for air infiltration by assuming that CO_2 and CH_4 are the primary (100 percent) constituents of landfill gas, and the following equation is used:

$$\frac{C_{NMOC}(\text{ppmv as hexane})\ (1 \times 10^6)}{C_{CO_2}\ (\text{ppmv}) + C_{CH_4}\ (\text{ppmv})} = \begin{matrix} C_{NMOC}\ \text{ppmv as hexane} \\ \text{(corrected for air infiltration)} \end{matrix} \qquad (2)$$

where:

C_{NMOC} = Total NMOC concentration in landfill gas, ppmv as hexane;
C_{CO_2} = CO_2 concentration in landfill gas, ppmv;
C_{CH_4} = CH_4 Concentration in landfill gas, ppmv; and
1×10^6 = Constant used to correct NMOC concentration to units of ppmv.

Values for C_{CO_2} and C_{CH_4} can be usually be found in the source test report for the particular landfill along with the total NMOC concentration data.

To estimate total NMOC emissions, the following equation should be used:

$$Q_{NMOC} = 2\ Q_{CH_4} * C_{NMOC}/(1 \times 10^6) \qquad (3)$$

where:

Q_{NMOC} = NMOC emission rate, m^3/yr;
Q_{CH_4} = CH_4 generation rate, m^3/yr (from the Landfill Air Emissions Estimation model);
C_{NMOC} = Total NMOC concentration in landfill gas, ppmv as hexane; and
2 = Multiplication factor (assumes that approximately 50 percent of landfill gas is CH_4).

The mass emissions per year of total NMOCs (as hexane) can be estimated by the following equation:

$$M_{NMOC} = Q_{NMOC} * \left[\frac{1050.2}{(273+T)}\right] \quad (4)$$

where:

M_{NMOC} = NMOC (total) mass emissions (kg/yr);
Q_{NMOC} = NMOC emission rate (m^3/yr); and
T = Temperature of landfill gas (°C).

This equation assumes that the operating pressure of the system is approximately 1 atmosphere, and represents total NMOCs, based on the molecular weight of hexane. If the temperature of the landfill gas is not known, a temperature of 25°C (75°F) is recommended.

Uncontrolled emission concentrations of individual NMOCs along with some inorganic compounds are presented in Table 2.4-1. These individual NMOC and inorganic concentrations have already been corrected for air infiltration and can be used as input parameters in the Landfill Air Emission Estimation model for estimating individual NMOC emissions from landfills when site-specific data are not available. An analysis of the data based on the co-disposal history (with hazardous wastes) of the individual landfills from which the concentration data were derived indicates that for benzene and toluene, there is a difference in the uncontrolled concentration. Table 2.4-2 presents the corrected concentrations for benzene and toluene to use based on the site's co-disposal history.

Similar to the estimation of total NMOC emissions, individual NMOC emissions can be estimated by the following equation:

$$Q_{NMOC} = 2\ Q_{CH_4} * C_{NMOC}/(1 \times 10^6) \quad (5)$$

where:

Q_{NMOC} = NMOC emission rate, m^3/yr;
QCH_4 = CH_4 generation rate, m^3/yr (from the Landfill Air Emission Estimation model);
C_{NMOC} = NMOC concentration in landfill gas, ppmv; and
2 = Multiplication factor (assumes that approximately 50 percent of landfill gas is CH_4).

The mass emissions per year of each individual landfill gas compound can be estimated by the following equation:

$$I_{NMOC} = Q_{NMOC} * \frac{(\text{Molecular weight of compound})}{(8.205 \times 10^{-5}\ m^3\text{-atm/mol-}^\circ K)\ (1000\ g)\ (273 + T)} \quad (6)$$

where:

I_{NMOC} = Individual NMOC mass emissions (kg/yr);
Q_{NMOC} = NMOC emission rate (m^3/yr); and
T = Temperature of landfill gas (°C).

Table 2.4-1. UNCONTROLLED LANDFILL GAS CONCENTRATIONS[a]

Compound	Molecular Weight	Median ppmv	EMISSION FACTOR RATING
1,1,1-Trichloroethane (methyl chloroform)*	133.42	0.27	B
1,1,2,2-Tetrachloroethane*	167.85	0.20	C
1,1,2-Trichloroethane*	133.42	0.10	E
1,1-Dichloroethane (ethylidene dichloride)*	98.95	2.07	B
1,1-Dichloroethene (vinylidene chloride)*	96.94	0.22	B
1,2-Dichloroethane (ethylene dichloride)*	98.96	0.79	B
1,2-Dichloropropane (propylene dichloride)*	112.98	0.17	C
Acetone	58.08	6.89	B
Acrylonitrile*	53.06	7.56	D
Bromodichloromethane	163.87	2.06	C
Butane	58.12	3.83	B
Carbon disulfide*	76.13	1.00	E
Carbon monoxide	28.01	309.32	C
Carbon tetrachloride*	153.84	0.00	B
Carbonyl sulfide*	60.07	24.00	E
Chlorobenzene*	112.56	0.20	D
Chlorodiflouromethane	67.47	1.22	B
Chloroethane (ethyl chloride)*	64.52	1.17	B
Chloroform*	119.39	0.27	B
Chloromethane	50.49	1.14	B
Dichlorodifluoromethane	120.91	12.17	B
Dichlorofluoromethane	102.92	4.37	C
Dichloromethane (methylene chloride)*	84.94	14.30	C
Dimethyl sulfide (methyl sulfide)	62.13	76.16	B
Ethane	30.07	227.65	D
Ethyl mercaptan (ethanethiol)	62.13	0.86	C
Ethyl benzene*	106.16	4.49	B
Fluorotrichloromethane	137.38	0.73	B
Hexane*	86.17	6.64	B
Hydrogen sulfide	34.08	36.51	B
Methyl ethyl ketone*	72.10	6.13	B
Methyl isobutyl ketone*	100.16	1.22	B
Methyl mercaptan	48.10	10.43	B
NMOC (as hexane)	86.17	1170	D
Pentane	72.15	3.32	B
Perchloroethylene (tetrachloroethylene)*	165.83	3.44	B

Table 2.4-1 (cont.).

Compound	Molecular Weight	Median ppmv	EMISSION FACTOR RATING
Propane	44.09	10.60	B
Trichloroethylene*	131.40	2.08	B
t-1,2-Dichloroethene	96.94	4.01	B
Vinyl chloride*	62.50	7.37	B
Xylene*	106.16	12.25	B

[a] References 9-35. Source Classification Code 5-02-006-02. * = Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.4-2. UNCONTROLLED CONCENTRATIONS OF BENZENE AND TOLUENE BASED ON HAZARDOUS WASTE DISPOSAL HISTORY[a]

Compound	Molecular Weight	Concentration ppmv	EMISSION FACTOR RATING
Benzene*	78.11		
Co-disposal		24.99	D
Unknown		2.25	B
No co-disposal		0.37	D
Toluene*	92.13		
Co-disposal		102.62	D
Unknown		31.63	B
No co-disposal		8.93	D

[a] References 9-35. Source Classification Code 5-02-006-02. * = Hazardous air pollutants listed in the *Clean Air Act*.

2.4.4.2 Controlled Emissions -

Emissions from landfills are typically controlled by installing a gas collection system, and destroying the collected gas through the use of internal combustion engines, flares, or turbines. Gas collection systems are not 100 percent efficient in collecting landfill gas, so emissions of CH_4 and NMOCs at a landfill with a gas recovery system still occur. To estimate controlled emissions of CH_4, NMOCs, and other constituents in landfill gas, the collection efficiency of the system must first be estimated. Reported collection efficiencies typically range from 60 to 85 percent, with an average of 75 percent most commonly assumed. If site-specific collection efficiencies are available, they should be used instead of the 75 percent average.

Uncollected CH_4, CO_2, and NMOCs can be calculated with the following equation:

$$1 - \frac{\text{Collection Efficiency}}{100} \qquad (7)$$

Controlled emission estimates also need to take into account the control efficiency of the control device. Control efficiencies of CH_4 and NMOCs with differing control devices are presented in Table 2.4-3. Emissions from the control devices need to be added to the uncollected emissions to estimate total controlled emissions.

Emission factors for secondary compounds (CO_2, CO, and NO_x) exiting the control device are presented in Tables 2.4-4 and 2.4-5.

The reader is referred to Sections 13.2-2 (Unpaved Roads, SCC 5-01-004-01), and Section 13.2.3 (Heavy Construction Operations) of Volume I, and Section II-7 (Heavy-duty Construction Equipment) of Volume II, of the AP-42 document for determination of associated dust and exhaust emissions from these emission sources at MSW landfills.

Table 2.4-3. CONTROL EFFICIENCIES FOR LANDFILL GAS CONSTITUENTS[a]

Control Device	Compound	Average Control Efficiency	EMISSION FACTOR RATING
IC Engine (no SCC)	Benzene*	83.83	E
	Trichloroethylene*	89.60	E
	Perchloroethylene*	89.41	E
	NMOCs (as hexane*)	79.75	E
	1,1,1-Trichloroethane*	92.47	E
	Chloroform*	99.00	E
	Toluene*	79.71	E
	Carbon tetrachloride*	98.50	E
Turbine (no SCC)	Perchloroethylene*	99.97	E
	Toluene*	99.91	E
	1,1,1-Trichloroethane*	95.18	E
	Trichloroethylene*	99.92	E
	Vinyl chloride*	98.00	E
Flare (5-02-006-01) (5-03-006-01)	Chloroform*	93.04	D
	Perchloroethylene*	85.02	C
	Toluene*	93.55	C
	Xylene*	99.28	E
	1,1,1-Trichloroethane*	85.24	C
	1,2-Dichloroethane*	88.68	E
	Benzene*	89.50	C
	Carbon tetrachloride*	95.05	D
	Methylene chloride*	97.60	E
	NMOCs (as hexane*)	83.16	E
	Trichloroethylene*	96.20	C
	t-1,2-Dichloroethene*	99.59	E
	Vinyl chloride*	97.61	C

[a] References 9-35. Source Classification Codes in parentheses. * = Hazardous air pollutant listed in the *Clean Air Act*.

Table 2.4-4 (Metric Units). EMISSION RATES FOR SECONDARY COMPOUNDS EXITING CONTROL DEVICES[a]

Control Device	Compound	Average Rate, kg/hr/dscmm Uncontrolled Methane	EMISSION FACTOR RATING
Flare (5-02-006-01) (5-03-006-01)	Carbon dioxide	85.7[b]	B
	Carbon monoxide	0.80	B
	Nitrogen dioxide	0.11	C
	Methane	1.60	C
	Sulfur dioxide	0.03	E
IC Engine (no SCC)	Carbon dioxide	85.7[b]	B
	Nitrogen dioxide	0.80	E
Turbine (no SCC)	Carbon dioxide	85.7[b]	B
	Carbon monoxide	0.32	E

[a] Source Classification Codes in parentheses.

[b] Carbon dioxide emission factors are based on a mass balance on the combustion of a 50/50 mixture of methane and CO_2.

Table 2.4-5 (English Units). EMISSION RATES FOR SECONDARY COMPOUNDS EXITING CONTROL DEVICES[a]

Control Device	Compound	Average Rate, lb/hr/dscfm Uncontrolled Methane	EMISSION FACTOR RATING
Flare (5-02-006-01) (5-03-006-01)	Carbon dioxide	5.3[b]	B
	Carbon monoxide	0.050	B
	Nitrogen dioxide	0.007	C
	Methane	0.105	C
	Sulfur dioxide	0.002	E
IC Engine (no SCC)	Carbon dioxide	5.3[b]	B
	Nitrogen dioxide	0.050	E
Turbine (no SCC)	Carbon dioxide	5.3[b]	B
	Carbon monoxide	0.021	E

[a] Source Classification Codes in parentheses.

[b] Carbon dixoide emission factors are based on a mass balance on the combustion of a 50/50 mixture of methane and CO_2.

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2.5 Open Burning

2.5.1 General[1]

Open burning can be done in open drums or baskets, in fields and yards, and in large open dumps or pits. Materials commonly disposed of in this manner include municipal waste, auto body components, landscape refuse, agricultural field refuse, wood refuse, bulky industrial refuse, and leaves.

Current regulations prohibit open burning of hazardous waste. One exception is for open burning and detonation of explosives, particularly waste explosives that have the potential to detonate, and bulk military propellants which cannot safely be disposed of through other modes of treatment.

The following Source Classification Codes (SCCs) pertain to open burning:

Government

5-01-002-01	General Refuse
5-01-002-02	Vegetation Only

Commercial/Institutional

5-02-002-01	Wood
5-02-002-02	Refuse

Industrial

5-03-002-01	Wood/Vegetation/Leaves
5-03-002-02	Refuse
5-03-002-03	Auto Body Components
5-03-002-04	Coal Refuse Piles
5-03-002-05	Rocket Propellant

2.5.2 Emissions[1-22]

Ground-level open burning emissions are affected by many variables, including wind, ambient temperature, composition and moisture content of the debris burned, and compactness of the pile. In general, the relatively low temperatures associated with open burning increase emissions of particulate matter, carbon monoxide, and hydrocarbons and suppress emissions of nitrogen oxides. Emissions of sulfur oxides are a direct function of the sulfur content of the refuse.

2.5.2.1 Municipal Refuse -

Emission factors for the open burning of municipal refuse are presented in Table 2.5-1.

2.5.2.2 Automobile Components -

Emission factors for the open burning of automobile components including upholstery, belts, hoses, and tires are presented in Table 2.5-1.

Emission factors for the burning of scrap tires only are presented in Tables 2.5-2, 2.5-3, and 2.5-4. Although it is illegal in many states to dispose of tires using open burning, fires often occur at

Table 2.5-1 (Metric And English Units). EMISSION FACTORS FOR OPEN BURNING OF MUNICIPAL REFUSE

EMISSION FACTOR RATING: D

Source	Particulate	Sulfur Oxides	Carbon Monoxide	TOC[a]		Nitrogen Oxides
				Methane	Nonmethane	
Municipal Refuse[b]						
kg/Mg	8	0.5	42	6.5	15	3
lb/ton	16	1.0	85	13	30	6
Automobile Components[c]						
kg/Mg	50	Neg	62	5	16	2
lb/ton	100	Neg	125	10	32	4

[a] Data indicate that total organic compounds (TOC) emissions are approximately 25% methane, 8% other saturates, 18% olefins, 42% others (oxygenates, acetylene, aromatics, trace formaldehyde).

[b] References 2 and 7.

[c] Reference 2. Upholstery, belts, hoses, and tires burned together.

tire stockpiles and through illegal burning activities. If the emission factors presented here are used to estimate emissions from an accidental tire fire, it should be kept in mind that emissions from burning tires are generally dependent on the burn rate of the tire. A greater potential for emissions exists at lower burn rates, such as when a tire is smoldering, rather than burning out of control. In addition, the emission factors presented here for tire "chunks" are probably more appropriate than for "shredded" tires for estimating emissions from an accidental tire fire because there is likely to be more air-space between the tires in an actual fire. As discussed in Reference 21, it is difficult to estimate emissions from a large pile of tires based on these results, but emissions can be related to a mass burn rate. To use the information presented here, it may be helpful to use the following estimates: tires tested in Reference 21 weighed approximately 7 kilograms (kg) (15.4 pounds [lb]) and the volume of 1 tire is approximately 0.2 cubic meter (m^3) (7 cubic feet [ft^3]). Table 2.5-2 presents emission factors for particulate metals. Table 2.5-3 presents emission factors for polycyclic aromatic hydrocarbons (PAH), and Table 2.5-4 presents emissions for other volatile hydrocarbons. For more detailed information on this subject consult the reference cited at the end of this chapter.

2.5.2.3 Agricultural Waste -

Organic Agricultural Waste -

Organic refuse burning consists of burning field crops, wood, and leaves. Emissions from organic agricultural refuse burning are dependent mainly on the moisture content of the refuse and, in the case of the field crops, on whether the refuse is burned in a headfire or a backfire. Headfires are started at the upwind side of a field and allowed to progress in the direction of the wind, whereas backfires are started at the downwind edge and forced to progress in a direction opposing the wind.

Other variables such as fuel loading (how much refuse material is burned per unit of land area) and how the refuse is arranged (in piles, rows, or spread out) are also important in certain instances. Emission factors for open agricultural burning are presented in Table 2.5-5 as a function of refuse type and also, in certain instances, as a function of burning techniques and/or moisture content when these variables are known to significantly affect emissions. Table 2.5-5 also presents typical fuel loading values associated with each type of refuse. These values can be used, along with

Table 2.5-2 (Metric And English Units). PARTICULATE METALS EMISSION FACTORS FROM OPEN BURNING OF TIRES[a]

EMISSION FACTOR RATING: C

Tire Condition	Chunk[b]		Shredded[b]	
Pollutant	mg / kg tire	lb / 1000 tons tire	mg / kg tire	lb / 1000 tons tire
Aluminum	3.07	6.14	2.37	4.73
Antimony[c]	2.94	5.88	2.37	4.73
Arsenic[c]	0.05	0.10	0.20	0.40
Barium	1.46	2.92	1.18	2.35
Calcium	7.15	14.30	4.73	9.47
Chromium[c]	1.97	3.94	1.72	3.43
Copper	0.31	0.62	0.29	0.58
Iron	11.80	23.61	8.00	15.99
Lead[c]	0.34	0.67	0.10	0.20
Magnesium	1.04	2.07	0.75	1.49
Nickel[c]	2.37	4.74	1.08	2.15
Selenium[c]	0.06	0.13	0.20	0.40
Silicon	41.00	82.00	27.52	55.04
Sodium	7.68	15.36	5.82	11.63
Titanium	7.35	14.70	5.92	11.83
Vanadium	7.35	14.70	5.92	11.83
Zinc	44.96	89.92	24.75	49.51

[a] Reference 21.

[b] Values are weighted averages.

[c] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.5-3 (Metric And English). POLYCYCLIC AROMATIC HYDROCARBON EMISSION FACTORS FROM OPEN BURNING OF TIRES[a]

EMISSION FACTOR RATING: D

Tire Condition	Chunk[b,c]		Shredded[b,c]	
Pollutant	mg/kg tire	lb/1000 tons tire	mg/kg tire	lb/1000 tons tire
Acenaphthene	718.20	1436.40	2385.60	4771.20
Acenaphthylene	570.20	1140.40	568.08	1136.17
Anthracene	265.60	531.20	49.61	99.23
Benzo(A)pyrene	173.80	347.60	115.16	230.32
Benzo(B)fluoranthene	183.10	366.20	89.07	178.14
Benzo(G,H,I)perylene	36.20	72.40	160.84	321.68
Benzo(K)fluoranthene	281.80	563.60	100.24	200.48
Benz(A)anthracene	7.90	15.80	103.71	207.43
Chrysene	48.30	96.60	94.83	189.65
Dibenz(A,H)anthracene	54.50	109.00	0.00	0.00
Fluoranthene	42.30	84.60	463.35	926.69
Fluorene	43.40	86.80	189.49	378.98
Indeno(1,2,3-CD)pyrene	58.60	117.20	86.38	172.76
Naphthalene[d]	0.00	0.00	490.85	981.69
Phenanthrene	28.00	56.00	252.73	505.46
Pyrene	35.20	70.40	153.49	306.98

[a] Reference 21.

[b] 0.00 values indicate pollutant was not found.

[c] Values are weighted averages.

[d] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.5-4 (Metric And English Units). EMISSION FACTORS FOR ORGANIC COMPOUNDS FROM OPEN BURNING OF TIRES[a]

EMISSION FACTOR RATING: C

Tire Condition	Chunk[b,c]		Shredded[b,c]	
Pollutant	mg / kg tire	lb / 1000 tons tire	mg / kg tire	lb / 1000 tons tire
1,1'Biphenyl, methyl	12.71	25.42	0.00	0.00
1h Fluorene	191.27	382.54	315.18	630.37
1-Methyl naphthalene	299.20	598.39	227.87	455.73
2-Methyl naphthalene	321.47	642.93	437.06	874.12
Acenaphthalene	592.70	1185.39	549.32	1098.63
Benzaldehyde	223.34	446.68	322.05	644.10
Benzene[d]	1526.39	3052.79	1929.93	3859.86
Benzodiazine	13.12	26.23	17.43	34.87
Benzofuran	40.62	81.24	0.00	0.00
Benzothiophene	10.31	20.62	914.91	1829.82
Benzo(B)thiophene	50.37	100.74	0.00	0.00
Benzsisothiazole	0.00	0.00	151.66	303.33
Biphenyl[d]	190.08	380.16	329.65	659.29
Butadiene[d]	117.14	234.28	138.97	277.95
Cyanobenzene	203.81	407.62	509.34	1018.68
Cyclopentadiene	67.40	134.80	0.00	0.00

Table 2.5-4 (cont.).

Tire Condition	Chunk[b,c]		Shredded[b,c]	
Pollutant	$\frac{\text{mg}}{\text{kg tire}}$	$\frac{\text{lb}}{\text{1000 tons tire}}$	$\frac{\text{mg}}{\text{kg tire}}$	$\frac{\text{lb}}{\text{1000 tons tire}}$
Dihydroindene	9.82	19.64	30.77	61.53
Dimethyl benzene	323.58	647.16	940.91	1881.83
Dimethyl hexadiene	6.22	12.44	73.08	146.15
Dimethyl naphthalene	35.28	70.55	155.28	310.57
Dimethyldihydro indene	5.02	10.04	27.60	55.20
Ethenyl, dimethyl benzene	11.50	23.01	196.34	392.68
Ethenyl, methyl benzene	12.48	24.95	21.99	43.98
Ethenyl benzene[d]	539.72	1079.44	593.15	1186.31
Ethenyl cyclohexene	4.85	9.70	89.11	178.22
Ethenylmethyl benzene	103.13	206.26	234.59	469.19
Ethyenylmethyl benzene	0.00	0.00	42.04	84.07
Ethyl, methyl benzene	79.29	158.58	223.79	447.58
Ethyl benzene	138.94	277.87	335.12	670.24
Ethynyl, methyl benzene	459.31	918.62	345.25	690.50
Ethynyl benzene	259.82	519.64	193.49	386.98
Heptadiene	6.40	12.79	42.12	84.24
Hexahydro azepinone	64.35	128.69	764.03	1528.05

Table 2.5-4 (cont.).

Tire Condition	Chunk[b,c]		Shredded[b,c]	
Pollutant	mg/kg tire	lb/1000 tons tire	mg/kg tire	lb/1000 tons tire
Indene	472.74	945.48	346.23	692.47
Isocyano benzene	283.78	567.55	281.13	562.25
Isocyano naphthalene	10.75	21.51	0.00	0.00
Limonene	48.11	96.22	2309.57	4619.14
Methyl, ethenyl benzene	21.15	42.30	67.05	134.10
Methyl, methylethenyl benzene	35.57	71.13	393.78	787.56
Methyl, methylethyl benzene	109.69	219.39	1385.03	2770.07
Methyl benzaldehyde	0.00	0.00	75.49	150.98
Methyl benzene	1129.80	2259.60	1395.04	2790.08
Methyl cyclohexene	3.91	7.83	33.44	66.88
Methyl hexadiene	15.59	31.18	102.20	204.40
Methyl indene	50.04	100.07	286.68	573.36
Methyl, methylethyl benzene	11.76	23.52	114.33	228.66
Methyl naphthalene	144.78	289.56	122.68	245.37
Methyl, propyl benzene	0.00	0.00	30.14	60.28
Methyl thiophene	4.39	8.78	10.52	21.03
Methylene indene	30.37	60.75	58.91	117.82

Table 2.5-4 (cont.).

Tire Condition	Chunk[b,c]		Shredded[b,c]	
Pollutant	mg / kg tire	lb / 1000 tons tire	mg / kg tire	lb / 1000 tons tire
Methylethyl benzene	41.40	82.79	224.23	448.46
Phenol[d]	337.71	675.41	704.90	1409.80
Propenyl, methyl benzene	0.00	0.00	456.59	913.18
Propenyl naphthalene	26.80	53.59	0.00	0.00
Propyl benzene	19.43	38.87	215.13	430.26
Styrene[d]	618.77	1237.53	649.92	1299.84
Tetramethyl benzene	0.00	0.00	121.72	243.44
Thiophene	17.51	35.02	31.11	62.22
Trichlorofluoromethane	138.10	276.20	0.00	0.00
Trimethyl benzene	195.59	391.18	334.80	669.59
Trimethyl naphthalene	0.00	0.00	316.26	632.52

[a] Reference 21.

[b] 0.00 values indicate the pollutant was not found.

[c] Values are weight averages.

[d] Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.5-5 (Metric And English Units). EMISSION FACTORS AND FUEL LOADING FACTORS FOR OPEN BURNING OF AGRICULTURAL MATERIALS[a]

EMISSION FACTOR RATING: D

Refuse Category	Particulate[b]		Carbon Monoxide		TOC[c] Methane		TOC[c] Nonmethane		Fuel Loading Factors (waste production)	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	Mg/hectare	ton/acre
Field Crops[d]										
Unspecified	11	21	58	117	2.7	5.4	9	18	4.5	2
Burning techniques not significant[e]										
Asparagus[f]	20	40	75	150	10	20	33	66	3.4	1.5
Barley	11	22	78	157	2.2	4.5	7.5	15	3.8	1.7
Corn	7	14	54	108	2	4	6	12	9.4	4.2
Cotton	4	8	88	176	0.7	1.4	2.5	5	3.8	1.7
Grasses	8	16	50	101	2.2	4.5	7.5	15		
Pineapple[g]	4	8	56	112	1	2	3	6		
Rice[h]	4	9	41	83	1.2	2.4	4	8	6.7	3.0
Safflower	9	18	72	144	3	6	10	20	2.9	1.3
Sorghum	9	18	38	77	1	2	3.5	7	6.5	2.9
Sugar cane[i]	2.3-3.5	6-8.4	30-41	60-81	0.6-2	1.2-3.8	2-6	4-12	8-46	3-17
Headfire Burning[j]										
Alfalfa	23	45	53	106	4.2	8.5	14	28	1.8	0.8
Bean (red)	22	43	93	186	5.5	11	18	36	5.6	2.5
Hay (wild)	16	32	70	139	2.5	5	8.5	17	2.2	1.0
Oats	22	44	68	137	4	7.8	13	26	3.6	1.6
Pea	16	31	74	147	4.5	9	15	29	5.6	2.5
Wheat	11	22	64	128	2	4	6.5	13	4.3	1.9

Table 2.5-5 (cont.).

Refuse Category	Particulate[b]		Carbon Monoxide		TOC[c]				Fuel Loading Factors (waste production)	
					Methane		Nonmethane			
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	Mg/hectare	ton/acre
Backfire Burning[k]										
Alfalfa	14	29	60	119	4.5	9	14	29	1.8	0.8
Bean (red)	7	14	72	148	3	6	10	19	5.6	2.5
Hay (wild)	8	17	75	150	2	4	6.5	13	2.2	1.0
Oats	11	21	68	136	2	4	7	14	3.6	1.6
Wheat	6	13	54	108	1.3	2.6	4.5	9	4.3	1.9
Vine Crops	3	5	26	51	0.8	1.7	3	5	5.6	2.5
Weeds										
Unspecified	8	15	42	85	1.5	3	4.5	9	7.2	3.2
Russian thistle (tumbleweed)	11	22	154	309	0.2	0.5	0.8	1.5	0.2	0.1
Tales (wild reeds)	3	5	17	34	3.2	6.5	10	21		
Orchard Crops[d,l,m]										
Unspecified	3	6	26	52	1.2	2.5	4	8	3.6	1.6
Almond	3	6	23	46	1	2	3	6	3.6	1.6
Apple	2	4	21	42	0.5	1	1.5	3	5.2	2.3
Apricot	3	6	24	49	1	2	3	6	4	1.8
Avocado	10	21	58	116	3.8	7.5	12	25	3.4	1.5
Cherry	4	8	22	44	1.2	2.5	4	8	2.2	1.0
Citrus (orange, lemon)	3	6	40	81	1.5	3	5	9	2.2	1.0
Date palm	5	10	28	56	0.8	1.7	3	5	2.2	1.0
Fig	4	7	28	57	1.2	2.5	4	8	4.9	2.2
Nectarine	2	4	16	33	0.5	1	1.5	3	4.5	2.0

Table 2.5-5 (cont.).

Refuse Category	Particulate[b]		Carbon Monoxide		TOC[c] Methane		TOC[c] Nonmethane		Fuel Loading Factors (waste production)	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	Mg/hectare	ton/acre
Orchard Crops[d,l,m]										
Olive	6	12	57	114	2	4	7	14	2.7	1.2
Peach	3	6	21	42	0.6	1.2	2	4	5.6	2.5
Pear	4	9	28	57	1	2	3.5	7	5.8	2.6
Prune	2	3	24	47	1	2	3	6	2.7	1.2
Walnut	3	6	24	47	1	2	3	6	2.7	1.2
Forest Residues[n]										
Unspecified	8	17	70	140	2.8	5.7	9	19	157	70
Hemlock, Douglas fir, cedar[p]	2	4	45	90	0.6	1.2	2	4	ND	ND
Ponderosa pine[q]	6	12	98	195	1.7	3.3	5.5	11	ND	ND

[a] Expressed as weight of pollutant emitted per weight of refuse material burned. ND = no data.

[b] Reference 12. Particulate matter from most agricultural refuse burning has been found to be in the submicrometer size range.

[c] Data indicate that total organic compound (TOC) emissions average 22% methane, 7.5% other saturates, 17% olefins, 15% acetylene, 38.5% unidentified. Unidentified TOCs are expected to include aldehydes, ketones, aromatics, cycloparaffins.

[d] References 12-13 for emission factors, Reference 14 for fuel loading factors.

[e] For these refuse materials, no significant difference exists between emissions from headfiring and backfiring.

[f] Factors represent emissions under typical high moisture conditions. If ferns are dried to < 15% moisture, particulate emissions will be reduced by 30%, CO emissions 23%, TOC emissions 74%.

[g] Reference 11. When pineapple is allowed to dry to <20% moisture, as it usually is, firing technique is not important. When headfired at 20% moisture, particulate emissions will increase to 11.5 kg/Mg (23 lb/ton) and TOCs will increase to 6.5 kg/Mg (13 lb/ton).

[h] Factors are for dry (15% moisture) rice straw. If rice straw is burned at higher moisture levels, particulate emissions will increase to 14.5 kg/Mg (29 lb/ton), CO emissions to 80.5 kg/Mg (181 lb/ton), and VOC emissions to 11.5 kg/Mg (23 lb/ton).

[i] Reference 20. See Section 8.12 for discussion of sugar cane burning. The following fuel loading factors are to be used in the corresponding states: Louisiana, 8 - 13.6 Mg/hectare (3 - 5 ton/acre); Florida, 11 - 19 Mg/hectare (4 - 7 ton/acre); Hawaii, 30 - 48 Mg/hectare (11 - 17 ton/acre). For other areas, values generally increase with length of growing season. Use larger end of the emission factor range for lower loading factors.

Table 2.5-5 (cont.).

[j] See text for definition of headfiring.

[k] See text for definition of backfiring. This category, for emission estimation purposes, includes another technique used occasionally to limit emissions, called into-the-wind striplighting, which is lighting fields in strips into the wind at 100 - 200 meter (300 - 600 feet) intervals.

[l] Orchard prunings are usually burned in piles. There are no significant differences in emissions between burning a "cold pile" and using a roll-on technique, where prunings are bulldozed onto the embers of a preceding fire.

[m] If orchard removal is the purpose of a burn, 66 Mg/hectare (30 ton/acre) of waste will be produced.

[n] Reference 10. NO_x emissions estimated at 2 kg/Mg (4 lb/ton).

[p] Reference 15.

[q] Reference 16.

the corresponding emission factors, to estimate emissions from certain categories of agricultural burning when the specific fuel loadings for a given area are not known.

Emissions from leaf burning are dependent upon the moisture content, density, and ignition location of the leaf piles. Increasing the moisture content of the leaves generally increases the amount of carbon monoxide, hydrocarbon, and particulate emissions. Carbon monoxide emissions decrease if moisture content is high but increase if moisture content is low. Increasing the density of the piles increases the amount of hydrocarbon and particulate emissions, but has a variable effect on carbon monoxide emissions.

The highest emissions from open burning of leaves occur when the base of the leaf pile is ignited. The lowest emissions generally arise from igniting a single spot on the top of the pile. Particulate, hydrocarbon, and carbon monoxide emissions from windrow ignition (piling the leaves into a long row and igniting one end, allowing it to burn toward the other end) are intermediate between top and bottom ignition. Emission factors for leaf burning are presented in Table 2.5-6. For more detailed information on this subject, the reader should consult the reference cited at the end of this section.

2.5.2.4 Agricultural Plastic Film -

Agricultural plastic film that has been used for ground moisture and weed control. Large quantities of plastic film are commonly disposed of when field crops are burned. The plastic film may also be gathered into large piles and burned separately or burned in an air curtain. Emissions from burning agricultural plastic are dependent on whether the film is new or has been exposed to exposed to vegetation and possibly pesticides. Table 2.5-7 presents emission factors for organic compounds emitted from burning new and used plastic film in piles or in piles where air has been forced through them to simulate combustion in an air curtain. Table 2.5-8 presents emission factors for PAHs emitted from open burning of inorganic plastic film.

Table 2.5-6 (Metric And English Units). EMISSION FACTORS FOR LEAF BURNING[a]

EMISSION FACTOR RATING: D

Leaf Species	Particulate[b]		Carbon Monoxide		TOC[c]			
					Methane		Nonmethane	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Black Ash	18	36	63.5	127	5.5	11	13.5	27
Modesto Ash	16	32	81.5	163	5	10	12	24
White Ash	21.5	43	57	113	6.5	13	16	32
Catalpa	8.5	17	44.5	89	2.5	5	6.5	13
Horse Chestnut	27	54	73.5	147	8	17	20	40
Cottonwood	19	38	45	90	6	12	14	28
American Elm	13	26	59.5	119	4	8	9.5	19
Eucalyptus	18	36	45	90	5.5	11	13.5	27
Sweet Gum	16.5	33	70	140	5	10	12.5	25
Black Locust	35	70	65	130	11	22	26	52
Magnolia	6.5	13	27.5	55	2	4	5	10
Silver Maple	33	66	51	102	110	20	24.5	49
American Sycamore	7.5	15	57.5	115	2.5	5	5.5	11
California Sycamore	5	10	52	104	1.5	3	3.5	7
Tulip	10	20	38.5	77	3	6	7.5	15
Red Oak	46	92	68.5	137	14	28	34	69
Sugar Maple	26.5	53	54	108	8	16	20	40
Unspecified	19	38	56	112	6	12	14	28

[a] References 18-19. Factors are an arithmetic average of results obtained by burning high and low moisture content conical piles, ignited either at the top or around the periphery of the bottom. The windrow arrangement was only tested on Modesto Ash, Catalpa, American Elm, Sweet Gum, Silver Maple, and Tulip Poplar, and results are included in the averages for these species.

[b] The majority of particulate is submicrometer in size.

[c] Tests indicate that total organic compound (TOC) emissions average 29% methane, 11% other saturates, 33% olefins, 27% other (aromatics, acetylene, oxygenates).

Table 2.5-7 (Metric And English Units). EMISSION FACTORS FOR ORGANIC COMPOUNDS FROM BURNING PLASTIC FILM[a]

EMISSION FACTOR RATING: C

		Condition Of Plastic			
		Unused Plastic		Used Plastic	
Pollutant	Units	Pile[b]	Forced Air[c]	Pile[b]	Forced Air[c]
Benzene	mg/kg plastic	0.0478	0.0288	0.0123	0.0244
	lb/1000 tons plastic	0.0955	0.0575	0.0247	0.0488
Toluene	mg/kg plastic	0.0046	0.0081	0.0033	0.0124
	lb/1000 tons plastic	0.0092	0.0161	0.0066	0.0248
Ethyl benzene	mg/kg plastic	0.0006	0.0029	0.0012	0.0056
	lb/1000 tons plastic	0.0011	0.0058	0.0025	0.0111
1-Hexene	mg/kg plastic	0.0010	0.0148	0.0043	0.0220
	lb/1000 tons plastic	0.0020	0.0296	0.0086	0.0440

[a] Reference 22.

[b] Emission factors are for plastic gathered in a pile and burned.

[c] Emission factors are for plastic burned in a pile with a forced air current.

Table 2.5-8 (Metric And English Units). POLYCYCLIC AROMATIC HYDROCARBON EMISSION FACTORS FROM OPEN BURNING OF AGRICULTURAL PLASTIC FILM[a]

EMISSION FACTOR RATING: C

		Condition Of Plastic			
		Unused Plastic		Used Plastic	
Pollutant	Units	Pile[b]	Forced Air[c]	Pile[b]	Forced Air[c,d]
Anthracene	µg/kg plastic film	7.14	0.66	1.32	0.40
	lb/1000 tons plastic film	0.0143	0.0013	0.0026	0.0008
Benzo(A)pyrene	µg/kg plastic film	41.76	1.45	7.53	0.00
	lb/1000 tons plastic film	0.0835	0.0029	0.0151	0.0000
Benzo(B)fluoranthene	µg/kg plastic film	34.63	1.59	9.25	0.93
	lb/1000 tons plastic film	0.0693	0.0032	0.0185	0.0019
Benzo(e)pyrene	µg/kg plastic film	32.38	1.45	9.65	0.00
	lb/1000 tons plastic film	0.0648	0.0029	0.0193	0.0000
Benzo(G,H,I)perylene	µg/kg plastic film	49.43	2.11	14.93	0.00
	lb/1000 tons plastic film	0.0989	0.0042	0.0299	0.0000
Benzo(K)fluoranthene	µg/kg plastic film	13.74	0.66	2.51	0.00
	lb/1000 tons plastic film	0.0275	0.0013	0.0050	0.0000
Benz(A)anthracene	µg/kg plastic film	52.73	2.91	14.41	1.19
	lb/1000 tons plastic film	0.1055	0.0058	0.0288	0.0024
Chrysene	µg/kg plastic film	54.98	3.70	17.18	1.19
	lb/1000 tons plastic film	0.1100	0.0074	0.0344	0.0024

Table 2.5-8 (cont.).

Pollutant	Units	Condition Of Plastic			
		Unused Plastic		Used Plastic	
		Pile[b]	Forced Air[c]	Pile[b]	Forced Air[c,d]
Fluoranthene	μg/kg plastic film	313.08	53.39	107.05	39.12
	lb/1000 tons plastic film	0.6262	0.1068	0.2141	0.0782
Indeno(1,2,3-CD)pyrene	μg/kg plastic film	40.04	2.78	10.70	0.00
	lb/1000 tons plastic film	0.0801	0.0056	0.0214	0.0000
Phenanthrene	μg/kg plastic film	60.40	12.56	24.05	8.72
	lb/1000 tons plastic film	0.1208	0.0251	0.0481	0.0174
Pyrene	μg/kg plastic film	203.26	18.24	58.81	5.95
	lb/1000 tons plastic film	0.4065	0.0365	0.1176	0.0119
Retene	μg/kg plastic film	32.38	2.91	18.77	3.04
	lb/1000 tons plastic film	0.0648	0.0058	0.0375	0.0061

[a] Reference 22.

[b] Emission factors are for plastic gathered in a pile and burned.

[c] Emission factors are for plastic burned in a pile with a forced air current.

[d] 0.00 and 0.0000 values indicate pollutant was not found at that factor level.

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2.6 Automobile Body Incineration

The information presented in this section has been reviewed but not updated since it was originally prepared because no recent data were found and it is rarely practiced today. Auto bodies are likely to be shredded or crushed and used as scrap metal in secondary metal production operations, which are discussed in Chapter 12 (Metallurgical Industry).

2.6.1 Process Description

Auto incinerators consist of a single primary combustion chamber in which one or several partially stripped cars are burned. (Tires are removed.) Approximately 30 to 40 minutes is required to burn two bodies simultaneously.[2] As many as 50 cars per day can be burned in this batch-type operation, depending on the capacity of the incinerator. Continuous operations in which cars are placed on a conveyor belt and passed through a tunnel-type incinerator have capacities of more than 50 cars per 8-hour day.

2.6.2 Emissions And Controls[1]

Both the degree of combustion as determined by the incinerator design and the amount of combustible material left on the car greatly affect emissions. Temperatures on the order of 650°C (1200°F) are reached during auto body incineration.[2] This relatively low combustion temperature is a result of the large incinerator volume needed to contain the bodies as compared with the small quantity of combustible material. The use of overfire air jets in the primary combustion chamber increases combustion efficiency by providing air and increased turbulence.

In an attempt to reduce the various air pollutants produced by this method of burning, some auto incinerators are equipped with emission control devices. Afterburners and low-voltage electrostatic precipitators have been used to reduce particulate emissions; the former also reduces some of the gaseous emissions.[3,4] When afterburners are used to control emissions, the temperature in the secondary combustion chamber should be at least 815°C (1500°F). Lower temperatures result in higher emissions. Emission factors for auto body incinerators are presented in Table 2.6-1. Particulate matter is likely to be mostly in the PM-10 range, but no data are available to support this hypothesis. Although no data are available, emissions of HCl are expected due to the increased use of chlorinated plastic materials in automobiles.

Table 2.6-1 (English And Metric Units). EMISSION FACTORS FOR AUTO BODY INCINERATION[a]

EMISSION FACTOR RATING: D

Pollutants	Uncontrolled		With Afterburner	
	lb/car	kg/car	lb/car	kg/car
Particulates[b]	2	0.9	1.5	0.68
Carbon monoxide[c]	2.5	1.1	Neg	Neg
TOC (as CH_4)[c]	0.5	0.23	Neg	Neg
Nitrogen oxides (NO_2)[d]	0.1	0.05	0.02	0.01
Aldehydes (HCOH)[d]	0.2	0.09	0.06	0.03
Organic acids (acetic)[d]	0.21	0.10	0.07	0.03

[a] Based on 250 lb (113 kg) of combustible material on stripped car body.

[b] References 2 and 4.

[c] Based on data for open burning and References 2 and 5.

[d] Reference 3.

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2.7 Conical Burners

The information presented in this section has not been updated since it was originally prepared because no recent data were found. The use of conical burners is much less prevalent now than in the past and they are essentially obsolete.

2.7.1 Process Description[1]

Conical burners are generally truncated metal cones with screened top vents. The charge is placed on a raised grate by either conveyor or bulldozer; however, the use of a conveyor results in more efficient burning. No supplemental fuel is used, but combustion air is often supplemented by underfire air blown into the chamber below the grate and by overfire air introduced through peripheral openings in the shell.

2.7.2 Emissions And Controls

The quantities and types of pollutants released from conical burners are dependent on the composition and moisture content of the charged material, control of combustion air, type of charging system used, and the condition in which the incinerator is maintained. The most critical of these factors seems to be the level of maintenance on the incinerators. It is not uncommon for conical burners to have missing doors and numerous holes in the shell, resulting in excessive combustion air, low temperatures, and, therefore, high emission rates of combustible pollutants.[2]

Particulate control systems have been adapted to conical burners with some success. These control systems include water curtains (wet caps) and water scrubbers. Emission factors for conical burners are shown in Table 2.7-1.

Table 2.7-1 (English And Metric Units). EMISSION FACTORS FOR WASTE INCINERATION IN CONICAL BURNERS WITHOUT CONTROLS[a]

EMISSION FACTOR RATING: D

Type of Waste	Particulates		Sulfur Oxides		Carbon Monoxide		NMOC		Nitrogen Oxides	
	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg
Municipal refuse[b]	20 (10 to 60)[c,d]	10	2	1	60	30	20	10	5	2.5
Wood refuse[e]	1[f] 7[g] 20[h]	0.5 3.5 10	0.1	0.05	130	65	11	5.5	1	0.5

[a] Moisture content as fired is approximately 50% for wood waste. Blanks indicate no data.

[b] Except for particulates, factors are based on comparison with other waste disposal practices.

[c] Use high side of range for intermittent operations charged with a bulldozer.

[d] Based on Reference 3.

[e] References 4-9.

[f] Satisfactory operation: properly maintained burner with adjustable underfire air supply and adjustable, tangential overfire air inlets, approximately 500% excess air, and 370°C (700°F) exit gas temperature.

[g] Unsatisfactory operation: properly maintained burner with radial overfire air supply near bottom of shell, approximately 1200% excess air, and 204°C (400°F) exit gas temperature.

[h] Very unsatisfactory operation: improperly maintained burner with radial overfire air supply near bottom of shell and many gaping holes in shell, approximately 1500% excess air and 204°C (400°F) exit gas temperature.

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3. STATIONARY INTERNAL COMBUSTION SOURCES

Internal combustion engines often are used in applications similar to those associated with external combustion sources. The major items within this category are gas turbines and large heavy-duty general utility reciprocating engines. Most stationary internal combustion engines are used to generate electric power, to pump gas or other fluids, or to compress air for pneumatic machinery. The major pollutants of concern are total organic compounds and oxides of nitrogen. There also may be organic compounds that may be toxic or hazardous.

3.1 Stationary Gas Turbines For Electricity Generation

3.1.1 General

Stationary gas turbines are applied in electric power generators, in gas pipeline pump and compressor drives, and in various process industries. Gas turbines (greater than 4021 horsepower (electric) or 3 megawatts (electric) are used in electrical generation for continuous, peaking, or standby power. The primary fuels used are natural gas and distillate (No. 2) fuel oil, although residual fuel oil is used in a few applications.

3.1.2 Emissions And Controls

Emission control technologies for gas turbines have advanced to a point where all new and most existing units are complying with various levels of specified emission limits. For these sources, the emission factors become an operational specification rather than a parameter to be quantified by testing. This section treats uncontrolled (i. e., baseline) emissions and controlled emissions with specific control technologies.

The emission factors presented are for simple cycle gas turbines. These factors also apply to cogeneration/combined cycle gas turbines. In general, if the heat recovery steam generator (HRSG) is not supplementary fired, the simple cycle input-specific emission factors (nanograms per joule [ng/J] and pounds per million British thermal unit [lb/MMBtu]) will apply to cogeneration/combined cycle systems. The output-specific emissions (grams per kilowatt-hour [g/kw-hr] and pounds per horsepower-hour [lb/hp-hr]) will decrease according to the ratio of simple cycle to combined cycle power output. If the HRSG is supplementary fired, the emissions and fuel usage must be considered to estimate stack emissions. Nitrogen oxides (NO_x) emissions from regenerative cycle turbines (which account for only a small percentage of turbines in use) are greater than emissions from simple cycle turbines because of the increased combustion air temperature entering the turbine. The carbon monoxide (CO) and total organic compounds (TOC) emissions may be lower with the regenerative system for a comparable design. More power is produced from the same energy input, so the input-specific emissions factor will be affected by changes in emissions, while output-specific emissions will reflect the increased power output.

Water/steam injection is the most prevalent NO_x control for cogeneration/combined cycle gas turbines. The water or steam is injected with the air and fuel into the turbine combustion to lower the peak temperatures that, in turn, decreases the thermal NO_x produced. The lower average temperature within the combustor may produce higher levels of CO and TOCs as a result of incomplete combustion.

Selective catalytic reduction (SCR) is a postcombustion control that selectively reduces NO_x by reaction of ammonia (NH_3) and NO_x on a catalytic surface to form nitrogen gas (N_2) and water (H_2O). Although SCR systems can be used alone, all existing applications of SCR have been used in conjunction with water/steam injection controls. For optimum SCR operation, the flue gas must be within a temperature range of 315 - 426°C (600 - 800°F) with the precise limits dependent on the catalyst. Some SCR systems also utilize a CO catalyst to give simultaneous catalytic CO/NO_x control.

Advanced combustor can designs are currently being phased into production turbines. These dry techniques decrease turbine emissions by modifying the combustion mixing, air staging, and flame stabilization to allow operation at a much leaner air/fuel ratio relative to normal operation. Operating at leaner conditions will lower peak temperatures within the primary flame zone of the combustor. The lower temperatures may also increase CO and TOC emissions.

With the proliferation and advancement of NO_x control technologies for gas turbines during the past 15 years, the emission factors for the installed gas turbine population are quite different than those for uncontrolled turbines. However, uncontrolled turbine emissions have not changed significantly. Therefore a careful review of specific turbine details should be performed before applying uncontrolled emission factors. Today, most gas turbines are controlled to meet local, state, and/or federal regulations.

The average gaseous emission factors for uncontrolled gas turbines (firing natural gas and fuel oil) are presented in Tables 3.1-1 and 3.1-2. There is some variation in emissions over the population of large uncontrolled gas turbines because of the diversity of engine designs and models. Tables 3.1-3 and 3.1-4 present emission factors for gas turbines controlled for NO_x using water injection, steam injection, or SCR. Tables 3.1-5 and 3.1-6 present emission factors for large distillate oil-fired turbines controlled for NO_x using water injection.

Gas turbines firing distillate or residual oil may emit trace metals carried over from the metals content of the fuel. If the fuel analysis is known, the metals content of the fuel should be used for flue gas emission factors assuming all metals pass through the turbine. If the fuel analysis is not known, Table 3.1-7 provides order-of-magnitude levels of trace elements for turbines fired with distillate oil.

Table 3.1-1 (Metric Units). EMISSION FACTORS FOR LARGE UNCONTROLLED GAS TURBINES[a]

Pollutant	EMISSION FACTOR RATING[b]	Natural Gas (SCC 2-01-002-01)		Fuel Oil (Distillate) (SCC 2-01-001-01)	
		g/kW-hr[c] (power output)	ng/J (fuel input)	g/kW-hr[c] (power output)	ng/J (fuel input)
NO_x	C	2.15	190	3.41	300
CO	D	0.52	46	0.233	20.6
CO_2[d]	B	546	48,160	799	70,520
TOC (as methane)	D	0.117	10.32	0.083	7.31
SO_x (as SO_2)[e]	B	4.57S	404S	4.92S	434.3S
PM-10					
Solids	E	0.094	8.30	0.185	16.3
Condensables	E	0.11	9.72	0.113	9.89
Sizing %					
<0.05 μm	D	15%	15%	16%	16%
<0.10 μm	D	40%	40%	48%	48%
<0.15 μm	D	63%	63%	72%	72%
<0.20 μm	D	78%	78%	85%	85%
<0.25 μm	D	89%	89%	93%	93%
< 1 μm	D	100%	100%	100%	100%

[a] References 1-8. SCC = Source Classification Code. PM-10 = particulate matter less than or equal to 10 micrometers (μm) aerodynamic diameter, and sizing % is expressed in μm.

[b] Ratings reflect limited data and/or a lack of documentation of test results, may not apply to specific facilities or populations, and should be used with care.

[c] Calculated from ng/J assuming an average heat rate of 11,318 kJ/kW-hr.

[d] Based on 100% conversion of the fuel carbon to CO_2. CO_2 [ng/J] = 3.67*C/E, where C = carbon content of the fuel by weight (0.75), and E = energy content of fuel, 55.6 kJ/g. The uncontrolled CO_2 emission factors are also applicable to controlled gas turbines.

[e] All sulfur in the fuel is assumed to be converted to SO_2. S = % sulfur in fuel.

Table 3.1-2 (English Units). EMISSION FACTORS FOR LARGE UNCONTROLLED GAS TURBINES[a]

Pollutant	EMISSION FACTOR RATING[b]	Natural Gas (SCC 2-01-002-01)		Fuel Oil (Distillate) (SCC 2-01-001-01)	
		lb/hp-hr[c] (power output)	lb/MMBtu (fuel input)	lb/hp-hr[c] (power output)	lb/MMBtu (fuel input)
NO_x	C	3.53 E-03	0.44	5.60 E-03	0.698
CO	D	8.60 E-04	0.11	3.84 E-04	0.048
CO_2[d]	B	0.897	112	1.31	164
TOC (as methane)	D	1.92 E-04	0.024	1.37 E-04	0.017
SO_x (as SO_2)[e]	B	7.52 E-03S	0.94S	8.09 E-03S	1.01S
PM-10					
Solids	E	1.54 E-04	0.0193	3.04 E-04	0.038
Condensables	E	1.81 E-04	0.0226	1.85 E-04	0.023
Sizing %					
<0.05 μm	D	15%	15%	16%	16%
<0.10 μm	D	40%	40%	48%	48%
<0.15 μm	D	63%	63%	72%	72%
<0.20 μm	D	78%	78%	85%	85%
<0.25 μm	D	89%	89%	93%	93%
<1 μm	D	100%	100%	100%	100%

[a] References 1-8. SCC = Source Classification Code. PM-10 = particulate matter less than or equal to 10 μm aerodynamic diameter, and sizing % is expressed in μm.

[b] Ratings reflect limited data and/or a lack of documentation of test results, may not apply to specific facilities or populations, and should be used with care.

[c] Calculated from lb/MMBtu assuming an average heat rate of 8,000 Btu/hp-hr.

[d] Based on 100% conversion of the fuel carbon to CO_2. CO_2 [lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, (0.0239 MMBtu/lb). The uncontrolled CO_2 emission factors are also applicable to controlled gas turbines.

[e] All sulfur in the fuel is assumed to be converted to SO_2. S = % sulfur in fuel.

Table 3.1-3 (Metric Units). EMISSION FACTORS FOR LARGE GAS-FIRED CONTROLLED GAS TURBINES[a]

EMISSION FACTOR RATING: C

Pollutant	Water Injection (0.8 water/fuel ratio)		Steam Injection (1.2 water/fuel ratio)		Selective Catalytic Reduction (with water injection)
	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	ng/J (fuel input)
NO_x	0.66	61	0.59	52	3.78[b]
CO	1.3	120	0.71	69	3.61
TOC (as methane)	ND	ND	ND	ND	6.02
NH_3	ND	ND	ND	ND	2.80
NMHC	ND	ND	ND	ND	1.38
Formaldehyde[c]	ND	ND	ND	ND	1.16

[a] References 3,10-15. Source Classification Code 2-01-002-01. All data are averages of a limited number of tests and may not be typical of those reductions that can be achieved at a specific location. NMHC = nonmethane hydrocarbons. ND = no data.

[b] An SCR catalyst reduces NO_x by an average of 78%.

[c] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.1-4 (English Units). EMISSION FACTORS FOR LARGE GAS-FIRED CONTROLLED GAS TURBINES[a]

EMISSION FACTOR RATING: C

	Water Injection (0.8 water/fuel ratio)		Steam Injection (1.2 water/fuel ratio)		Selective Catalytic Reduction (with water injection)
Pollutant	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	ng/J (fuel input)
NO_x	1.10 E-03	0.14	9.70 E-04	0.12	0.03[b]
CO	2.07 E-03	0.28	1.17 E-03	0.16	0.0084
TOC (as methane)	ND	ND	ND	ND	0.014
NH_3	ND	ND	ND	ND	0.0065
NMHC	ND	ND	ND	ND	0.0032
Formaldehyde[c]	ND	ND	ND	ND	0.0027

[a] References 3,10-15. Source Classification Code 2-01-002-01. All data are averages of a limited number of tests and may not be typical of those reductions that can be achieved at a specific location. NMHC = nonmethane hydrocarbons. ND = no data.

[b] An SCR catalyst reduces NO_x by an average of 78%.

[c] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.1-5 (Metric Units). EMISSION FACTORS FOR LARGE DISTILLATE OIL-FIRED CONTROLLED GAS TURBINES[a]

Pollutant	EMISSION FACTOR RATING	Water Injection (0.8 water/fuel ratio)	
		g/kW-hr[b] (power output)	ng/J (fuel input)
NO_x	E	1.41	125
CO	E	0.090	8.26
TOC (as methane)	E	0.023	2.06
SO_x	B	—[c]	—[c]
PM-10[d]	E	0.181	16.00

[a] Reference 16. Source Classification Code 2-01-001-01. PM-10 = particulate matter $\leq$ 10 μm aerometric diameter.

[b] Calculated from fuel input assuming an average heat rate of 11,319 kJ/kW-hr.

[c] All sulfur in the fuel is assumed to be converted to SO_x.

[d] All PM is $\leq$ 1 μm in size.

Table 3.1-6 (English Units). EMISSION FACTORS FOR LARGE DISTILLATE OIL-FIRED CONTROLLED GAS TURBINES[a]

Pollutant	EMISSION FACTOR RATING	Water Injection (0.8 water/fuel ratio)	
		lb/hp-hr[b] (power output)	lb/MMBtu (fuel input)
NO_x	E	2.31 E-03	0.290
CO	E	1.48 E-04	0.0192
TOC (as methane)	E	3.75 E-05	0.0048
SO_x	B	—[c]	—[c]
PM-10[d]	E	2.98 E-04	0.0372

[a] Reference 16. Source Classification Code 2-01-001-01. PM-10 = particulate matter $\leq$ 10 μm aerometric diameter.

[b] Calculated from fuel input assuming an average heat rate of 8,000 Btu/hp-hr.

[c] All sulfur in the fuel is assumed to be converted to SO_x.

[d] All PM is $\leq$ 1 μm in size.

Table 3.1-7 (Metric And English Units). TRACE ELEMENT EMISSION FACTORS FOR DISTILLATE OIL-FIRED GAS TURBINES[a]

EMISSION FACTOR RATING: E[b]

Trace Element	pg/J	lb/MMBtu
Aluminum	64	1.5 E-04
Antimony[c]	9.4	2.2 E-05
Arsenic[c]	2.1	4.9 E-06
Barium	8.4	2.0 E-05
Beryllium[c]	0.14	3.3 E-07
Boron	28	6.5 E-05
Bromine	1.8	4.2 E-06
Cadmium[c]	1.8	4.2 E-06
Calcium	330	7.7 E-04
Chromium[c]	20	4.7 E-05
Cobalt[c]	3.9	9.1 E-06
Copper	578	1.3 E-03
Iron	256	6.0 E-04
Lead[c]	25	5.8 E-05
Magnesium	100	2.3 E-04
Manganese[c]	145	3.4 E-04
Mercury[c]	0.39	9.1 E-07
Molybdenum	3.6	8.4 E-06
Nickel[c]	526	1.2 E-03
Phosphorus[c]	127	3.0 E-04
Potassium	185	4.3 E-04
Selenium[c]	2.3	5.3 E-06
Silicon	575	1.3 E-03
Sodium	590	1.4 E-03
Tin	35	8.1 E-05
Vanadium	1.9	4.4 E-06
Zinc	294	6.8 E-04

[a] Reference 1. Source Classification Code 2-01-001-01.

[b] Ratings reflect limited data, may not apply to specific facilities or populations, and should be used with care.

[c] Hazardous air pollutant listed in the *Clean Air Act*.

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3.2 Heavy-duty Natural Gas-fired Pipeline Compressor Engines

3.2.1 General

Engines in the natural gas industry are used primarily to power compressors used for pipeline transportation, field gathering (collecting gas from wells), underground storage, and gas processing plant applications, i. e., prime movers. Pipeline engines are concentrated in the major gas-producing states (such as those along the Gulf Coast) and along the major gas pipelines. Gas turbines emit considerably smaller amounts of pollutants than do reciprocating engines; however, reciprocating engines are generally more efficient in their use of fuel.

Reciprocating engines are separated into 3 design classes: 2-cycle (stroke) lean burn, 4-stroke lean burn, and 4-stroke rich burn. Each of these have design differences that affect both baseline emissions as well as the potential for emissions control. Two-stroke engines complete the power cycle in a single engine revolution compared to 2 revolutions for 4-stroke engines. With the 2-stroke engine, the air/fuel charge is injected with the piston near the bottom of the power stroke. The valves are all covered or closed, and the piston moves to the top of the cylinder compressing the charge. Following ignition and combustion, the power stroke starts with the downward movement of the piston. Exhaust ports or valves are then uncovered to remove the combustion products, and a new air/fuel charge is ingested. Two-stroke engines may be turbocharged using an exhaust-powered turbine to pressurize the charge for injection into the cylinder. Nonturbocharged engines may be either blower scavenged or piston scavenged to improve removal of combustion products.

Four-stroke engines use a separate engine revolution for the intake/compression stroke and the power/exhaust stroke. These engines may be either naturally aspirated, using the suction from the piston to entrain the air charge, or turbocharged, using a turbine to pressurize the charge. Turbocharged units produce a higher power output for a given engine displacement, whereas naturally aspirated units have lower initial cost and maintenance. Rich burn engines operate near the air/fuel stoichiometric limit with exhaust excess oxygen levels less than 4 percent. Lean burn engines may operate up to the lean flame extinction limit, with exhaust oxygen levels of 12 percent or greater. Pipeline population statistics show a nearly equal installed capacity of turbines and reciprocating engines. For reciprocating engines, 2-stroke designs contribute approximately two-thirds of installed capacity.

3.2.2 Emissions And Controls

The primary pollutant of concern is nitrogen oxides (NO_x), which readily forms in the high-temperature, pressure, and excess air environment found in natural gas-fired compressor engines. Lesser amounts of carbon monoxide (CO) and total organic compounds (TOC) are emitted, although for each unit of natural gas burned, compressor engines (particularly reciprocating engines) emit significantly more of these pollutants than do external combustion boilers. Sulfur oxides emissions are proportional to the sulfur content of the fuel and will usually be quite low because of the negligible sulfur content of most pipeline gas. This section will also discuss the major variables affecting NO_x emissions and the various control technologies that will reduce uncontrolled NO_x emissions.

The major variables affecting NO_x emissions from compressor engines include the air/fuel ratio, engine load (defined as the ratio of the operating horsepower to the rated horsepower), intake (manifold) air temperature, and absolute humidity. In general, NO_x emissions increase with increasing load and intake air temperature, and decrease with increasing absolute humidity and air/fuel ratio (the latter already being, in most compressor engines, on the "lean" side of that air/fuel ratio at which maximum NO_x formation occurs). Quantitative estimates of the effects of these variables are presented in Reference 10.

Because NO_x is the primary pollutant of significance emitted from pipeline compressor engines, control measures to date have been directed mainly at limiting NO_x emissions. Reference 11 summarizes control techniques and emission reduction efficiencies. For gas turbines, the early control applications used water or steam injection. New applications of dry low NO_x combustor can designs and selective catalytic reduction (SCR) are appearing. Water injection has achieved reductions of 70 to 80 percent with utility gas turbines. Efficiency penalties of 2 to 3 percent are typical due to the added heat load of the water. Turbine power outputs typically increase, however. Steam injection may also be used, but the resulting NO_x reductions may not be as great as with water injection, and it has the added disadvantage that a supply of steam must be readily available. Water injection has not been applied to pipeline compressor engines because of the lack of water availability.

The efficiency penalty and operational impacts associated with water injection have led manufacturers to develop dry low NO_x combustor can designs based on lean burn and/or staging to suppress NO_x formation. These are entering the market in the early 1990s. Stringent gas turbine NO_x limits have been achieved in California in the late 1980s with SCR. This is an ammonia-based postcombustion technology that can achieve in excess of 80 percent NO_x reductions. Water or steam injection is frequently used in combination with SCR to minimize ammonia costs.

For reciprocating engines, both combustion controls and postcombustion catalytic reduction have been developed. Controlled rich burn engines have mostly been equipped with non-SCR (NSCR) that uses unreacted TOCs and CO to reduce NO_x by 80 to 90 percent. Some rich burn engines can be prestratified charge engines that reduce the peak flame temperature in the NO_x- forming regions. Lean burn engines have mostly met NO_x-reduction requirements with lean combustion controls using torch ignition or chamber redesign to enhance flame stability. NO_x reductions of 70 to 80 percent are typical for numerous engines with retrofit or new unit controls. Lean burn engines may also be controlled with SCR, but the operational problems associated with engine control under low NO_x operation have been a deterrent.

Emission factors for natural gas-fired pipeline compressor engines are presented in Tables 3.2-1 and 3.2-2 for baseline operation and in Tables 3.2-4, 3.2-5, 3.2-6, and 3.2-7 for controlled operation. The factors for controlled operation are taken from a single source test. Table 3.2-3 lists noncriteria emission factors. Factors are expressed in units of grams per kilowatt-hour (g/kW-hr) and grams per horsepower-hour (g/hp-hr), and nanograms per joule (ng/J) and pounds per million British thermal unit (lb/MMBtu), indicating metric and English units, respectively, for each set of units.

Table 3.2-1 (Metric Units). CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]

EMISSION FACTOR RATING: A (except as noted)

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-53)		4-Cycle Rich Burn (SCC 2-02-002-54)	
	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)
NO_x	1.70	145	14.79	1,165	16.1	1,376	13.46	989
CO	1.11	71	2.04	165	2.15	181	11.55	687
CO_2[b]	543	47,424	543	47,424	543	47,424	543	47,424
TOC	0.24	22.8	8.14	645	6.57	516	1.66	116
TNMOC	0.013	0.86	0.58	47.3	0.97	77.4	0.19	12.9
CH_4	0.228	21.9	7.56	615	5.50	473	1.48	103

[a] References 1-5. Factors are based on entire population. Factors for individual engines from specific manufacturers may vary. SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

[b] EMISSION FACTOR RATING: B. Based on 100% conversion of the fuel carbon to CO_2. CO_2 [ng/J] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 55.6 kJ/g. The uncontrolled CO_2 emission factors are also applicable to natural gas prime movers controlled by combustion modifications, NSCR, and SCR.

Table 3.2-2 (English Units). CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]

EMISSION FACTOR RATING: A (except as noted)

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-53)		4-Cycle Rich Burn (SCC 2-02-002-54)	
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)
NO_x	2.87 E-03	0.34	0.024	2.7	0.026	3.2	0.022	2.3
CO	1.83 E-03	0.17	3.31 E-03	0.38	3.53 E-03	0.42	0.019	1.6
CO_2[b]	0.89	110	0.89	110	0.89	110	0.89	110
TOC	3.97 E-04	0.053	0.013	1.5	0.011	1.2	2.65 E-03	0.27
TNMOC	2.20 E-05	0.002	9.48 E-04	0.11	1.59 E-03	0.18	3.09 E-04	0.03
CH_4	3.75 E-04	0.051	0.012	1.4	9.04 E-03	1.1	2.43 E-03	0.24

[a] References 1-5. Factors are based on entire population. Factors for individual engines from specific manufacturers may vary. SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

[b] EMISSION FACTOR RATING: B. Based on 100% conversion of the fuel carbon to CO_2. CO_2 [lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0239 MMBtu/lb. The uncontrolled CO_2 emission factors are also applicable to natural gas prime movers controlled by combustion modifications, NSCR, and SCR.

Table 3.2-3 (Metric And English Units). NONCRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]

EMISSION FACTOR RATING: E

Pollutant	2-Cycle Lean Burn	
	ng/J	lb/hp-hr
Formaldehyde[b]	140	2.93 E-03
Benzene[b]	0.17	3.62 E-06
Toluene[b]	0.17	3.62 E-06
Ethylbenzene[b]	0.086	1.81 E-06
Xylenes[b]	0.26	5.43 E-06

[a] Reference 1. Source Classification Code 2-02-002-52. Ratings reflect very limited data and may not apply to specific facilities.

[b] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.2-4 (Metric And English Units). EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: COMBUSTION MODIFICATIONS ON 2-STROKE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: E

Pollutant	Baseline				Increased Air/Fuel Ratio With Intercooling			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	13	0.022	1300	2.9	6.8	0.011	650	1.5
CO	1.3	2.07 E-03	120	0.28	2.1	3.31 E-03	200	0.46
TOC	10	0.017	960	2.2	11	0.019	1100	2.6
TNMOC	7.0	0.011	670	1.6	8.1	0.013	780	1.8
CH_4	3.1	5.07 E-03	290	0.68	3.4	5.51 E-03	320	0.75
PM-10								
Total (front+back halves)	0.21	3.53 E-04	20	0.046	0.25	3.97 E-04	24	0.055
Solids (front half)	0.13	2.16 E-04	13	0.029	0.17	2.87 E-04	16	0.038
Condensables (back half)	0.076	1.26 E-04	7.3	0.017	0.078	1.28 E-04	7.3	0.017

[a] Reference 6. Ratings reflect a single data set. Source Classification Code 2-02-002-52. CO_2 emissions are not affected by control. TNMOC = total nonmethane organic compounds. PM-10 = particulate matter ≤ 10 micrometers (μm) aerodynamic diameter (all particulate is assumed to be ≤ 1 μm aerodynamic diameter).

Table 3.2-5 (Metric And English Units). EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: NSCR ON 4-CYCLE RICH BURN ENGINE[a]

EMISSION FACTOR RATING: E

Pollutant	Inlet				Outlet			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	10	0.017	770	1.8	3.4	5.51 E-03	250	0.58
CO	16	0.026	1208	2.8	14	0.022	1000	2.4
TOC	0.44	7.28 E-04	33.97	0.079	0.27	4.41 E-04	20	0.047
NH_3	0.07	1.10 E-04	5.16	0.012	1.10	1.81 E-03	82	0.19
C7 - C16	0.026	4.19 E-05	1.81	0.0042	0.0055	9.04 E-06	0.39	0.0009
C16+	0.029	3.75 E-05	1.72	0.004	0.0008	1.32 E-06	0.043	0.0001
PM solids (front half)	0.004	6.61 E-06	0.301	0.0007	0.004	6.61 E-06	0.30	0.0007
Benzene[b]	ND	ND	0.31	7.1 E-04	ND	ND	0.047	1.1 E-04
Toluene[b]	ND	ND	0.099	2.3 E-04	ND	ND	0.0099	<2.3 E-05
Xylenes[b]	ND	ND	0.025	<5.9 E-05	ND	ND	0.017	<4.0 E-05
Propylene	ND	ND	0.069	<1.6 E-04	ND	ND	0.069	<1.6 E-04
Naphthalene[b]	ND	ND	0.021	<4.9 E-05	ND	ND	0.021	<4.9 E-05
Formaldehyde[b]	ND	ND	0.69	<1.6 E-03	ND	ND	0.003	<7.2 E-06
Acetaldehyde[b]	ND	ND	0.026	<6.1 E-05	ND	ND	0.0021	<4.8 E-06
Acrolein[b]	ND	ND	0.016	<3.7 E-05	ND	ND	0.0041	<9.6 E-06

[a] References 4,7. Ratings reflect very limited data and may not apply to specific facilities. ND = no data.

[b] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.2-6 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR NATURAL GAS PRIME MOVERS: SCR ON 4-CYCLE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: E

Pollutant	Inlet				Outlet			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	26	0.042	2,800	6.4	4.8	7.94 E-03	510	1.2
CO	1.6	2.65 E-03	160	0.38	1.5	2.43 E-03	160	0.37
NH_3	ND	ND	ND	ND	0.36	5.95 E-04	39	0.091
C7 - C16	0.009	1.54 E-05	0.99	0.0023	0.0042	6.83 E-06	0.56	0.0013
C16+	0.017	2.87 E-05	1.9	0.0044	0.0032	5.29 E-06	0.34	0.0008

[a] Reference 8. Ratings reflect very limited data and may not apply to specific facilities. CO_2 emissions are not affected by control. ND = no data.

Table 3.2-7 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR NATURAL GAS PRIME MOVERS: CLEAN BURN AND PRECOMBUSTION CHAMBER ON 2-CYCLE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: C

Pollutant	Clean Burn				Precombustion Chamber			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	3.1	5.07 E-03	360	0.83	3.9	6.39 E-03	370	0.85
CO	1.5	2.43 E-03	130	0.30	3.3	5.29 E-03	290	0.67
TOC	3.4	5.51 E-03	330	0.77	8.6	0.014	760	1.8
TNMOC	0.16	2.65 E-04	65	0.15	1.2	1.94 E-03	110	0.25
CH_4	3.3	5.29 E-03	260	0.62	7.4	0.012	650	1.5

[a] Reference 9. Source Classification Code 2-02-002-52. CO_2 emissions are not affected by control. TNMOC = total nonmethane organic compounds.

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10. *Standards Support And Environmental Impact Statement, Volume I: Stationary Internal Combustion Engines*, EPA-450/2-78-125a, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1979.

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3.3 Gasoline And Diesel Industrial Engines

3.3.1 General

The engine category addressed by this section covers a wide variety of industrial applications of both gasoline and diesel internal combustion (IC) engines such as aerial lifts, fork lifts, mobile refrigeration units, generators, pumps, industrial sweepers/scrubbers, material handling equipment (such as conveyors), and portable well-drilling equipment. The rated power of these engines covers a rather substantial range, up to 186 kilowatts (kW) (250 horsepower [hp]) for gasoline engines and up to 447 kW (600 hp) for diesel engines. (Diesel engines greater than 447 kW or 600 hp are covered in Section 3.4, "Large Stationary Diesel And All Stationary Dual-fuel Engines".) Understandably, substantial differences in engine duty cycles exist. It was necessary, therefore, to make reasonable assumptions concerning usage in order to formulate some of the emission factors.

3.3.2 Process Description

All reciprocating IC engines operate by the same basic process. A combustible mixture is first compressed in a small volume between the head of a piston and its surrounding cylinder. The mixture is then ignited, and the resulting high-pressure products of combustion push the piston through the cylinder. This movement is converted from linear to rotary motion by a crankshaft. The piston returns, pushing out exhaust gases, and the cycle is repeated.

There are 2 methods used for stationary reciprocating IC engines: compression ignition (CI) and spark ignition (SI). This section deals with both types of reciprocating IC engines. All diesel-fueled engines are compression ignited, and all gasoline-fueled engines are spark ignited.

In CI engines, combustion air is first compression heated in the cylinder, and diesel fuel oil is then injected into the hot air. Ignition is spontaneous because the air is above the autoignition temperature of the fuel. SI engines initiate combustion by the spark of an electrical discharge. Usually the fuel is mixed with the air in a carburetor (for gasoline) or at the intake valve (for natural gas), but occasionally the fuel is injected into the compressed air in the cylinder.

CI engines usually operate at a higher compression ratio (ratio of cylinder volume when the piston is at the bottom of its stroke to the volume when it is at the top) than SI engines because fuel is not present during compression; hence there is no danger of premature autoignition. Since engine thermal efficiency rises with increasing pressure ratio (and pressure ratio varies directly with compression ratio), CI engines are more efficient than SI engines. This increased efficiency is gained at the expense of poorer response to load changes and a heavier structure to withstand the higher pressures.

3.3.3 Emissions And Controls

The most accurate method for calculating such emissions is on the basis of "brake-specific" emission factors (grams per kilowatt-hour [g/kW-hr] or pounds per horsepower-hour [lb/hp-hr]). Emissions are the product of the brake-specific emission factor, the usage in hours, the rated power available, and the load factor (the power actually used divided by the power available). However, for emission inventory purposes, it is often easier to assess this activity on the basis of fuel used.

Once reasonable usage and duty cycles for this category were ascertained, emission values were aggregated to arrive at the factors for criteria and organic pollutants presented in Tables 3.3-1 and 3.3-2. Factors are also expressed in units of nanograms per joule (ng/J) and pounds per million British thermal unit (lb/MMBtu). Emission data for a specific design type were weighted according to estimated material share for industrial engines. The emission factors in these tables, because of their aggregate nature, are most appropriately applied to a population of industrial engines rather than to an individual power plant. Table 3.3-3 shows unweighted speciated organic compound and air toxic emission factors based upon only 2 engines. Their inclusion in this section is intended for rough order-of-magnitude estimates only.

Table 3.3-4 summarizes whether the various diesel emission reduction technologies (some of which may be applicable to gasoline engines) will generally increase or decrease the selected parameter. These technologies are categorized into fuel modifications, engine modifications, and exhaust after treatments. Current data are insufficient to quantify the results of the modifications. Table 3.3-4 provides general information on the trends of changes on selected parameters.

Table 3.3-1 (Metric Units). EMISSION FACTORS FOR UNCONTROLLED GASOLINE AND DIESEL INDUSTRIAL ENGINES[a]

Pollutant	Gasoline Fuel (SCC 2-02-003-01, 2-03-003-01)		Diesel Fuel (SCC 2-02-001-02, 2-03-001-01)		EMISSION FACTOR RATING
	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	
NO_x	6.92	699	18.8	1,896	D
CO	267	26,947	4.06	410	D
SO_x	0.359	36	1.25	126	D
PM-10[b]	0.439	44	1.34	135	D
CO_2[c]	661	66,787	704	71,065	B
Aldehydes	0.30	29	0.28	28	D
TOC					
Exhaust	8.96	905	1.50	152	D
Evaporative	0.40	41	0.00	0.00	E
Crankcase	2.95	298	0.03	2.71	E
Refueling	0.66	66	0.00	0.00	E

[a] References 1,3,6. When necessary, the average brake-specific fuel consumption (BSFC) value used to convert from ng/J to g/kW-hr was 9,902 kJ/kW-hr. SCC = Source Classification Code. TOC = total organic compounds.

[b] PM-10 = particulate matter less than or equal to 10 micrometers (μm) aerodynamic diameter. All particulate is assumed to be ≤ 1 μm in size.

[c] Assumes 100% conversion of carbon in fuel to CO_2 with 87 weight % carbon in diesel, 86 weight % carbon in gasoline, average BSFC of 9,901,600 J/kW-hr, diesel heating value of 44,900 J/g, and gasoline heating value of 47,200 J/g.

Table 3.3-2 (English Units). EMISSION FACTORS FOR UNCONTROLLED GASOLINE AND DIESEL INDUSTRIAL ENGINES[a]

Pollutant	Gasoline Fuel (SCC 2-02-003-01, 2-03-003-01)		Diesel Fuel (SCC 2-02-001-02, 2-03-001-01)		EMISSION FACTOR RATING
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	
NO_x	0.011	1.63	0.031	4.41	D
CO	0.439	62.7	6.68 E-03	0.95	D
SO_x	5.91 E-04	0.084	2.05 E-03	0.29	D
PM-10[b]	7.21 E-04	0.10	2.20 E-03	0.31	D
CO_2[c]	1.09	155	1.16	165	B
Aldehydes	4.85 E-04	0.07	4.63 E-04	0.07	D
TOC					
Exhaust	0.015	2.10	2.47 E-03	0.35	D
Evaporative	6.61 E-04	0.09	0.00	0.00	E
Crankcase	4.85 E-03	0.69	4.41 E-05	0.01	E
Refueling	1.08 E-03	0.15	0.00	0.00	E

[a] References 1,3,6. When necessary, the average brake-specific fuel consumption (BSFC) value used to convert from lb/MMBtu to lb/hp-hr was 7,000 Btu/hp-hr. SCC = Source Classification Code.

[b] PM-10 = particulate matter less than or equal to 10 μm aerodynamic diameter. All particulate is assumed to be ≤ 1 μm in size.

[c] Assumes 100% conversion of carbon in fuel to CO_2 with 87 weight % carbon in diesel, 86 weight % carbon in gasoline, average BSFC of 7,000 Btu/hp-hr, diesel heating value of 19,300 Btu/lb, and gasoline heating value of 20,300 Btu/lb.

Table 3.3-3 (Metric And English Units). SPECIATED ORGANIC COMPOUND EMISSION FACTORS FOR UNCONTROLLED DIESEL ENGINES[a]

EMISSION FACTOR RATING: E

Pollutant	Fuel Input	
	ng/J	lb/MMBtu
Benzene[b]	0.401	9.33 E-04
Toluene[b]	0.176	4.09 E-04
Xylenes[b]	0.122	2.85 E-04
Propylene[b]	1.109	2.58 E-03
1,3-Butadiene[b,c]	<0.017	<3.91 E-05
Formaldehyde[b]	0.509	1.18 E-03
Acetaldehyde[b]	0.330	7.67 E-04
Acrolein[b]	<0.040	<9.25 E-05
Polycyclic aromatic hydrocarbons (PAH)		
Naphthalene[b]	3.64 E-02	8.48 E-05
Acenaphthylene	<2.17 E-03	<5.06 E-06
Acenaphthene	<6.11 E-04	<1.42 E-06
Fluorene	1.26 E-02	2.92 E-05
Phenanthrene	1.26 E-02	2.94 E-05
Anthracene	8.02 E-04	1.87 E-06
Fluoranthene	3.27 E-03	7.61 E-06
Pyrene	2.06 E-03	4.78 E-06
Benz(a)anthracene	7.21 E-04	1.68 E-06
Chrysene	1.52 E-04	3.53 E-07
Benzo(b)fluoranthene	<4.26 E-05	<9.91 E-08
Benzo(k)fluoranthene	<6.67 E-05	<1.55 E-07
Benzo(a)pyrene	<8.07 E-05	<1.88 E-07
Indeno(1,2,3-cd)pyrene	<1.61 E-04	<3.75 E-07
Dibenz(a,h)anthracene	<2.50 E-04	<5.83 E-07
Benzo(g,h,l)perylene	<2.10 E-04	<4.89 E-07
TOTAL PAH	7.22 E-02	1.68 E-04

[a] Based on the uncontrolled levels of 2 diesel engines from References 6-7. Source Classification Codes 2-02-001-02, 2-03-001-01.

[b] Hazardous air pollutant listed in the *Clean Air Act*.

[c] Based on data from 1 engine.

Table 3.3-4. DIESEL EMISSION CONTROL TECHNOLOGY[a]

Technology	Affected Parameter	
	Increase	Decrease
Fuel modifications		
Sulfur content increase	PM, wear	
Aromatic content increase	PM, NO_x	
Cetane number		PM, NO_x
10% and 90% boiling point		PM
Fuel additives		PM, NO_x
Water/Fuel emulsions		NO_x
Engine modifications		
Injection timing retard	PM, BSFC	NO_x, power
Fuel injection pressure	PM, NO_x	
Injection rate control		NO_x, PM
Rapid spill nozzles		PM
Electronic timing & metering		NO_x, PM
Injector nozzle geometry		PM
Combustion chamber modifications		NO_x, PM
Turbocharging	PM, power	NO_x
Charge cooling		NO_x
Exhaust gas recirculation	PM, power, wear	NO_x
Oil consumption control		PM, wear
Exhaust after-treatment		
Particulate traps		PM
Selective catalytic reduction		NO_x
Oxidation catalysts		TOC, CO, PM

[a] Reference 4. PM = particulate matter. BSFC = brake-specific fuel consumption.

References For Section 3.3

1. C. T. Hare and K. J. Springer, *Exhaust Emissions From Uncontrolled Vehicles And Related Equipment Using Internal Combustion Engines, Part 5: Farm, Construction, And Industrial Engines*, APTD-1494, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1973.

2. H. I. Lips, *et al.*, *Environmental Assessment Of Combustion Modification Controls For Stationary Internal Combustion Engines*, EPA-600/7-81-127, U. S. Environmental Protection Agency, Cincinnati, OH, July 1981.

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4. *Technical Feasibility Of Reducing NO_x And Particulate Emissions From Heavy-duty Engines*, CARB Contract A132-085, California Air Resources Board, Sacramento, CA, March 1992.

5. *Nonroad Engine And Vehicle Emission Study - Report*, EPA-460/3-91-02, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 1991.

6. *Pooled Source Emission Test Report: Oil And Gas Production Combustion Sources, Fresno And Ventura Counties, California*, ENSR 7230-007-700, Western States Petroleum Association, Bakersfield, CA, December 1990.

7. W. E. Osborn and M. D. McDannel, *Emissions Of Air Toxic Species: Test Conducted Under AB2588 For The Western States Petroleum Association*, CR 72600-2061, Western States Petroleum Association, Glendale, CA, May 1990.

3.4 Large Stationary Diesel And All Stationary Dual-fuel Engines

3.4.1 General

The primary domestic use of large stationary diesel engines (greater than 447 kilowatts [kW] [600 horsepower (hp)]) is in oil and gas exploration and production. These engines, in groups of 3 to 5, supply mechanical power to operate drilling (rotary table), mud pumping, and hoisting equipment, and may also operate pumps or auxiliary power generators. Another frequent application of large stationary diesels is electricity generation for both base and standby service. Smaller uses include irrigation, hoisting, and nuclear power plant emergency cooling water pump operation.

Dual-fuel engines were developed to obtain compression ignition performance and the economy of natural gas, using a minimum of 5 to 6 percent diesel fuel to ignite the natural gas. Large dual-fuel engines have been used almost exclusively for prime electric power generation. This section includes all dual-fuel engines.

3.4.2 Process Description

All reciprocating internal combustion (IC) engines operate by the same basic process. A combustible mixture is first compressed in a small volume between the head of a piston and its surrounding cylinder. The mixture is then ignited, and the resulting high-pressure products of combustion push the piston through the cylinder. This movement is converted from linear to rotary motion by a crankshaft. The piston returns, pushing out exhaust gases, and the cycle is repeated.

There are 2 ignition methods used in stationary reciprocating IC engines, compression ignition (CI) and spark ignition (SI). This discussion deals only with CI engines.

In CI engines, combustion air is first compression heated in the cylinder, and diesel fuel oil is then injected into the hot air. Ignition is spontaneous because the air is above the autoignition temperature of the fuel. SI engines initiate combustion by the spark of an electrical discharge. Usually the fuel is mixed with the air in a carburetor (for gasoline) or at the intake valve (for natural gas), but occasionally the fuel is injected into the compressed air in the cylinder. Although all diesel-fueled engines are compression ignited and all gasoline- and gas-fueled engines are spark ignited, gas can be used in a CI engine if a small amount of diesel fuel is injected into the compressed gas/air mixture to burn any mixture ratio of gas and diesel oil (hence the name dual fuel), from 6 to 100 percent diesel oil.

CI engines usually operate at a higher compression ratio (ratio of cylinder volume when the piston is at the bottom of its stroke to the volume when it is at the top) than SI engines because fuel is not present during compression; hence there is no danger of premature autoignition. Since engine thermal efficiency rises with increasing pressure ratio (and pressure ratio varies directly with compression ratio), CI engines are more efficient than SI engines. This increased efficiency is gained at the expense of poorer response to load changes and a heavier structure to withstand the higher pressures.

3.4.3 Emissions And Controls

Most of the pollutants from IC engines are emitted through the exhaust. However, some total organic compounds (TOC) escape from the crankcase as a result of blowby (gases that are vented from the oil pan after they have escaped from the cylinder past the piston rings) and from the fuel tank and carburetor because of evaporation. Nearly all of the TOCs from diesel CI engines enter the atmosphere from the exhaust. Crankcase blowby is minor because TOCs are not present during compression of the charge. Evaporative losses are insignificant in diesel engines due to the low volatility of diesel fuels. In general, evaporative losses are also negligible in engines using gaseous fuels because these engines receive their fuel continuously from a pipe rather than via a fuel storage tank and fuel pump.

The primary pollutants from IC engines are oxides of nitrogen (NO_x), TOCs, carbon monoxide (CO), and particulates, which include both visible (smoke) and nonvisible emissions. The other pollutants are primarily the result of incomplete combustion. Ash and metallic additives in the fuel also contribute to the particulate content of the exhaust. Oxides of sulfur (SO_x) also appear in the exhaust from IC engines.

The primary pollutant of concern from large stationary diesel and all stationary dual-fuel engines is NO_x, which readily forms in the high temperature, pressure, nitrogen content of the fuel, and excess air environment found in these engines. Lesser amounts of CO and organic compounds are emitted. The sulfur compounds, mainly sulfur dioxide (SO_2), are directly related to the sulfur content of the fuel. SO_x emissions will usually be quite low because of the negligible sulfur content of diesel fuels and natural gas.

Tables 3.4-1 and 3.4-2 contain gaseous emission factors, which are expressed in units of grams per kilowatt hour (g/kw-hr) and pounds per horsepower-hour (lb/hp-hr), and nanograms per joule (ng/J) and pounds per million British thermal unit (lb/MMBtu).

Table 3.4-3 shows the speciated organic compound emission factors and Table 3.4-4 shows the emission factors for polycyclic aromatic hydrocarbons (PAH). These tables do not provide a complete speciated organic compound and PAH listing because they are based only on a single engine test; they are to be used for rough order of magnitude comparisons.

Table 3.4-5 shows the particulate and particle-sizing emission factors.

Control measures to date have been directed mainly at limiting NO_x emissions because NO_x is the primary pollutant from diesel and dual-fuel engines. Table 3.4-6 shows the NO_x reduction and fuel consumption penalties for diesel and dual-fueled engines based on some of the available control techniques. All of these controls are engine control techniques except for the selective catalytic reduction (SCR) technique, which is a postcombustion control. The emission reductions shown are those that have been demonstrated. The effectiveness of controls on an particular engine will depend on the specific design of each engine and the effectiveness of each technique could vary considerably. Other NO_x control techniques exist but are not included in Table 3.4-6. These techniques include internal/external exhaust gas recirculation, combustion chamber modification, manifold air cooling, and turbocharging.

Table 3.4-1 (Metric Units). GASEOUS EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL AND ALL STATIONARY DUAL-FUEL ENGINES[a]

Pollutant	Diesel Fuel (SCC 2-02-004-01)			Dual Fuel[b] (SCC 2-02-004-02)		
	g/kW-hr (power output)	ng/J (fuel input)	EMISSION FACTOR RATING	g/kW-hr (power output)	ng/J (fuel input)	EMISSION FACTOR RATING
NO_x	14	1,322	C	12.3	1,331	D
CO	3.2	349	C	3.1	340	D
SO_x[c]	$4.92S_1$	$434S_1$	B	$0.25S_1 + 4.34S_2$	$21.7S_1 + 384S_2$	B
CO_2[d]	703	70,942	B	469	47,424	B
TOC (as CH_4)	0.43	38	C	3.2	352	D
Methane	0.04	4	E[e]	2.4	240	E[f]
Nonmethane	0.44	45	E[e]	0.8	80	E[f]

[a] Based on uncontrolled levels for each fuel, from References 4-6. When necessary, the average heating value of diesel was assumed to be 44,900 J/g with a density of 851 g/liter. The power output and fuel input values were averaged independently from each other, because of the use of actual brake-specific fuel consumption (BSFC) values for each data point and of the use of data possibly sufficient to calculate only 1 of the 2 emission factors (e. g., enough information to calculate ng/J, but not g/kW-hr). Factors are based on averages across all manufacturers and duty cycles. The actual emissions from a particular engine or manufacturer could vary considerably from these levels. SCC = Source Classification Code.

[b] Dual fuel assumes 95% natural gas and 5% diesel fuel.

[c] Assumes that all sulfur in the fuel is converted to SO_2. S_1 = % sulfur in fuel oil; S_2 = % sulfur in natural gas.

[d] Assumes 100% conversion of carbon in fuel to CO_2 with 87 weight % carbon in diesel, 70 weight % carbon in natural gas, dual-fuel mixture of 5% diesel with 95% natural gas, average BSFC of 9,901,600 J/kW-hr, diesel heating value of 44,900 J/g, and natural gas heating value of 47,200 J/g.

[e] Based on data from 1 engine.

[f] Assumes that nonmethane organic compounds are 25% of TOC emissions from dual-fuel engines. Molecular weight of nonmethane gas stream is assumed to be that of methane.

Table 3.4-2 (English Units). GASEOUS EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL AND ALL STATIONARY DUAL-FUEL ENGINES[a]

Pollutant	Diesel Fuel (SCC 2-02-004-01)			Dual Fuel[b] (SCC 2-02-004-02)		
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	EMISSION FACTOR RATING	lb/hp-hr (power output)	lb/MMBtu (fuel input)	EMISSION FACTOR RATING
NO_x	0.024	3.1	C	0.020	3.1	D
CO	5.29 E-03	0.81	C	5.07 E-03	0.79	D
SO_x[c]	8.09 E-03S_1	1.01S_1	B	4.06 E-04S_1 + 9.57 E-03S_2	0.05S_1 + 0.895S_2	B
CO_2[d]	1.16	165	B	0.772	110	B
TOC (as CH_4)	7.05 E-04	0.09	C	5.29 E-03	0.8	D
Methane	6.61 E-05	0.01	E[e]	3.97 E-03	0.6	E[f]
Nonmethane	7.28 E-04	0.10	E[e]	1.32 E-03	0.2	E[f]

[a] Based on uncontrolled levels for each fuel, from References 4-6. When necessary, the average heating value of diesel was assumed to be 19,300 Btu/lb with a density of 7.1 lb/gallon. The power output and fuel input values were averaged independently from each other, because of the use of actual brake-specific fuel consumption (BSFC) values for each data point and of the use of data possibly sufficient to calculate only 1 of the 2 emission factors (e. g., enough information to calculate lb/MMBtu, but not lb/hp-hr). Factors are based on averages across all manufacturers and duty cycles. The actual emissions from a particular engine or manufacturer could vary considerably from these levels. SCC = Source Classification Code.

[b] Dual fuel assumes 95% natural gas and 5% diesel fuel.

[c] Assumes that all sulfur in the fuel is converted to SO_2. S_1 = % sulfur in fuel oil; S_2 = % sulfur in natural gas.

[d] Assumes 100% conversion of carbon in fuel to CO_2 with 87 weight % carbon in diesel, 70 weight % carbon in natural gas, dual-fuel mixture of 5% diesel with 95% natural gas, average BSFC of 7,000 Btu/hp, diesel heating value of 19,300 Btu/lb, and natural gas heating value of 20,300 Btu/lb.

[e] Based on data from 1 engine.

[f] Assumes that nonmethane organic compounds are 25% of TOC emissions from dual-fuel engines. Molecular weight of nonmethane gas stream is assumed to be that of methane.

Table 3.4-3 (Metric And English Units). SPECIATED ORGANIC COMPOUND EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL ENGINES[a]

EMISSION FACTOR RATING: E

Pollutant	ng/J	lb/MMBtu
Benzene[b]	3.34 E-01	7.76 E-04
Toluene[b]	1.21 E-01	2.81 E-04
Xylenes[b]	8.30 E-02	1.93 E-04
Propylene	1.20 E-00	2.79 E-03
Formaldehyde[b]	3.39 E-02	7.89 E-05
Acetaldehyde[b]	1.08 E-02	2.52 E-05
Acrolein[b]	3.39 E-03	7.88 E-06

[a] Based on 1 uncontrolled diesel engine from Reference 5. Source Classification Code 2-02-004-01. There was enough information to compute the input-specific emission factors of ng/J and lb/MMBtu, but not enough to calculate the output-specific emission factors of g/kW-hr and lb/hp-hr.

[b] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.4-4 (Metric And English Units). PAH EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL ENGINES[a]

EMISSION FACTOR RATING: E

PAH	Fuel Input	
	ng/J	lb/MMBtu
Naphthalene[b]	5.59 E-02	1.30 E-04
Acenaphthylene	3.97 E-03	9.23 E-06
Acenaphthene	2.01 E-03	4.68 E-06
Fluorene	5.50 E-03	1.28 E-05
Phenanthrene	1.75 E-02	4.08 E-05
Anthracene	5.29 E-04	1.23 E-06
Fluoranthene	1.73 E-03	4.03 E-06
Pyrene	1.60 E-03	3.71 E-06
Benz(a)anthracene	2.67 E-04	6.22 E-07
Chrysene	6.58 E-04	1.53 E-06
Benzo(b)fluoranthene	4.77 E-04	1.11 E-06
Benzo(k)fluoranthene	<9.37 E-05	<2.18 E-07
Benzo(a)pyrene	<1.10 E-04	<2.57 E-07
Indeno(1,2,3-cd)pyrene	<1.78 E-04	<4.14 E-07
Dibenz(a,h)anthracene	<1.49 E-04	<3.46 E-07
Benzo(g,h,l)perylene	<2.39 E-04	<5.56 E-07
TOTAL PAH	9.09 E-02	2.12 E-04

[a] Based on 1 uncontrolled diesel engine from Reference 5. Source Classification Code 2-02-004-01. There was enough information to compute the input-specific emission factors of ng/J and lb/MMBtu but not enough to calculate the output-specific emission factors of g/kW-hr and lb/hp-hr.

[b] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.4-5 (Metric And English Units). PARTICULATE AND PARTICLE-SIZING EMISSION FACTORS FOR LARGE UNCONTROLLED STATIONARY DIESEL ENGINES[a]

EMISSION FACTOR RATING: E

Pollutant	Fuel Input	
	ng/J	lb/MMBtu
Filterable particulate[b]		
< 1 μm	20.6	0.0478
< 3 μm	20.6	0.0479
< 10 μm	21.3	0.0496
Total filterable particulate	26.7	0.0620
Condensable particulate	3.31	0.0077
Total PM-10[c]	24.7	0.0573
Total particulate[d]	30.0	0.0697

[a] Based on 1 uncontrolled diesel engine from Reference 6. Source Classification Code 2-02-004-01. The data for the particulate emissions were collected using Method 5, and the particle size distributions were collected using a Source Assessment Sampling System. PM-10 = particulate matter ≤ 10 micrometers (μm) aerometric diameter.

[b] Particle size is expressed as aerodynamic diameter.

[c] Total PM-10 is the sum of filterable particulate less than 10 μm aerodynamic diameter and condensable particulate.

[d] Total particulate is the sum of the total filterable particulate and condensable particulate.

Table 3.4-6. NO_x REDUCTION AND FUEL CONSUMPTION PENALTIES FOR LARGE STATIONARY DIESEL AND DUAL-FUEL ENGINES[a]

Control Approach		Diesel (SCC 2-02-004-01)		Dual Fuel (SCC 2-02-004-02)	
		NO_x Reduction (%)	ΔBSFC[b] (%)	NO_x Reduction (%)	ΔBSFC (%)
Derate	10%	ND	ND	<20	4
	20%	<20	4	ND	ND
	25%	5 - 23	1 - 5	1 - 33	1 - 7
Retard	2°	<20	4	<20	3
	4°	<40	4	<40	1
	8°	28 - 45	2 - 8	50 - 73	3 - 5
Air-to-fuel	3%	ND	ND	<20	0
	±10%	7 - 8	3	25 - 40	1 - 3
Water injection (H_2O/fuel ratio)	50%	25 - 35	2 - 4	ND	ND
SCR		80 - 95	0	80 - 95	0

[a] References 1-3. The reductions shown are typical and will vary depending on the engine and duty cycle. SCC = Source Classification Code. ΔBSFC = change in brake-specific fuel consumption. ND = no data.

References For Section 3.4

1. H. I. Lips, *et al.*, *Environmental Assessment Of Combustion Modification Controls For Stationary Internal Combustion Engines*, EPA-600/7-81-127, U. S. Environmental Protection Agency, Cincinnati, OH, July 1981.

2. L. M. Campbell, *et al.*, *Sourcebook: NO_x Control Technology Data, Control Technology Center*, EPA-600/2-91-029, U. S. Environmental Protection Agency, Cincinnati, OH, July 1991.

3. *Catalysts For Air Pollution Control*, Manufacturers Of Emission Controls Association (MECA), Washington, DC, March 1992.

4. *Standards Support And Environmental Impact Statement, Volume I: Stationary Internal Combustion Engines*, EPA-450/2-78-125a, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1979.

5. *Pooled Source Emission Test Report: Oil And Gas Production Combustion Sources, Fresno And Ventura Counties, California*, ENSR # 7230-007-700, Western States Petroleum Association, Bakersfield, CA, December 1990.

6. C. Castaldini, *Environmental Assessment Of NO_x Control On A Compression Ignition Large Bore Reciprocating Internal Combustion Engine, Volume I: Technical Results*, EPA-600/7-86/001a, U. S. Environmental Protection Agency, Cincinnati, OH, April 1984.

4. EVAPORATION LOSS SOURCES

Evaporation losses include the organic solvents emitted from dry cleaning plants, surface coating operations, and degreasing operations. This chapter presents the volatile organic emissions from these sources. Where possible, the effect is shown of controls to reduce the emissions of organic compounds.

4.1 Dry Cleaning

4.1.1 General[1,2]

Dry cleaning involves the cleaning of fabrics with nonaqueous organic solvents. The dry cleaning process requires 3 steps: (1) washing the fabric in solvent, (2) spinning to extract excess solvent, and (3) drying by tumbling in a hot air stream.

Two general types of cleaning fluids are used in the industry, petroleum solvents and synthetic solvents. Petroleum solvents, such as Stoddard or 140-F, are inexpensive combustible hydrocarbon mixtures similar to kerosene. Operations using petroleum solvents are known as petroleum plants. Synthetic solvents are nonflammable but more expensive halogenated hydrocarbons. Perchloroethylene and trichlorotrifluoroethane are the 2 synthetic dry cleaning solvents presently in use. Operations using these synthetic solvents are respectively called "perc" plants and fluorocarbon plants.

There are 2 basic types of dry cleaning machines, transfer and dry-to-dry. Transfer machines accomplish washing and drying in separate machines. Usually, the washer extracts excess solvent from the clothes before they are transferred to the dryer, but some older petroleum plants have separate extractors for this purpose. Dry-to-dry machines are single units that perform all of the washing, extraction, and drying operations. All petroleum solvent machines are the transfer type, but synthetic solvent plants can be either type.

The dry cleaning industry can be divided into 3 sectors: coin-operated facilities, commercial operations, and industrial cleaners. Coin-operated facilities are usually part of a laundry supplying "self-service" dry cleaning for consumers. Only synthetic solvents are used in coin operated dry cleaning machines. Such machines are small, with a capacity of 3.6 to 11.5 kg (8 to 25 lb) of clothing.

Commercial operations, such as small neighborhood or franchise dry cleaning shops, clean soiled apparel for the consumer. Generally, perchloroethylene and petroleum solvents are used in commercial operations. A typical "perc" plant operates a 14 to 27 kg (30 to 60 lb) capacity washer/extractor and an equivalent size reclaiming dryer.

Industrial cleaners are larger dry cleaning plants which supply rental service of uniforms, mats, mops, etc., to businesses or industries. Perchloroethylene is used by approximately 50 percent of the industrial dry cleaning establishments. A typical large industrial cleaner has a 230 kg (500 lb) capacity washer/extractor and 3 to 6 38-kg (100-lb) capacity dryers.

A typical perc plant is shown in Figure 4.1-1. Although 1 solvent tank may be used, the typical perc plant uses 2 tanks for washing. One tank contains pure solvent, and the other contains "charged" solvent (used solvent to which small amounts of detergent have been added to aid in cleaning). Generally, clothes are cleaned in charged solvent and rinsed in pure solvent. A water bath may also be used.

After the clothes have been washed, the used solvent is filtered, and part of the filtered solvent is returned to the charged solvent tank for washing the next load. The remaining solvent is then distilled to remove oils, fats, greases, etc., and is returned to the pure solvent tank. The

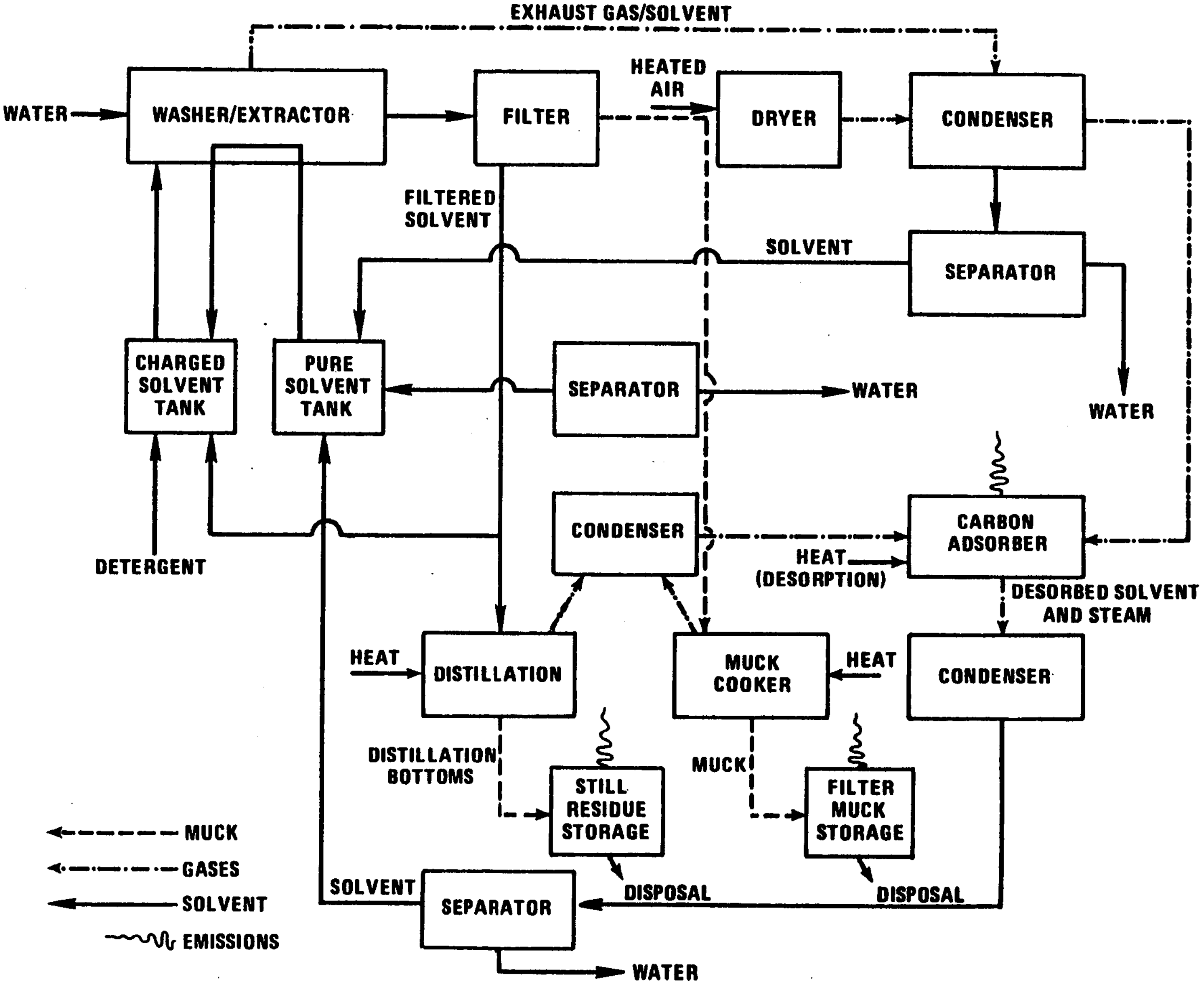


Figure 4.1-1. Perchloroethylene dry cleaning plant flow diagram.

collected solids (muck) are usually removed from the filter once a day. Before disposal, the muck may be "cooked" to recover additional solvent. Still and muck cooker vapors are vented to a condenser and separator, where more solvent is reclaimed. In many perc plants, the condenser offgases are vented to a carbon adsorption unit for additional solvent recovery.

After washing, the clothes are transferred to the dryer to be tumbled in a heated air stream. Exhaust gases from the dryer, along with a small amount of exhaust gases from the washer/extractor, are vented to a water-cooled condenser and water separator. Recovered solvent is returned to the pure solvent storage tank. In 30 to 50 percent of the perc plants, the condenser offgases are vented to a carbon adsorption unit for additional solvent recovery. To reclaim this solvent, the unit must be periodically desorbed with steam, usually at the end of each day. Desorbed solvent and water are condensed and separated, and recovered solvent is returned to the pure solvent tank.

A petroleum plant would differ from Figure 4.1-1 chiefly in that there would be no recovery of solvent from the washer and dryer and no muck cooker. A fluorocarbon plant would differ in that an unvented refrigeration system would be used in place of a carbon adsorption unit. Another difference is that a typical fluorocarbon plant could use a cartridge filter which is drained and disposed of after several hundred cycles.

4.1.2 Emissions And Controls[1-3]

The solvent itself is the primary emission from dry cleaning operations. Solvent is given off by washer, dryer, solvent still, muck cooker, still residue, and filter muck storage areas, as well as by leaky pipes, flanges, and pumps.

Petroleum plants have not generally employed solvent recovery, because of the low cost of petroleum solvents and the fire hazards associated with collecting vapors. Some emission control, however, can be obtained by maintaining all equipment (e. g., preventing lint accumulation, solvent leakage, etc.) and by using good operating practices (e. g., not overloading machinery). Both carbon adsorption and incineration appear to be technically feasible controls for petroleum plants, but costs are high.

Solvent recovery is necessary in perc plants due to the higher cost of perchloroethylene. As shown in Figure 4.1-1, recovery is effected on the washer, dryer, still, and muck cooker through the use of condensers, water/solvent separators and carbon adsorption units. Typically once a day, solvent in the carbon adsorption unit is desorbed with steam, condensed, separated from the condensed water, and returned to the pure solvent storage tank. Residual solvent emitted from treated distillation bottoms and muck is not recovered. As in petroleum plants, good emission control can be obtained by good housekeeping (maintaining all equipment and using good operating practices).

All fluorocarbon machines are of the dry-to-dry variety to conserve solvent vapor, and all are closed systems with built in solvent recovery. High emissions can occur, however, as a result of poor maintenance and operation of equipment. Refrigeration systems are installed on newer machines to recover solvent from the washer/dryer exhaust gases.

Emission factors for dry cleaning operations are presented in Table 4.1-1.

Typical coin-operated and commercial plants emit less than 10^6 grams (1 ton) per year. Some applications of emission estimates are too broad to identify every small facility. For estimates over large areas, the factors in Table 4.1-2 may be applied for coin-operated and commercial dry cleaning emissions.

Table 4.1-1 (Metric And English Units). SOLVENT LOSS EMISSION FACTORS FOR DRY CLEANING OPERATIONS

EMISSION FACTOR RATING: B

Solvent Type (Process Used)	Source	Emission Rate[a]	
		Typical System, kg/100 kg (lb/100 lb)	Well-Controlled System, kg/100 kg (lb/100 lb)
Petroleum	Washer/dryer[b]	18	2[c]
(transfer process)	Filter disposal		
	Uncooked (drained)	8	
	Centrifuged		0.5 - 1
	Still residue disposal	1	0.5 - 1
	Miscellaneous[d]	1	1
Perchloroethylene	Washer/dryer/still/muck cooker	8[e]	0.3[c]
(transfer process)	Filter disposal		
	Uncooked muck	14	
	Cooked muck	1.3	0.5 - 1.3
	Cartridge filter	1.1	0.5 - 1.1
	Still residue disposal	1.6	0.5 - 1.6
	Miscellaneous[d]	1.5	1
Trichlorotrifluoroethane	Washer/dryer/still[f]	0	0
(dry-to-dry process)	Cartridge filter disposal	1	1
	Still residue disposal	0.5	0.5
	Miscellaneous[d]	1 - 3	1 - 3

Table 4.1-1 (cont.).

[a] References 1-4. Units are in terms of weight solvent per weight of clothes cleaned (capacity x loads). Emissions also may be estimated by determining the amount of solvent consumed. Assuming that all solvent input is eventually evaporated to the atmosphere, an emission factor of 1000 kg/Mg (2000 lb/ton) of solvent consumed can be applied.

[b] Different materials in wash retain a different amount of solvent (synthetics, 10 kg/100 kg [10 lb/100 lb]; cotton, 20 kg/100 kg [20 lb/100 lb]; leather, 40 kg/100 kg [40 lb/100 lb]).

[c] Emissions from washer, dryer, still, and muck cooker are passed collectively through a carbon adsorber.

[d] Miscellaneous sources include fugitives from flanges, pumps, pipes, and storage tanks, and fixed losses such as opening and closing dryers, etc.

[e] Uncontrolled emissions from washer, dryer, still, and muck cooker average about 8 kg/100 kg (8 lb/100 lb). About 15% of solvent emitted is from washer, 75% dryer, 5% each from still and muck cooker.

[f] Based on the typical refrigeration system installed in fluorocarbon plants.

Table 4.1-2 (Metric And English Units). PER CAPITA SOLVENT LOSS EMISSION FACTORS FOR DRY CLEANING PLANTS[a]

EMISSION FACTOR RATING: B

Operation	Emission Factors	
	kg/yr/capita (lb/year/cap)	g/day/capita[b] (lb/day/cap)
Commercial	0.6 (1.3)	1.9 (0.004)
Coin-operated	0.2 (0.4)	0.6 (0.001)

[a] References 2-4. All nonmethane VOC.

[b] Assumes a 6-day operating week (313 days/yr).

References For Section 4.1

1. *Study To Support New Source Performance Standards For The Dry Cleaning Industry*, EPA Contract No. 68-02-1412, TRW, Inc., Vienna, VA, May 1976.

2. *Perchloroethylene Dry Cleaners — Background Information For Proposed Standards*, EPA-450/3-79-029a, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1980.

3. *Control Of Volatile Organic Emissions From Perchloroethylene Dry Cleaning Systems*, EPA-450/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1978.

4. *Control Of Volatile Organic Emissions From Petroleum Dry Cleaners (Draft)*, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1981.

4.2 Surface Coating

Surface coating operations involve the application of paint, varnish, lacquer, or paint primer, for decorative or protective purposes. This is accomplished by brushing, rolling, spraying, flow coating, and dipping operations. Some industrial surface coating operations include automobile assembly, job enameling, and manufacturing of aircraft, containers, furniture, appliances, and plastic products. Nonindustrial applications of surface coatings include automobile refinishing and architectural coating of domestic, industrial, government, and institutional structures, including building interiors and exteriors and exteriors and signs and highway markings. Nonindustrial Surface Coating is discussed below in Section 4.2.1, and Industrial Surface Coating in Section 4.2.2.

Emissions of volatile organic compounds (VOC) occur in surface coating operations because of evaporation of the paint vehicle, thinner, or solvent used to facilitate the application of coatings. The major factor affecting these emissions is the amount of volatile matter contained in the coating. The volatile portion of most common surface coatings averages about 50 percent, and most, if not all, of this is emitted during the application of coatings. The compounds released include aliphatic and aromatic hydrocarbons, alcohols, ketones, esters, alkyl and aryl hydrocarbon solvents, and mineral spirits. Table 4.2-1 presents emission factors for general surface coating operations.

Table 4.2-1 (Metric And English Units). EMISSION FACTORS FOR GENERAL SURFACE COATING APPLICATIONS[a]

EMISSION FACTOR RATING: B

Coating Type	VOC Emissions	
	kg/Mg	lb/ton
Paint	560	1,120
Varnish and shellac	500	1,000
Lacquer	770	1,540
Enamel	420	840
Primer (zinc chromate)	660	1,320

[a] References 1-2.

References For Section 4.2

1. *Products Finishing*, *41*(6A):4-54, March 1977.

2. *Air Pollution Engineering Manual*, Second Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1973. Out of Print.

4.2.1 Nonindustrial Surface Coating[1,3,5]

Nonindustrial surface coating operations are nonmanufacturing applications of surface coating. Two major categories are architectural surface coating and automobile refinishing. Architectural surface coating is considered to involve both industrial and nonindustrial structures. Automobile refinishing pertains to the painting of damaged or worn highway vehicle finishes and not to the painting of vehicles during manufacture.

Emissions from coating a single architectural structure or an automobile are calculated by using total volume and content and specific application. To estimate emissions for a large geographical area which includes many major and minor applications of nonindustrial surface coatings requires that area source estimates be developed. Architectural surface coating and auto refinishing emissions data are often difficult to compile for a large geographical area. In cases where a large emissions inventory is being developed and/or where resources are unavailable for detailed accounting of actual coatings volume for these applications, emissions may be assumed proportional to population or to number of employees in the activity. Table 4.2.1-1 presents factors from national emission data and gives emissions per population or employee for architectural surface coating and automobile refinishing.

Table 4.2.1-1 (Metric And English Units). NATIONAL EMISSIONS AND EMISSION FACTORS FOR VOC FROM ARCHITECTURAL SURFACE COATING AND AUTOMOBILE REFINISHING[a]

EMISSION FACTOR RATING: C

Emissions	Architectural Surface Coating	Automobile Refinishing
National		
Mg/yr (ton/yr)	446,000 (491,000)	181,000 (199,000)
Per capita		
kg/yr (lb/yr)	2.09 (4.6)	0.84 (1.9)
g/day (lb/day)	5.8 (0.013)[b]	2.7 (0.006)[c]
Per employee		
Mg/yr (ton/yr)	ND	2.3 (2.6)
kg/day (lb/day)	ND	7.4 (16.3)[c]

[a] References 3,5-8. All nonmethane organics. ND = no data.

[b] Reference 8. Calculated by dividing kg/yr (lb/yr) by 365 days and converting to appropriate units.

[c] Assumes a 6-day operating week (312 days/yr).

Using waterborne architectural coatings reduces VOC emissions. Current consumption trends indicate increasing substitution of waterborne architectural coatings for those using solvent. Automobile refinishing often is done in areas only slightly enclosed, which makes emissions control difficult. Where automobile refinishing takes place in an enclosed area, control of the gaseous emissions can be accomplished by the use of adsorbers (activated carbon) or afterburners. The collection efficiency of activated carbon has been reported at 90 percent or greater. Water curtains or filler pads have little or no effect on escaping solvent vapors, but they are widely used to stop paint particulate emissions.

References For Section 4.2.1

1. *Air Pollution Engineering Manual*, Second Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1973. Out of Print.

2. *Control Techniques For Hydrocarbon And Organic Gases From Stationary Sources*, AP-68, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1969.

3. *Control Techniques Guideline For Architectural Surface Coatings (Draft)*, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1979.

4. *Air Pollutant Emission Factors*, HEW Contract No. CPA-22-69-119, Resources Research Inc., Reston, VA, April 1970.

5. *Procedures For The Preparation Of Emission Inventories For Volatile Organic Compounds, Volume I*, Second Edition, EPA-450/2-77-028, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1980.

6. W. H. Lamason, "Technical Discussion Of Per Capita Emission Factors For Several Area Sources Of Volatile Organic Compounds", Technical Support Division, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 15, 1981. Unpublished.

7. *End Use Of Solvents Containing Volatile Organic Compounds*, EPA-450/3-79-032, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

8. Written communications between Bill Lamason and Chuck Mann, Technical Support Division, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1980, and March 1981.

4.2.2 Industrial Surface Coating

4.2.2.1 General Industrial Surface Coatings

4.2.2.2 Can Coating

4.2.2.3 Magnet Wire Coating

4.2.2.4 Other Metal Coating

4.2.2.5 Flat Wood Interior Panel Coating

4.2.2.6 Paper Coating

4.2.2.7 Polymeric Coating Of Supporting Substrates

4.2.2.8 Automobile And Light Duty Truck Surface Coating Operations

4.2.2.9 Pressure Sensitive Tapes And Labels

4.2.2.10 Metal Coil Surface Coating

4.2.2.11 Large Appliance Surface Coating

4.2.2.12 Metal Furniture Surface Coating

4.2.2.13 Magnetic Tape Manufacturing

4.2.2.14 Surface Coating Of Plastic Parts For Business Machines

4.2.2.1 General Industrial Surface Coating[1-4]

4.2.2.1.1 Process Description

Surface coating is the application of decorative or protective materials in liquid or powder form to substrates. These coatings normally include general solvent type paints, varnishes, lacquers, and water thinned paints. After application of coating by 1 of a variety of methods such as brushing, rolling, spraying, dipping and flow coating, the surface is air and/or heat dried to remove the volatile solvents from the coated surface. Powder type coatings can be applied to a hot surface or can be melted after application and caused to flow together. Other coatings can be polymerized after application by thermal curing with infrared or electron beam systems.

Coating Operations -

There are both "toll" ("independent") and "captive" surface coating operations. Toll operations fill orders to various manufacturer specifications, and thus change coating and solvent conditions more frequently than do captive companies, which fabricate and coat products within a single facility and which may operate continuously with the same solvents. Toll and captive operations differ in emission control systems applicable to coating lines, because not all controls are technically feasible in toll situations.

Coating Formulations -

Conventional coatings contain at least 30 volume percent solvents to permit easy handling and application. They typically contain 70 to 85 percent solvents by volume. These solvents may be of 1 component or of a mixture of volatile ethers, acetates, aromatics, cellosolves, aliphatic hydrocarbons, and/or water. Coatings with 30 volume percent of solvent or less are called low solvent or "high solids" coatings.

Waterborne coatings, which have recently gained substantial use, are of several types: water emulsion, water soluble and colloidal dispersion, and electrocoat. Common ratios of water to solvent organics in emulsion and dispersion coatings are 80:20 and 70:30.

Two-part catalyzed coatings to be dried, powder coatings, hot melts, and radiation cured (ultraviolet and electron beam) coatings contain essentially no volatile organic compounds (VOC), although some monomers and other lower molecular weight organics may volatilize.

Depending on the product requirements and the material being coated, a surface may have 1 or more layers of coating applied. The first coat may be applied to cover surface imperfections or to assure adhesion of the coating. The intermediate coats usually provide the required color, texture or print, and a clear protective topcoat is often added. General coating types do not differ from those described, although the intended use and the material to be coated determine the composition and resins used in the coatings.

Coating Application Procedures -

Conventional spray, which is air atomized and usually hand operated, is 1 of the most versatile coating methods. Colors can be changed easily, and a variety of sizes and shapes can be painted under many operating conditions. Conventional, catalyzed, or waterborne coatings can be applied with little modification. The disadvantages are low efficiency from overspray and high energy requirements for the air compressor.

In hot airless spray, the paint is forced through an atomizing nozzle. Since volumetric flow is less, overspray is reduced. Less solvent is also required, thus reducing VOC emissions. Care must be taken for proper flow of the coating, to avoid plugging and abrading of the nozzle orifice. Electrostatic spray is most efficient for low viscosity paints. Charged paint particles are attracted to an oppositely charged surface. Spray guns, spinning discs, or bell shaped atomizers can be used to atomize the paint. Application efficiencies of 90 to 95 percent are possible, with good "wraparound" and edge coating. Interiors and recessed surfaces are difficult to coat, however.

Roller coating is used to apply coatings and inks to flat surfaces. If the cylindrical rollers move in the same direction as the surface to be coated, the system is called a direct roll coater. If they rotate in the opposite direction, the system is a reverse roll coater. Coatings can be applied to any flat surface efficiently and uniformly and at high speeds. Printing and decorative graining are applied with direct rollers. Reverse rollers are used to apply fillers to porous or imperfect substrates, including papers and fabrics, to give a smooth uniform surface.

Knife coating is relatively inexpensive, but it is not appropriate for coating unstable materials, such as some knit goods, or when a high degree of accuracy in the coating thickness is required.

Rotogravure printing is widely used in coating vinyl imitation leathers and wallpaper, and in the application of a transparent protective layer over the printed pattern. In rotogravure printing, the image area is recessed, or "intaglio", relative to the copper plated cylinder on which the image is engraved. The ink is picked up on the engraved area, and excess ink is scraped off the nonimage area with a "doctor blade". The image is transferred directly to the paper or other substrate, which is web fed, and the product is then dried.

Dip coating requires that the surface of the subject be immersed in a bath of paint. Dipping is effective for coating irregularly shaped or bulky items and for priming. All surfaces are covered, but coating thickness varies, edge blistering can occur, and a good appearance is not always achieved.

In flow coating, materials to be coated are conveyed through a flow of paint. Paint flow is directed, without atomization, toward the surface through multiple nozzles, then is caught in a trough and recycled. For flat surfaces, close control of film thickness can be maintained by passing the surface through a constantly flowing curtain of paint at a controlled rate.

4.2.2.1.2 Emissions And Controls

Essentially all of the VOC emitted from the surface coating industry is from the solvents which are used in the paint formulations, used to thin paints at the coating facility, or used for cleanup. All unrecovered solvent can be considered potential emissions. Monomers and low molecular weight organics can be emitted from those coatings that do not include solvents, but such emissions are essentially negligible.

Emissions from surface coating for an uncontrolled facility can be estimated by assuming that all VOC in the coatings is emitted. Usually, coating consumption volume will be known, and some information about the types of coatings and solvents will be available. The choice of a particular emission factor will depend on the coating data available. If no specific information is given for the coating, it may be estimated from the data in Table 4.2.2.1-1.

All solvents separately purchased as solvent that are used in surface coating operations and are not recovered subsequently can be considered potential emissions. Such VOC emissions at a facility can result from onsite dilution of coatings with solvent, from "makeup solvents" required in flow

Table 4.2.2.1-1 (Metric And English Units). VOC EMISSION FACTORS FOR UNCONTROLLED SURFACE COATING[a]

EMISSION FACTOR RATING: B

	Emissions Of VOC[b]
Available Information On Coating	kg/liter Of Coating Or lb/gal Of Coating[c]
Conventional or waterborne paints:	
VOC, wt % (d)	d • (coating density)/100
or	
VOC, vol % (V)	V • (solvent density)/100
Waterborne paint:	
X = VOC as wt % of total volatiles including water; and d = total volatiles as wt % of coating	d • X • (coating density)/100
or	
Y = VOC as vol % of total volatiles including water; and V = total volatiles as vol % of coating	V • Y • (solvent density)/100

[a] Based on material balance, assuming entire VOC content is emitted.

[b] For special purposes, factors expressed in kg per liter of coating less water may be desired. These can be computed as follows:

$$\frac{\text{kg per liter of coating}}{1 - (\text{vol \% water}/100)} = \text{kg per liter of coating less water}$$

[c] If coating density is not known, typical densities are given in Table 4.2.2.1-2. If solvent density is not known, the average density of solvent in coatings is 0.88 kg/L (7.36 lb/gal).

coating and, in some instances, dip coating, and from the solvents used for cleanup. Makeup solvents are added to coatings to compensate for standing losses, concentration or amount, and thus to bring the coating back to working specifications. Solvent emissions should be added to VOC emissions from coatings to get total emissions from a coating facility.

Typical ranges of control efficiencies are given in Table 4.2.2.1-3. Emission controls normally fall under 1 of 3 categories: modification in paint formula, process changes, or add-on controls. These are discussed further in the specific subsections that follow.

Table 4.2.2.1-2 (Metric And English Units). TYPICAL DENSITIES AND SOLIDS CONTENTS OF COATINGS[a]

Type Of Coating	Density kg/L	Density lb/gal	Solids (Volume %)
Enamel, air dry	0.91	7.6	39.6
Enamel, baking	1.09	9.1	42.8
Acrylic enamel	1.07	8.9	30.3
Alkyd enamel	0.96	8.0	47.2
Primer surfacer	1.13	9.4	49.0
Primer, epoxy	1.26	10.5	57.2
Varnish, baking	0.79	6.6	35.3
Lacquer, spraying	0.95	7.9	26.1
Vinyl, roller coat	0.92	7.7	12.0
Polyurethane	1.10	9.2	31.7
Stain	0.88	7.3	21.6
Sealer	0.84	7.0	11.7
Magnet wire enamel	0.94	7.8	25.0
Paper coating	0.92	7.7	22.0
Fabric coating	0.92	7.7	22.0

[a] Reference 1.

Table 4.2.2.1-3. CONTROL EFFICIENCIES FOR SURFACE COATING OPERATIONS[a]

Control Option	Reduction[b] (%)
Substitute waterborne coatings	60 - 95
Substitute low solvent coatings	40 - 80
Substitute powder coatings	92 - 98
Add afterburners/incinerators	95

[a] References 2-4.

[b] Expressed as % of total uncontrolled emission load.

References For Section 4.2.2.1

1. *Controlling Pollution From the Manufacturing And Coating Of Metal Products: Metal Coating Air Pollution Control*, EPA-625/3-77-009, U. S. Environmental Protection Agency, Cincinnati, OH, May 1977.

2. H. R. Powers, "Economic And Energy Savings Through Coating Selection", The Sherwin-Williams Company, Chicago, IL, February 8, 1978.

3. *Air Pollution Engineering Manual*, Second Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1973. Out of Print.

4. *Products Finishing*, *41*(6A):4-54, March 1977.

4.2.2.2 Can Coating[1-4]

4.2.2.2.1 Process Description

Cans may be made from a rectangular sheet (body blank) and 2 circular ends (3-piece cans), or they can be drawn and wall ironed from a shallow cup to which an end is attached after the can is filled (2-piece cans). There are major differences in coating practices, depending on the type of can and the product packaged in it. Figure 4.2.2.2-1 depicts a 3-piece can sheet printing operation.

There are both "toll" and "captive" can coating operations. The former fill orders to customer specifications, and the latter coat the metal for products fabricated within one facility. Some can coating operations do both toll and captive work, and some plants fabricate just can ends.

Three-piece can manufacturing involves sheet coating and can fabricating. Sheet coating includes base coating and printing or lithographing, followed by curing at temperatures of up to 220°C (425°F). When the sheets have been formed into cylinders, the seam is sprayed, usually with a lacquer, to protect the exposed metal. If they are to contain an edible product, the interiors are spray coated, and the cans baked at up to 220°C (425°F).

Two-piece cans are used largely by beer and other beverage industries. The exteriors may be reverse roll coated in white and cured at 170 to 200°C (325 to 400°F). Several colors of ink are then transferred (sometimes by lithographic printing) to the cans as they rotate on a mandrel. A protective varnish may be roll coated over the inks. The coating is then cured in a single or multipass oven at temperatures of 180 to 200°C (350 to 400°F). The cans are spray coated on the interior and spray and/or roll coated on the exterior of the bottom end. A final baking at 110 to 200°C (225 to 400°F) completes the process.

4.2.2.2.2 Emissions And Controls

Emissions from can coating operations depend on composition of the coating, coated area, thickness of coat, and efficiency of application. Post-application chemical changes and nonsolvent contaminants like oven fuel combustion products may also affect the composition of emissions. All solvent used and not recovered can be considered potential emissions.

Sources of can coating VOC emissions include the coating area and the oven area of the sheet base and lithographic coating lines, the 3-piece can side seam and interior spray coating processes, and the 2-piece can coating and end sealing compound lines. Emission rates vary with line speed, can or sheet size, and coating type. On sheet coating lines, where the coating is applied by rollers, most solvent evaporates in the oven. For other coating processes, the coating operation itself is the major source. Emissions can be estimated from the amount of coating applied by using the factors in Table 4.2.2.1-1 or, if the number and general nature of the coating lines are known, from Table 4.2.2.2-1.

Incineration and the use of waterborne and low solvent coatings both reduce organic vapor emissions. Other technically feasible control options, such as electrostatically sprayed powder coatings, are not presently applicable to the whole industry. Catalytic and thermal incinerators both can be used. Primers, backers (coatings on the reverse or backside of the coil), and some waterborne low- to medium-gloss topcoats have been developed that equal the performance of organic

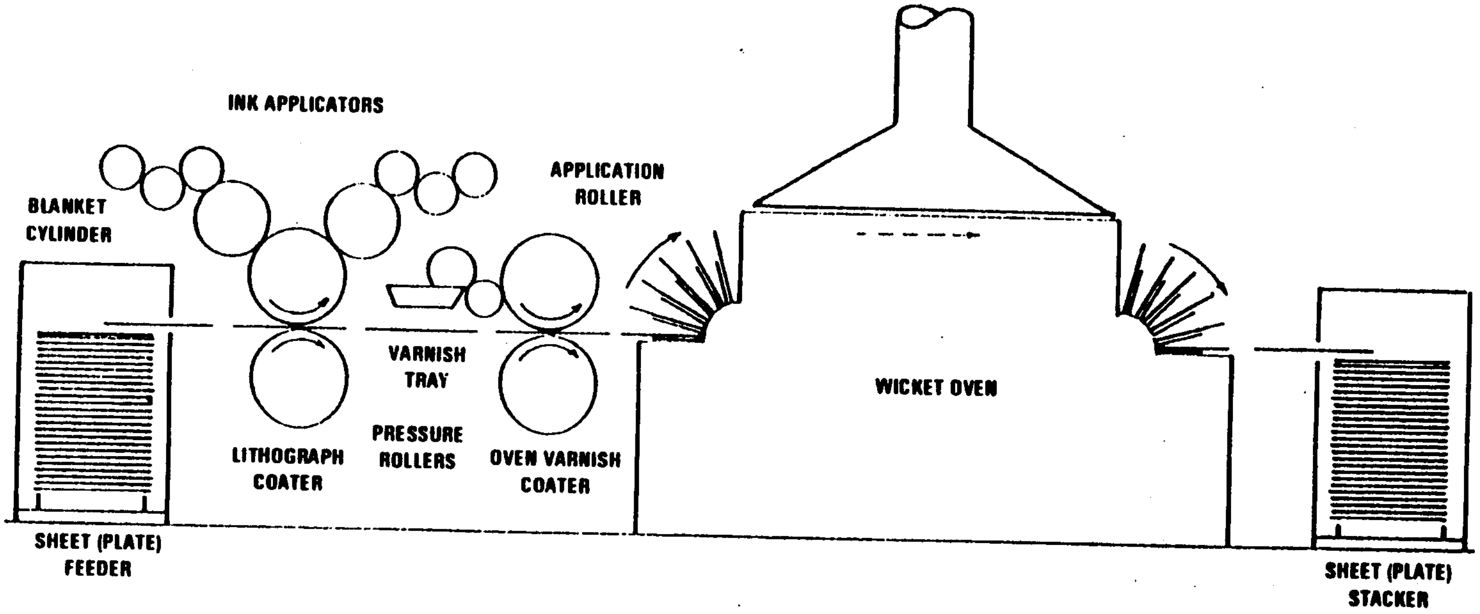


Figure 4.2.2.2-1. Three-piece can sheet printing operation.

Table 4.2.2.2-1 (Metric And English Units). VOC EMISSION FACTORS FOR CAN COATING PROCESSES[a]

EMISSION FACTOR RATING: B

Process	Typical Emissions From Coating Line[b]		Estimated Fraction From Coater Area (%)	Estimated Fraction From Oven (%)	Typical Organic Emissions[c]	
	kg/hr	lb/hr			Mg/yr	ton/yr
Three-piece can sheet base coating line	51	112	9 - 12	88 - 91	160	176
Three-piece can sheet lithographic coating line	30	65	8 - 11	89 - 92	50	55
Three-piece beer and beverage can — side seam spray coating process	5	12	100	air dried	18	20
Three-piece beer and beverage can — interior body spray coating process	25	54	75 - 85	15 - 25	80	88
Two-piece can coating line	39	86	ND	ND	260	287
Two-piece can end sealing compound line	4	8	100	air dried	14	15

[a] Reference 3. ND = no data.

[b] Organic solvent emissions will vary according to line speed, size of can or sheet being coated, and type of coating used.

[c] Based upon normal operating conditions.

solventborne coatings for aluminum but have not yet been applied at full line speed in all cases. Waterborne coatings for other metals are being developed.

Available control technology includes the use of add-on devices like incinerators and carbon adsorbers and a conversion to low solvent and ultraviolet curable coatings. Thermal and catalytic incinerators both may be used to control emissions from 3-piece can sheet base coating lines, sheet lithographic coating lines, and interior spray coating. Incineration is applicable to 2-piece can coating lines. Carbon adsorption is most acceptable to low temperature processes which use a limited number of solvents. Such processes include 2- and 3-piece can interior spray coating, 2-piece can end sealing compound lines, and 3-piece can side seam spray coating.

Low solvent coatings are not yet available to replace all the organic solventborne formulations presently used in the can industry. Waterborne basecoats have been successfully applied to 2-piece cans. Powder coating technology is used for side seam coating of noncemented 3-piece cans.

Ultraviolet curing technology is available for rapid drying of the first 2 colors of ink on 3-piece can sheet lithographic coating lines.

The efficiencies of various control technologies for can coating lines are presented in Table 4.2.2.2-2.

Table 4.2.2.2-2. CONTROL EFFICIENCIES FOR CAN COATING LINES[a]

Affected Facility[b]	Control Option	Reduction (%)[c]
Two-piece Can Lines		
Exterior coating	Thermal and catalytic incineration	90
	Waterborne and high solids coating	60 - 90
	Ultraviolet curing	≤100
Interior spraying coating	Thermal and catalytic incineration	90
	Waterborne and high solids coating	60 - 90
	Powder coating	100
	Carbon adsorption	90
Three-piece Can Lines		
Sheet coating lines		
Exterior coating	Thermal and catalytic incineration	90
	Waterborne and high solids coating	60 - 90
	Ultraviolet curing	≤100
Interior spray coating	Thermal and catalytic incineration	90
	Waterborne and high solids coating	60 - 90
Can fabricating lines		
Side seam spray coating	Waterborne and high solids coating	60 - 90
	Powder (only for uncemented seams)	100
Interior spray coating	Thermal and catalytic incineration	90
	Waterborne and high solids coating	60 - 90
	Powder (only for uncemented seams)	100
	Carbon adsorption	90
End Coating Lines		
Sealing compound	Waterborne and high solids coating	70 - 95
Sheet coating	Carbon adsorption	90
	Thermal and catalytic incineration	90
	Waterborne and high solids coating	60 - 90

[a] Reference 3.

[b] Coil coating lines consist of coaters, ovens, and quench areas. Sheet, can, and end wire coating lines consist of coaters and ovens.

[c] Compared to conventional solvent base coatings used without any added thinners.

References For Section 4.2.2.2

1. T. W. Hughes, *et al.*, *Source Assessment: Prioritization Of Air Pollution From Industrial Surface Coating Operations*, EPA-650/2-75-019a, U. S. Environmental Protection Agency, Cincinnati, OH, November 1975.

2. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume I: Control Methods For Surface Coating Operations*, EPA-450/2-76- 028, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1977.

3. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume II: Surface Coating Of Cans, Coils, Paper Fabrics, Automobiles, And Light Duty Trucks*, EPA-450/2-77-008, U. S. Environmental Protection Agency; Research Triangle Park, NC, May 1977.

4. *Air Pollution Control Technology Applicable To 26 Sources Of Volatile Organic Compounds*, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 27, 1977. Unpublished.

4.2.2.3 Magnet Wire Coating[1]

4.2.2.3.1 Process Description

Magnet wire coating is applying a coat of electrically insulating varnish or enamel to aluminum or copper wire used in electrical machinery. The wire is usually coated in large plants that both draw and insulate it and then sell it to electrical equipment manufacturers. The wire coating must meet rigid electrical, thermal, and abrasion specifications.

Figure 4.2.2.3-1 shows a typical wire coating operation. The wire is unwound from spools and passed through an annealing furnace. Annealing softens the wire and cleans it by burning off oil and dirt. Usually, the wire then passes through a bath in the coating applicator and is drawn through an orifice or coating die to scrape off the excess. It is then dried and cured in a 2-zone oven first at 200°C, then 430°C (400 and 806°F). Wire may pass through the coating applicator and the oven as many as 12 times to acquire the necessary thickness of coating.

4.2.2.3.2 Emissions And Controls

Emissions from wire coating operations depend on composition of the coating, thickness of coat and efficiency of application. Postapplication chemical changes, and nonsolvent contaminants such as oven fuel combustion products, may also affect the composition of emissions. All solvent used and not recovered can be considered potential emissions.

The exhaust from the oven is the most important source of solvent emissions in the wire coating plant. Emissions from the applicator are comparatively low, because a dip coating technique is used (see Figure 4.2.2.3-1).

Volatile organic compound (VOC) emissions may be estimated from the factors in Table 4.2.2.1-1, if the coating usage is known and if the coater has no controls. Most wire coaters built since 1960 do have controls, so the information in the following paragraph may be applicable. Table 4.2.2.3-1 gives estimated emissions for a typical wire coating line.

Incineration is the only commonly used technique to control emissions from wire coating operations. Since about 1960, all major wire coating designers have incorporated catalytic incinerators into their oven designs because of the economic benefits. The internal catalytic incinerator burns solvent fumes and circulates heat back into the wire drying zone. Fuel otherwise needed to operate the oven is eliminated or greatly reduced, as are costs. Essentially all solvent emissions from the oven can be directed to an incinerator with a combustion efficiency of at least 90 percent.

Ultraviolet cured coatings are available for special systems. Carbon adsorption is not practical. Use of low solvent coatings is only a potential control, because they have not yet been developed with properties that meet industry's requirements.

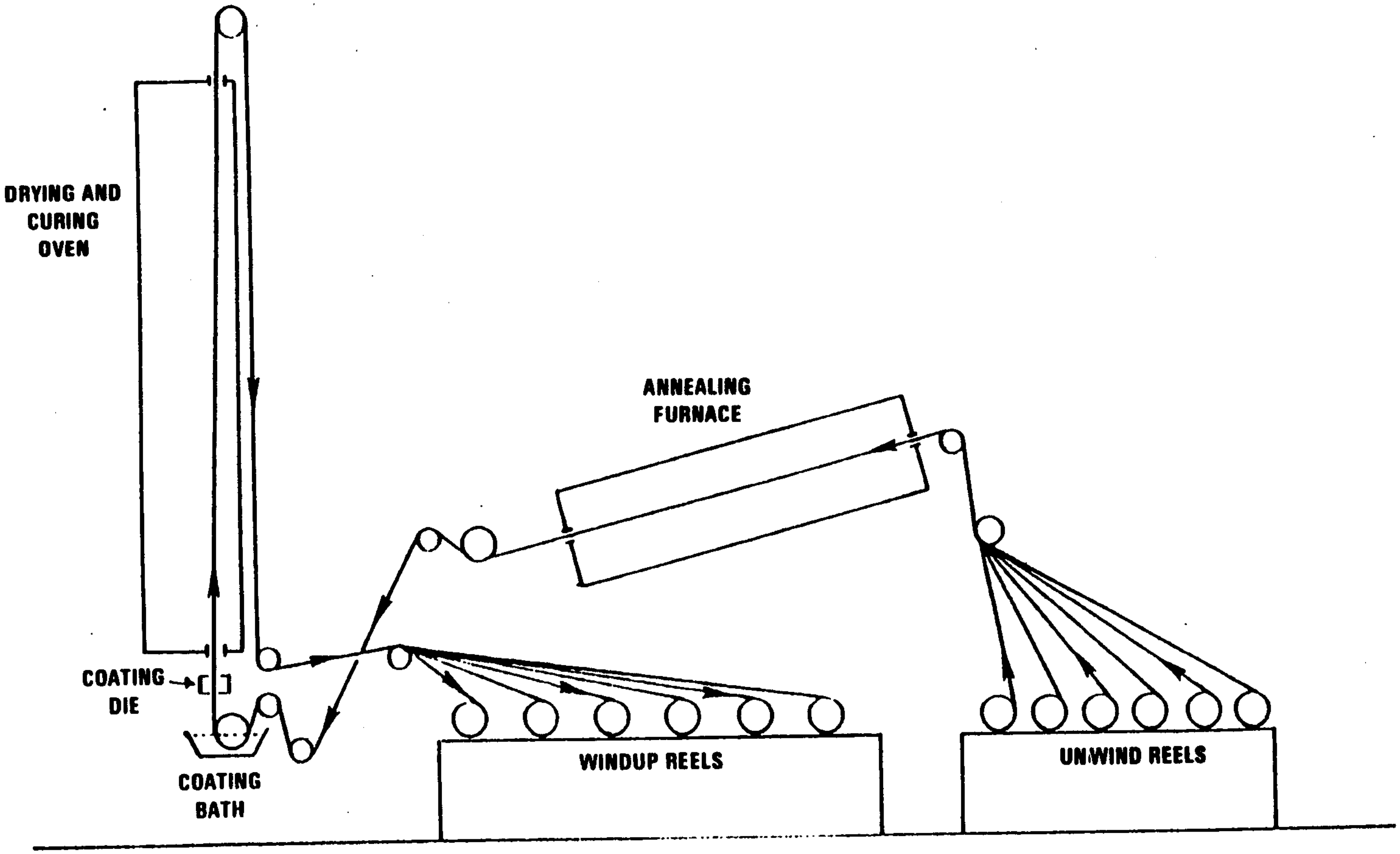


Figure 4.2.2.3-1. Wire coating line emission points.

Table 4.2.2.3-1 (Metric And English Units). ORGANIC SOLVENT EMISSIONS FROM A TYPICAL WIRE COATING LINE[a]

Coating Line[b]		Annual Totals[c]	
kg/hr	lb/hr	Mg/yr	ton/yr
12	26	84	93

[a] Reference 1.

[b] Organic solvent emissions vary from line to line by size and speed of wire, number of wires per oven, and number of passes through oven. A typical line may coat 544 kg (1,200 lb) wire/day. A plant may have many lines.

[c] Based upon normal operating conditions of 7,000 hr/yr for one line without incinerator.

References For Section 4.2.2.3

1. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume IV: Surface Coating For Insulation Of Magnet Wire*, EPA-450/2-77-033, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1977.

2. *Controlled And Uncontrolled Emission Rates And Applicable Limitations For Eighty Processes*, EPA Contract Number 68-02-1382, TRC Of New England, Wethersfield, CT, September 1976.

4.2.2.4 Other Metal Coating[1-4]

4.2.2.4.1 Process Description

Large appliance, metal furniture, and miscellaneous metal part and product coating lines have many common operations, similar emissions and emission points, and available control technology. Figure 4.2.2.4-1 shows a typical metal furniture coating line.

Large appliances include doors, cases, lids, panels, and interior support parts of washers, dryers, ranges, refrigerators, freezers, water heaters, air conditioners, and associated products. Metal furniture includes both outdoor and indoor pieces manufactured for household, business, or institutional use. "Miscellaneous parts and products" herein denotes large and small farm machinery, small appliances, commercial and industrial machinery, fabricated metal products and other industries that coat metal under Standard Industrial Classification (SIC) codes 33 through 39.

Large Appliances -

The coatings applied to large appliances are usually epoxy, epoxy/acrylic, or polyester enamels for the primer or single coat, and acrylic enamels for the topcoat. Coatings containing alkyd resins are also used. Prime and interior single coats are applied at 25 to 36 volume percent solids. Topcoats and exterior single coats are applied at 30 to 40 volume percent. Lacquers may be used to touch up any scratches that occur during assembly. Coatings contain 2 to 15 solvents, typical of which are esters, ketones, aliphatics, alcohols, aromatics, ethers, and terpenes.

Small parts are generally dip coated, and flow or spray coating is used for larger parts. Dip and flow coating are performed in an enclosed room vented either by a roof fan or by an exhaust system adjoining the drain board or tunnel. Down or side draft booths remove overspray and organic vapors from prime coat spraying. Spray booths are also equipped with dry filters or a water wash to trap overspray.

Parts may be touched up manually with conventional or airless spray equipment. Then they are sent to a flashoff area (either open or tunneled) for about 7 minutes and are baked in a multipass oven for about 20 minutes at 180 to 230°C (350 to 450°F). At that point, large appliance exterior parts go on to the topcoat application area, and single coated interior parts are moved to the assembly area of the plant.

The topcoat, and sometimes primers, are applied by automated electrostatic disc, bell, or other types of spray equipment. Topcoats often are more than 1 color, changed by automatically flushing out the system with solvent. Both the topcoat and touchup spray areas are designed with side- or down-draft exhaust control. The parts go through about a 10-minute flashoff period, followed by baking in a multipass oven for 20 to 30 minutes at 140 to 180°C (270 to 350°F).

Metal Furniture -

Most metal furniture coatings are enamels, although some lacquers are used. The most common coatings are alkyds, epoxies, and acrylics, which contain the same solvents used in large appliance coatings, applied at about 25 to 35 percent solids.

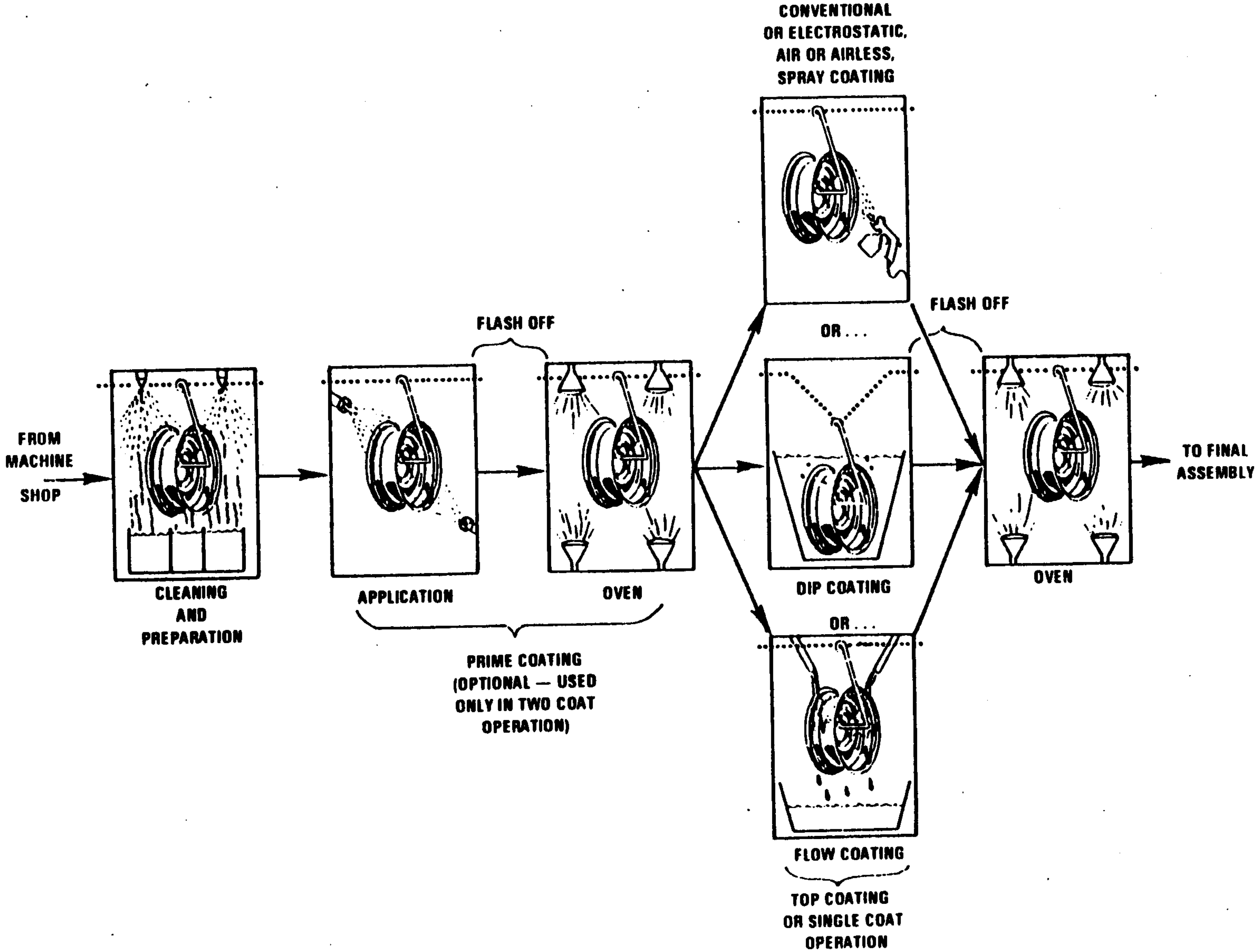


Figure 4.2.2.4-1. Metal product coating line emission points.

On a typical metal furniture coating line (see Figure 4.2.2.4-1), the prime coat can be applied with the same methods used for large appliances, but it may be cured at slightly lower temperatures, 150 to 200°C (300 to 400°F). The topcoat, usually the only coat, is applied with electrostatic spray or with conventional airless or air spray. Most spray coating is manual, in contrast to large appliance operations. Flow coating or dip coating is done, if the plant generally uses only 1 or 2 colors on a line.

The coated furniture is usually baked, but in some cases it is air dried. If it is to be baked, it passes through a flashoff area into a multizone oven at temperatures ranging from 150 to 230°C (300 to 450°F).

Miscellaneous Metal Parts And Products -

Both enamels (30 to 40 volume percent solids) and lacquers (10 to 20 volume percent solids) are used to coat miscellaneous metal parts and products, although enamels are more common. Coatings often are purchased at higher volume percent solids but are thinned before application (frequently with aromatic solvent blends). Alkyds are popular with industrial and farm machinery manufacturers. Most of the coatings contain several (up to 10) different solvents, including ketones, esters, alcohols, aliphatics, ethers, aromatics, and terpenes.

Single or double coatings are applied in conveyored or batch operations. Spraying is usually employed for single coats. Flow and dip coating may be used when only 1 or 2 colors are applied. For 2-coat operations, primers are usually applied by flow or dip coating, and topcoats are almost always applied by spraying. Electrostatic spraying is common. Spray booths and areas are kept at a slight negative pressure to capture overspray.

A manual 2-coat operation may be used for large items like industrial and farm machinery. The coatings on large products are often air dried rather than oven baked, because the machinery, when completely assembled, includes heat sensitive materials and may be too large to be cured in an oven. Miscellaneous parts and products can be baked in single or multipass ovens at 150 to 230°C (300 to 450°F).

4.2.2.4.2 Emissions And Controls

Volatile organic compounds (VOC) are emitted from application and flashoff areas and the ovens of metal coating lines (see Figure 4.2.2.4-1). The composition of emissions varies among coating lines according to physical construction, coating method, and type of coating applied, but distribution of emissions among individual operations has been assumed to be fairly constant, regardless of the type of coating line or the specific product coated, as Table 4.2.2.4-1 indicates. All solvent used can be considered potential emissions. Emissions can be calculated from the factors in Table 4.2.2.1-1 if coatings use is known, or from the factors in Table 4.2.2.4-1 if only a general description of the plant is available. For emissions from the cleansing and pretreatment area, see Section 4.6, Solvent Degreasing.

When powder coatings, which contain almost no VOC, are applied to some metal products as a coating modification, emissions are greatly reduced. Powder coatings are applied as single coats on some large appliance interior parts and as topcoat for kitchen ranges. They are also used on metal bed and chair frames, shelving, and stadium seating, and they have been applied as single coats on small appliances, small farm machinery, fabricated metal product parts, and industrial machinery components. The usual application methods are manual or automatic electrostatic spray.

Table 4.2.2.4-1 (Metric And English Units). EMISSION FACTORS FOR TYPICAL METAL COATING PLANTS[a]

EMISSION FACTOR RATING: B

Type Of Plant	Production Rate	Emissions		Estimated Emissions (%)	
		Mg/yr	ton/yr	Application And Flashoff	Ovens
Large appliances					
Prime and topcoat spray	768,000 units/yr	315	347	80	20
Metal furniture[b]					
Single spray[c]	48×10^6 ft^2/yr	500	550	65 - 80	20 - 35
Single dip[d]	23×10^6 ft^2/yr	160	176	50 - 60	40 - 50
Miscellaneous metal[b]					
Conveyor single flow[d]	16×10^6 ft^2/yr	111	122	50 - 60	40 - 50
Conveyor dip	16×10^6 ft^2/yr	111	122	40 - 50	50 - 60
Conveyor single spray[e]	16×10^6 ft^2/yr	200	220	70 - 80	20 - 30
Conveyor two coat, flow and spray	16×10^6 ft^2/yr	311	342	60 - 70	30 - 40
Conveyor two coat, dip and spray	16×10^6 ft^2/yr	311	342	60 - 70	30 - 40
Conveyor two coat, spray	16×10^6 ft^2/yr	400	440	70 - 80	20 - 30
Manual two coat, spray and air dry	8.5×10^6 ft^2/yr	212	223	100	0

[a] References 1-4.

[b] Estimated from area coated, assumed dry coating thickness of 1 mil, coating of 75% solvent by volume and 25% solids by volume, appropriate transfer efficiency (TE), and solvent density of 0.88 kg/liter (7.36 lb/gal). The equation to be used is:

$$E \text{ (tons/yr)} = 2.29 \times 10^{-6} \text{ area coated (ft}^2) \times \frac{V}{100 - V} \times \frac{1}{TE}$$

or

$$E \text{ (Mg/yr)} = 2.09 \times 10^{-6} \text{ area coated (ft}^2) \times \frac{V}{100 - V} \times \frac{1}{TE}$$

where V = VOC as volume %.

[c] Transfer efficiency assumed to be 60%, presuming the coater uses manual electrostatic equipment.

[d] Flow and dip coat transfer efficiencies assumed to be 90%.

[e] Transfer efficiency assumed to be 50%, presuming the coater uses electrostatic equipment but coats a wide range of product sizes and configurations.

Improving transfer efficiency is a method of reducing emissions. One such technique is the electrostatic application of the coating, and another is dip coating with waterborne paint. For example, many makers of large appliances are now using electrodeposition to apply prime coats to exterior parts and single coats to interiors, because this technique increases corrosion protection and resistance to detergents. Electrodeposition of these waterborne coatings is also being used at several metal furniture coating plants and at some farm, commercial machinery, and fabricated metal products facilities.

Automated electrostatic spraying is most efficient, but manual and conventional methods can be used, also. Roll coating is another option on some miscellaneous parts. Use of higher solids coatings is a practiced technique for reduction of VOC emissions.

Carbon adsorption is technically feasible for collecting emissions from prime, top, and single-coat applications and flashoff areas. However, the entrained sticky paint particles are a filtration problem, and adsorbers are not commonly used.

Incineration is used to reduce organic vapor emissions from baking ovens for large appliances, metal furniture, and miscellaneous products, and it is an option for control of emissions from application and flashoff areas.

Table 4.2.2.4-1 gives emission factors for large appliance, metal furniture, and miscellaneous metal parts coating lines, and Table 4.2.2.4-2 gives their estimated control efficiencies.

Table 4.2.2.4-2. ESTIMATED CONTROL EFFICIENCIES FOR METAL COATING LINES[a]

Control Technology	Application			Organic Emissions Reduction (%)		
	Large Appliances	Metal Furniture	Miscellaneous	Large Appliances	Metal Furniture	Miscellaneous
Powder	Top, exterior or interior single coat	Top or single coat	Oven-baked single coat or topcoat	95 - 99[b]	95 - 99[b]	95 - 98[c]
Waterborne (spray, dip, flowcoat)	All applications	Prime, top or single coat	Oven-baked single coat, primer and topcoat; air dried primer and topcoat	70 - 90[b]	60 - 90[b]	60 - 90[c]
Waterborne (electrodeposition)	Prime or interior single coat	Prime or single coat	Oven-baked single coat and primer	90 - 95[b]	90 - 95[b]	90 - 95[c]
Higher solids (spray)	Top or exterior single coat and sound deadener	Top or single coat	Oven-baked single coat and topcoat; air dried primer and topcoat	60 - 80[b]	50 - 80[b]	50 - 80[c]
Carbon absorption	Prime, single or topcoat application and flashoff areas	Prime, top or single coat application and flashoff areas	Oven-baked single coat, primer and topcoat application and flashoff areas; air dried primer and topcoat application and drying areas	90[d]	90[d]	90[d]
Incineration	Prime, top or single coat ovens	Ovens	Ovens	90[d]	90[d]	90+[d]

[a] References 1-3.

[b] The base case against which these % reductions were calculated is a high organic solvent coating that contains 25 volume % solids and 75 volume % organic solvents. Transfer efficiencies for liquid coatings are assumed to be about 80% for spray and 90% for dip or flowcoat, for powders about 93%, and for electrodeposition, 99%.

[c] Figures reflect the range of reduction possible. Actual reduction achieved depends on compositions of the conventional coating originally used and replacement low organic solvent coating, on transfer efficiency, and on relative film thicknesses of the two coatings.

[d] Reduction is only across the control device and does not account for capture efficiency.

References For Section 4.2.2.4

1. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume III: Surface Coating Of Metal Furniture*, EPA-450/2-77-032, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1977.

2. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume V: Surface Coating Of Large Appliances*, EPA-450/2-77-034, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1977.

3. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume V: Surface Coating Of Miscellaneous Metal Parts And Products*, EPA-450/2-78-015, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1978.

4. G. T. Helms, "Appropriate Transfer Efficiencies For Metal Furniture And Large Appliance Coating", Memorandum, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 28, 1980.

4.2.2.5 Flat Wood Interior Panel Coating

4.2.2.5.1 Process Description[1]

Finished flat wood construction products are interior panels made of hardwood plywoods (natural and lauan), particle board, and hardboard.

Fewer than 25 percent of the manufacturers of such flat wood products coat the products in their plants, and in some of the plants that do coat, only a small percentage of total production is coated. At present, most coating is done by toll coaters who receive panels from manufacturers and undercoat or finish them according to customer specifications and product requirements.

Some of the layers and coatings that can be factory-applied to flat woods are filler, sealer, groove coat, primer, stain, basecoat, ink, and topcoat. Solvents used in organic base flat wood coatings are usually component mixtures, including methyl ethyl ketone, methyl isobutyl ketone, toluene, xylene, butyl acetates, propanol, ethanol, butanol, naphtha, methanol, amyl acetate, mineral spirits, SoCal I and II, glycols, and glycol ethers. Those most often used in waterborne coatings are glycol, glycol ethers, propanol, and butanol.

Various forms of roll coating are the preferred techniques for applying coatings to flat woods. Coatings used for surface cover can be applied with a direct roller coater, and reverse roll coaters are generally used to apply fillers, forcing the filler into panel cracks and voids. Precision coating and printing (usually with offset gravure grain printers) are also forms of roll coating, and several types of curtain coating may be employed, also (usually for topcoat application). Various spray techniques and brush coating may be used, too.

Printed interior panelings are produced from plywoods with hardwood surfaces (primarily lauan) and from various wood composition panels, including hardboard and particle board. Finishing techniques are used to cover the original surface and to produce various decorative effects. Figure 4.2.2.5-1 is a flow diagram showing some, but not all, typical production line variations for printed interior paneling.

Groove coatings, applied in different ways and at different points in the coating procedure, are usually pigmented low resin solids reduced with water before use, therefore yielding few, if any, emissions. Fillers, usually applied by reverse roll coating, may be of various formulations: (1) polyester (which is ultraviolet cured) (2) water base, (3) lacquer base, (4) polyurethane, and (5) alkyd urea base. Water base fillers are in common use on printed paneling lines.

Sealers may be of water or solvent base, usually applied by airless spray or direct roll coating, respectively. Basecoats, which are usually direct roll coated, generally are of lacquer, synthetic, vinyl modified alkyd urea, catalyzed vinyl, or water base.

Inks are applied by an offset gravure printing operation similar to direct roll coating. Most lauan printing inks are pigments dispersed in alkyd resin, with some nitrocellulose added for better wipe and printability. Water base inks have a good future for clarity, cost, and environmental reasons. After printing, a board goes through 1 or 2 direct or precision roll coaters for application of the clear protective topcoat. Some topcoats are synthetic, prepared from solvent soluble alkyd or polyester resins, urea formaldehyde cross linkings, resins, and solvents.

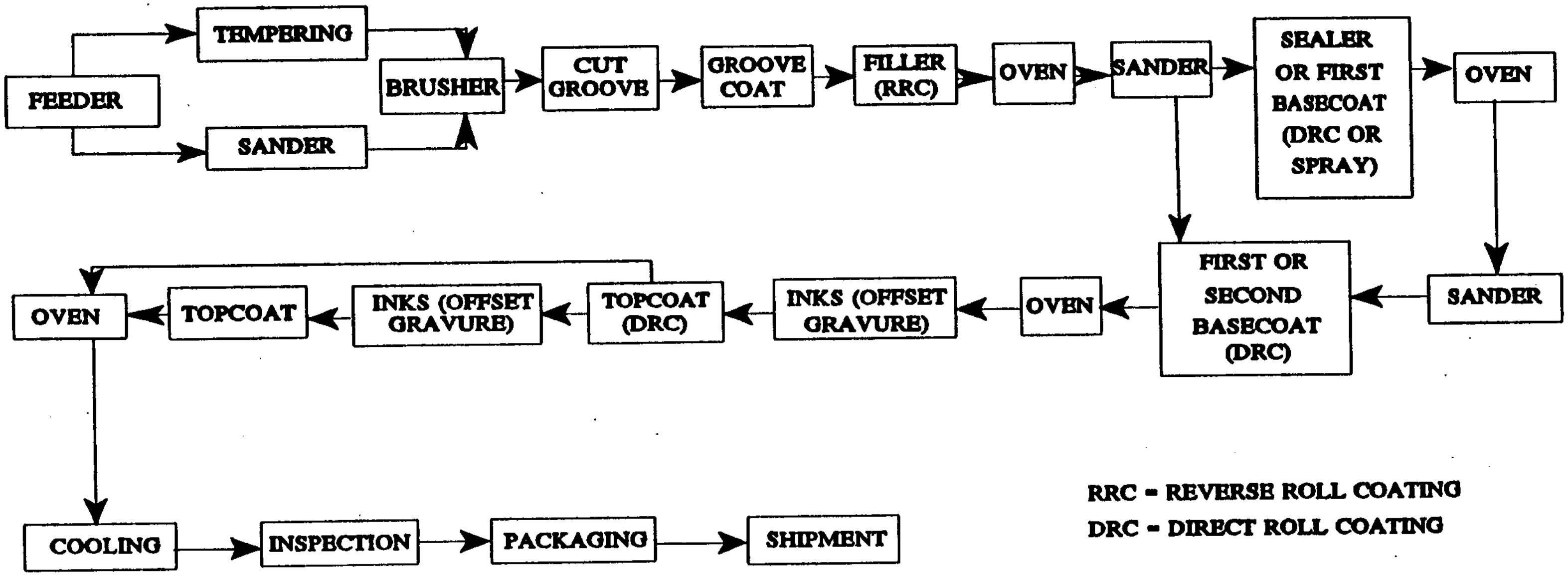


Figure 4.2.2.5-1. Flat wood interior panel coating line emission points.

Natural hardwood plywood panels are coated with transparent or clear finishes to enhance and protect their face ply of hardwood veneer. Typical production lines are similar to those for printed interior paneling, except that a primer sealer is applied to the filled panel, usually by direct roll coating. The panel is then embossed and "valley printed" to give a "distressed" or antique appearance. No basecoat is required. A sealer is also applied after printing but before application of the topcoat, which may be curtain coated, although direct roll coating remains the usual technique.

4.2.2.5.2 Emissions And Controls[1-2]

Emissions of volatile organic compounds (VOC) at flat wood coating plants occur primarily from reverse roll coating of filler, direct roll coating of sealer and basecoat, printing of wood grain patterns, direct roll or curtain coating of topcoat(s), and oven drying after 1 or more of those operations (see Figure 4.2.2.5-1). All solvent used and not recovered can be considered potential emissions. Emissions can be calculated from the factors in Table 4.2.2.1-1 if the coating use is known. Emissions for interior printed panels can be estimated from the factors in Table 4.2.2.5-1, if the area of coated panels is known.

Waterborne coatings are increasingly used to reduce emissions. They can be applied to almost all flat wood except redwood and, possibly, cedar. The major use of waterborne flat wood coatings is in the filler and basecoat applied to printed interior paneling. Limited use has been made of waterborne materials for inks, groove coats, and topcoats with printed paneling, and for inks and groove coats with natural hardwood panels.

Ultraviolet curing systems are applicable to clear or semitransparent fillers, topcoats on particle board coating lines, and specialty coating operations. Polyester, acrylic, urethane, and alkyd coatings can be cured by this method.

Afterburners can be used to control VOC emissions from baking ovens, and there would seem to be ample recovered heat to use. Extremely few flat wood coating operations have afterburners as add-on controls, though, despite the fact that they are a viable control option for reducing emissions where product requirements restrict the use of other control techniques.

Carbon adsorption is technically feasible, especially for specific applications (e. g., redwood surface treatment), but the use of multicomponent solvents and different coating formulations in several steps along the coating line has thus far precluded its use to control flat wood coating emissions and to reclaim solvents. The use of low solvent coatings to fill pores and to seal wood has been demonstrated.

Table 4.2.2.5-1 (Metric And English Units). VOC EMISSION FACTORS FOR INTERIOR PRINTED PANELS[a]

EMISSION FACTOR RATING: B

Paint Category	Coverage[b]				Uncontrolled VOC Emissions					
	liter/100 m^2		gal/1000 ft^2		kg/100 m^2 Coated			lb/1000 ft^2 Coated		
	Water-borne	Conven-tional	Water-borne	Conven-tional	Water-borne	Conven-tional	Ultra-violet[c]	Water-borne	Conven-tional	Ultra-violet[c]
Filler	6.5	6.9	1.6	1.7	0.3	3.0	Neg	0.6	6.1	Neg
Sealer	1.4	1.2	0.35	0.3	0.2	0.5	0	0.4	1.1	0
Basecoat	2.6	3.2	3.2	0.65	0.8	0.2	0.24	0.5	5.0	0.5
Ink	0.4	0.4	0.1	0.1	0.1	0.3	0.10	0.2	0.6	0.2
Topcoat	2.6	2.8	0.65	0.7	0.4	1.8	Neg	0.8	3.7	Neg
Total	13.5	14.5	3.4	3.6	1.2	8.0	0.4	2.5	16.5	0.8

[a] Reference 1. Organics are all nonmethane. Neg = negligible.

[b] Reference 3. From Abitibi Corp., Cucamonga, CA. Adjustments between water and conventional paints made using typical nonvolatiles content.

[c] UV line uses no sealer, uses waterborne basecoat and ink. Total adjusted to cover potential emissions from UV coatings.

References For Section 4.2.2.5

1. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume VII: Factory Surface Coating Of Flat Wood Interior Paneling*, EPA-450/2-78-032, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1978.

2. *Air Pollution Control Technology Applicable To 26 Sources Of Volatile Organic Compounds*, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 27, 1977. Unpublished.

3. *Products Finishing*, *41*(6A):4-54, March 1977.

4.2.2.6 Paper Coating

4.2.2.6.1 Process Description[1-2]

Paper is coated for various decorative and functional purposes with waterborne, organic solventborne, or solvent-free extruded materials. Paper coating is not to be confused with printing operations, which use contrast coatings that must show a difference in brightness from the paper to be visible. Coating operations are the application of a uniform layer or coating across a substrate. Printing results in an image or design on the substrate.

Waterborne coatings improve printability and gloss but cannot compete with organic solventborne coatings in resistance to weather, scuff, and chemicals. Solventborne coatings, as an added advantage, permit a wide range of surface textures. Most solventborne coating is done by paper converting companies that buy paper from mills and apply coatings to produce a final product. Among the many products that are coated with solventborne materials are adhesive tapes and labels, decorated paper, book covers, zinc oxide-coated office copier paper, carbon paper, typewriter ribbons, and photographic film.

Organic solvent formulations generally used are made up of film-forming materials, plasticizers, pigments, and solvents. The main classes of film formers used in paper coating are cellulose derivatives (usually nitrocellulose) and vinyl resins (usually the copolymer of vinyl chloride and vinyl acetate). Three common plasticizers are dioctyl phthalate, tricresyl phosphate, and castor oil. The major solvents used are toluene, xylene, methyl ethyl ketone, isopropyl alcohol, methanol, acetone, and ethanol. Although a single solvent is frequently used, a mixture is often necessary to obtain the optimum drying rate, flexibility, toughness, and abrasion resistance.

A variety of low solvent coatings, with negligible emissions, have been developed for some uses to form organic resin films equal to those of conventional solventborne coatings. They can be applied up to 1/8 inch thick (usually by reverse roller coating) to products like artificial leather goods, book covers, and carbon paper. Smooth hot melt finishes can be applied over rough textured paper by heated gravure or roll coaters at temperatures from 65 to 230°C (150 to 450°F).

Plastic extrusion coating is a type of hot melt coating in which a molten thermoplastic sheet (usually low or medium density polyethylene) is extruded from a slotted die at temperatures of up to 315°C (600°F). The substrate and the molten plastic coat are united by pressure between a rubber roll and a chill roll which solidifies the plastic. Many products, such as the polyethylene-coated milk carton, are coated with solvent-free extrusion coatings.

Figure 4.2.2.6-1 shows a typical paper coating line that uses organic solventborne formulations. The application device is usually a reverse roller, a knife, or a rotogravure printer. Knife coaters can apply solutions of much higher viscosity than roll coaters can, thus emitting less solvent per pound of solids applied. The gravure printer can print patterns or can coat a solid sheet of color on a paper web.

Ovens may be divided into from 2 to 5 temperature zones. The first zone is usually at about 430°C (110°F), and other zones have progressively higher temperatures to cure the coating after most solvent has evaporated. The typical curing temperature is 120°C (250°F), and ovens are generally limited to 200°C (400°F) to avoid damage to the paper. Natural gas is the fuel most often used in

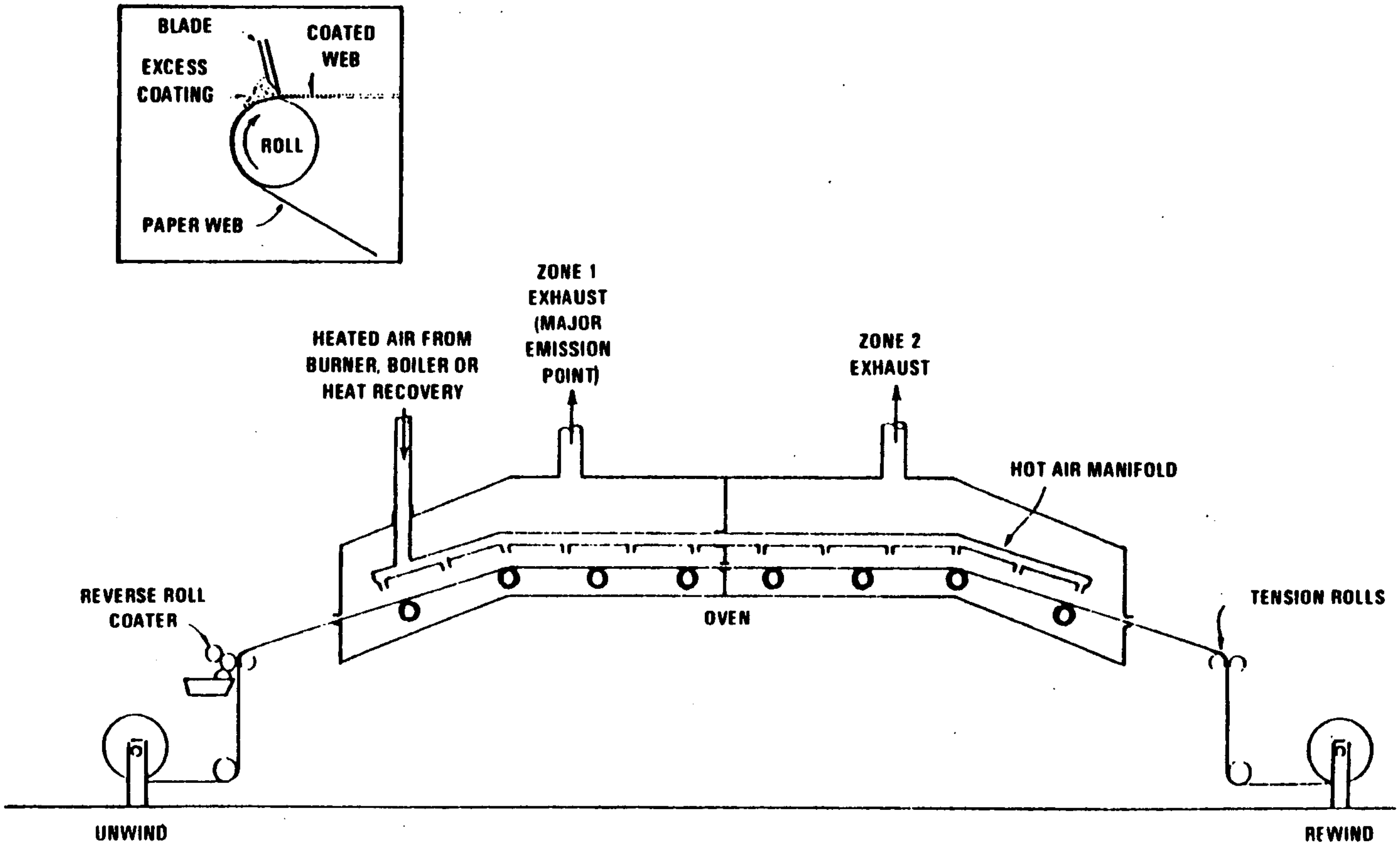


Figure 4.2.2.6-1. Paper coating line emission points.

direct-fired ovens, but fuel oil is sometimes used. Some of the heavier grades of fuel oil can create problems, because sulfur oxide (SO) and particulate may contaminate the paper coating. Distillate fuel oil usually can be used satisfactorily. Steam produced from burning solvent retrieved from an adsorber or vented to an incinerator may also be used to heat curing ovens.

4.2.2.6.2 Emissions And Controls[2]

The main emission points from paper coating lines are the coating applicator and the oven (see Figure 4.2.2.6-1). In a typical paper-coating plant, about 70 percent of all solvents used are emitted from the coating lines, with most coming from the first zone of the oven. The other 30 percent are emitted from solvent transfer, storage, and mixing operations and can be reduced through good housekeeping practices. All solvent used and not recovered or destroyed can be considered potential emissions.

Volatile organic compound (VOC) emissions from individual paper coating plants vary with size and number of coating lines, line construction, coating formulation, and substrate composition, so each must be evaluated individually. VOC emissions can be estimated from the factors in Table 4.2.2.6-1 if coating use is known and sufficient information on coating composition is available. Since many paper coating formulas are proprietary, it may be necessary to have information on the total solvent used and to assume that, unless a control device is used, essentially all solvent is emitted. Rarely would as much as 5 percent be retained in the product.

Table 4.2.2.6-1. CONTROL EFFICIENCIES FOR PAPER COATING LINES[a]

Affected Facility	Control Method	Efficiency (%)
Coating line	Incineration	95
	Carbon adsorption	90+
	Low solvent coating	80 - 99[b]

[a] Reference 2.

[b] Based on comparison with a conventional coating containing 35% solids and 65% organic solvent, by volume.

Almost all solvent emissions from the coating lines can be collected and sent to a control device. Thermal incinerators have been retrofitted to a large number of oven exhausts, with primary and even secondary heat recovery systems heating the ovens. Carbon adsorption is most easily adaptable to lines which use single solvent coating. If solvent mixtures are collected by adsorbers, they usually must be distilled for reuse.

Although available for some products, low solvent coatings are not yet available for all paper-coating operations. The nature of the products, such as some types of photographic film, may preclude development of a low-solvent option. Furthermore, the more complex the mixture of organic solvents in the coating, the more difficult and expensive to reclaim them for reuse with a carbon adsorption system.

References For Section 4.2.2.6

1. T. W. Hughes, *et al.*, *Source Assessment: Prioritization Of Air Pollution From Industrial Surface Coating Operations*, EPA-650/2-75-019a, U. S. Environmental Protection Agency, Cincinnati, OH, February 1975.

2. *Control Of Volatile Organic Emissions From Existing Stationary Sources, Volume II: Surface Coating Of Cans, Coils, Paper Fabrics, Automobiles, And Light Duty Trucks*, EPA-450/2-77-008, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1977.

4.2.2.7 Polymeric Coating Of Supporting Substrates[1-8]

"Polymeric coating of supporting substrates" is defined as a web coating process other than paper coating that applies an elastomer or other polymeric material onto a supporting substrate. Typical substrates include woven, knit, and nonwoven textiles; fiberglass; leather; yarn; and cord. Examples of polymeric coatings are natural and synthetic rubber, urethane, polyvinyl chloride, acrylic, epoxy, silicone, phenolic resins, and nitrocellulose. Plants have from 1 to more than 10 coating lines. Most plants are commission coaters where coated substrates are produced according to customer specifications. Typical products include rainwear, conveyor belts, V-belts, diaphragms, gaskets, printing blankets, luggage, and aircraft and military products. This industrial source category has been retitled from "Fabric Coating" to that listed above to reflect the general use of polymeric coatings on substrate materials including but not limited to conventional textile fabric substrates.

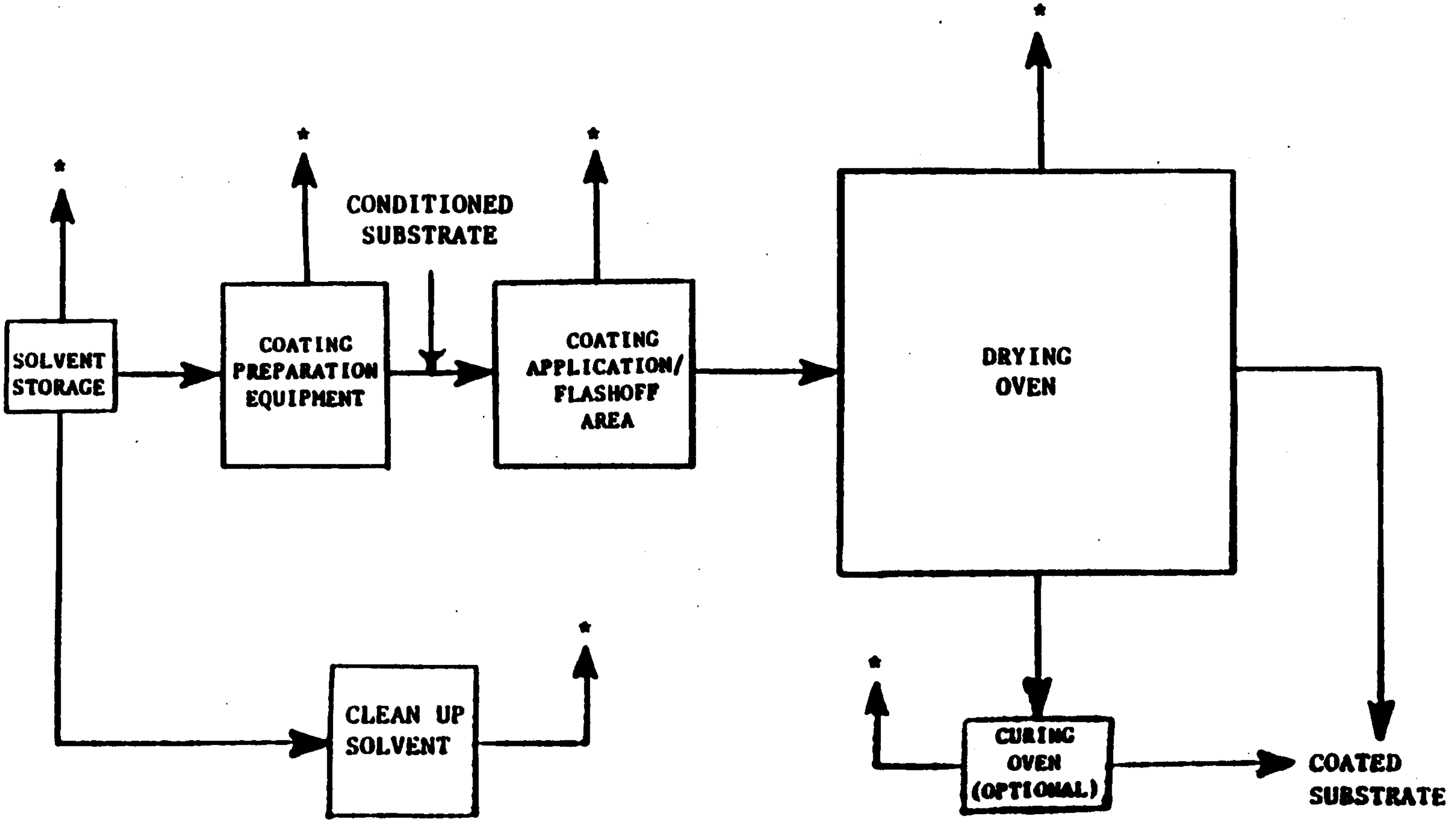
4.2.2.7.1 Process Description[1-3]

The process of applying a polymeric coating to a supporting substrate consists of mixing the coating ingredients (including solvents), conditioning the substrate, applying the coating to the substrate, drying/curing the coating in a drying oven, and subsequent curing or vulcanizing if necessary. Figure 4.2.2.7-1 is a schematic of a typical solvent-borne polymeric coating operation identifying volatile organic compound (VOC) emission locations. Typical plants have 1 or 2 small ($\leq$38 m^3 or 10,000 gallons) horizontal or vertical solvent storage tanks that are operated at atmospheric pressure; however, some plants have as many as 5. Coating preparation equipment includes the mills, mixers, holding tanks, and pumps used to prepare polymeric coatings for application. Urethane coatings typically are purchased premixed and require little or no mixing at the coating plant. The conventional types of equipment for applying organic solvent-borne and waterborne coatings include knife-over-roll, dip, and reverse-roll coaters Once applied to the substrate, liquid coatings are solidified by evaporation of the solvent in a steam-heated or direct-fired oven. Drying ovens usually are of forced-air convection design in order to maximize drying efficiency and prevent a dangerous localized buildup of vapor concentration or temperature. For safe operation, the concentration of organic vapors is usually held between 10 and 25 percent of the lower explosive limit (LEL). Newer ovens may be designed for concentrations of up to 50 percent of the LEL through the addition of monitors, alarms, and fail-safe shutdown systems. Some coatings require subsequent curing or vulcanizing in separate ovens.

4.2.2.7.2 Emission Sources[1-3]

The significant VOC emission sources in a polymeric coating plant include the coating preparation equipment, the coating application and flashoff area, and the drying ovens. Emissions from the solvent storage tanks and the cleanup area are normally only a small percentage of the total.

In the mixing or coating preparation area, VOCs are emitted from the individual mixers and holding tanks during the following operations: filling of mixers, transfer of the coating, intermittent activities such as changing the filters in the holding tanks, and mixing (if mix equipment is not equipped with tightly fitting covers). The factors affecting emissions in the mixing area include tank size, number of tanks, solvent vapor pressure, throughput, and the design and performance of tank covers.



VOC emissions are denoted by an "*."

Figure 4.2.2.7-1. Solventborne polymeric coating operation and VOC emission locations.[1]

Emissions from the coating application area result from the evaporation of solvent around the coating application equipment during the application process and from the exposed substrate as it travels from the coater to the drying oven entrance (flashoff). The factors affecting emissions are the solvent content of the coating, line width and speed, coating thickness, volatility of the solvent(s), temperature, distance between coater and oven, and air turbulence in the coating area.

Emissions from the drying oven result from the fraction of the remaining solvent that is driven off in the oven. The factors affecting uncontrolled emissions are the solvent content of the coating and the amount of solvent retained in the finished product. Fugitive emissions due to the opening of oven doors also may be significant in some operations. Some plasticizers and reaction byproducts may be emitted if the coating is subsequently cured or vulcanized. However, emissions from the curing or vulcanizing of the coating are usually negligible compared to the total emissions from the operation.

Solvent type and quantity are the common factors affecting emissions from all the operations in a polymeric coating facility. The rate of evaporation or drying is dependent upon solvent vapor pressure at a given temperature and concentration. The most commonly used organic solvents are toluene, dimethyl formamide (DHF), acetone, methyl ethyl ketone (MEK), isopropyl alcohol, xylene, and ethyl acetate. Factors affecting solvent selection are cost, solvency, toxicity, availability, desired rate of evaporation, ease of use after solvent recovery, and compatibility with solvent recovery equipment.

4.2.2.7.3 Emissions Control[1,2,4-7]

A control system for evaporative emissions consists of 2 components: a capture device and a control device. The efficiency of the control system is determined by the efficiencies of the 2 components.

A capture device is used to contain emissions from a process operation and direct them to a stack or to a control device. Covers, vents, hoods, and partial and total enclosures are alternative capture devices used on coating preparation equipment. Hoods and partial and total enclosures are typical capture devices for use in the coating application area. A drying oven can be considered a capture device because it both contains and directs VOC emissions from the process. The efficiency of capture devices is variable and depends upon the quality of design and the level of operation and maintenance.

A control device is any equipment that has as its primary function the reduction of emissions. Control devices typically used in this industry are carbon adsorbers, condensers, and incinerators. Tightly fitting covers on coating preparation equipment may be considered both capture and control devices.

Carbon adsorption units use activated carbon to adsorb VOCs from a gas stream; the VOCs are later recovered from the carbon. Two types of carbon adsorbers are available: fixed-bed and fluidized bed. Fixed-bed carbon adsorbers are designed with a steam-stripping technique to recover the VOC material and regenerate the activated carbon. The fluidized-bed units used in this industry are designed to use nitrogen for VOC vapor recovery and carbon regeneration. Both types achieve typical VOC control efficiencies of 95 percent when properly designed, operated, and maintained.

Condensation units control VOC emissions by cooling the solvent-laden gas to the dew point of the solvent(s) and collecting the droplets. There are 2 condenser designs commercially available: nitrogen (inert gas) atmosphere, and air atmosphere. These systems differ in the design and operation of the drying oven (i. e., use of nitrogen or air in the oven) and in the method of cooling the solvent laden air (i. e., liquified nitrogen or refrigeration). Both design types can achieve VOC control efficiencies of 95 percent.

Incinerators control VOC emissions through oxidation of the organic compounds into carbon dioxide and water. Incinerators used to control VOC emissions may be of thermal or catalytic design and may use primary or secondary heat recovery to reduce fuel costs. Thermal incinerators operate at approximately 890°C (1600°F) to ensure oxidation of the organic compounds. Catalytic incinerators operate in the rage of 325 to 430°C (600 to 800°F) while using a catalyst to achieve comparable oxidation of VOCs. Both design types achieve a typical VOC control efficiency of 98 percent.

Tightly fitting covers control VOC emissions from mix vessels by reducing evaporative losses. Airtight covers can be fitted with conservation vents to avoid excessive internal pressure or vacuum. The parameters affecting the efficiency of these controls are solvent vapor pressure, cyclic temperature change, tank size, throughput, and the pressure and vacuum settings on the conservation vents. A good system of tightly fitting covers on mixing area vessels is estimated to reduce emissions by approximately 40 percent. Control efficiencies of 95 or 98 percent can be obtained by directing the captured VOCs to an adsorber, condenser, or incinerator.

When the efficiencies of the capture device and control device are known, the efficiency of the control system can be computed by the following equation:

$$(\text{capture efficiency}) \times (\text{control efficiency}) = (\text{control system efficiency})$$

The terms of this equation are fractional efficiencies rather than percentages. For instance, a system of hoods delivering 60 percent of VOC emissions to a 90 percent efficient carbon adsorber would result in a control system efficiency of 54 percent (0.60 x 0.90 = 0.54). Table 4.2.2.7-1 summarizes the control system efficiencies that may be used in the absence of measured data on mix equipment and coating operations.

Table 4.2.2.7-1. SUMMARY OF CONTROL EFFICIENCIES[a]

Control Technology	Overall Control Efficiency, %[b]
Coating Preparation Equipment	
Uncontrolled	0
Sealed covers with conservation vents	40
Sealed covers with carbon adsorber/condenser	95
Coating Operations[c]	
Local ventilation with carbon adsorber/condenser	81
Partial enclosure with carbon adsorber/condenser	90
Total enclosure with carbon adsorber/condenser	93
Total enclosure with incinerator	96

[a] Reference 1. To be used in the absence of measured data.

[b] To be applied to uncontrolled emissions from indicated process area, not from entire plant.

[c] Includes coating application/flashoff area and drying oven.

4.2.2.7.4 Emissions Estimation Techniques[1,4-8]

In this diverse industry, realistic estimates of emissions require solvent usage data. Due to the wide variation found in coating formulations, line speeds, and products, no meaningful inferences can be made based simply on the equipment present.

Plantwide emissions can be estimated by performing a liquid material balance in uncontrolled plants and in those where VOCs are recovered for reuse or sale. This technique is based on the assumption that all solvent purchased replaces VOC's which have been emitted. Any identifiable and quantifiable side-streams should be subtracted from this total. The general formula for this is:

$$\begin{pmatrix}\text{solvent}\\ \text{purchased}\end{pmatrix} - \begin{pmatrix}\text{quantifiable}\\ \text{solvent output}\end{pmatrix} = \begin{pmatrix}\text{VOC}\\ \text{emitted}\end{pmatrix}$$

The first term encompasses all solvent purchased including thinners, cleaning agents, and the solvent content of any premixed coatings, as well as any solvent directly used in coating formulation. From this total, any quantifiable solvent outputs are subtracted. These outputs may include solvent retained in the finished product, reclaimed solvent sold for use outside the plant, and solvent contained in waste streams. Reclaimed solvent which is reused at the plant is <u>not</u> subtracted.

The advantages of this method are that it is based on data that are usually readily available, it reflects actual operations rather than theoretical steady-state production and control conditions, and it includes emissions from all sources at the plant. However, care should be taken not to apply this method over too short a time span. Solvent purchases, production, and waste removal occur in their own cycles, which may not coincide exactly.

Occasionally, a liquid material balance may be possible on a smaller scale than the entire plant. Such an approach may be feasible for a single coating line or group of lines served by a dedicated mixing area and a dedicated control and recovery system. In this case, the computation begins with total solvent metered to the mixing area instead of solvent purchased. Reclaimed solvent is subtracted from this volume whether or not it is reused onsite. Of course, other solvent input and output streams must be accounted for as previously indicated. The difference between total solvent input and total solvent output is then taken to be the quantity of VOCs emitted from the equipment in question.

The configuration of meters, mixing areas, production equipment, and controls usually will not make this approach possible. In cases where control devices destroy potential emissions or a liquid material balance is inappropriate for other reasons, plant-wide emissions can be estimated by summing the emissions calculated for specific areas of the plant. Techniques for these calculations are presented below.

Estimating VOC emissions from a coating operation (application/flashoff area and drying oven) starts with the assumption that the uncontrolled emission level is equal to the quantity of solvent contained in the coating applied. In other words, all the VOC in the coating evaporates by the end of the drying process. This quantity should be adjusted downward to account for solvent retained in the finished product in cases where it is quantifiable and significant.

Two factors are necessary to calculate the quantity of solvent applied: the solvent content of the coating and the quantity of coating applied. Coating solvent content can be directly measured using EPA Reference Method 24. Alternative ways of estimating the VOC content include the use of either data on coating formulation that are usually available from the plant owner/operator or premixed coating manufacturer or, if these cannot be obtained, approximations based on the information in Table 4.2.2.7-2. The amount of coating applied may be directly metered. If it is not, it must be determined from production data. These should be available from the plant owner/operator. Care should be taken in developing these 2 factors to ensure that they are in compatible units.

Table 4.2.2.7-2. SOLVENT AND SOLIDS CONTENT OF POLYMERIC COATINGS[a]

Polymer Type	Typical Percentage, By Weight	
	% solvent	% solids
Rubber	50 - 70	30 - 50
Urethanes	50 - 60	40 - 50
Acrylics	—[b]	50
Vinyl[c]	60 - 80	20 - 40
Vinyl plastisol	5	95
Organisol	15 - 40	60 - 85
Epoxies	30 - 40	60 - 70
Silicone	50 - 60	40 - 50
Nitrocellulose	70	30

[a] Reference 1.

[b] Organic solvents are generally not used in the formulation of acrylic coatings. Therefore, the solvent content for acrylic coatings represents nonorganic solvent use (i. e., water).

[c] Solventborne vinyl coating.

When an estimate of uncontrolled emissions is obtained, the controlled emissions level is computed by applying a control system efficiency factor:

$$\begin{pmatrix}\text{uncontrolled}\\ \text{VOC}\end{pmatrix} \times \begin{pmatrix}1 - \text{control system efficiency}\end{pmatrix} = \begin{pmatrix}\text{VOC}\\ \text{emitted}\end{pmatrix}$$

As previously explained, the control system efficiency is the product of the efficiencies of the capture device and the control device. If these values are not known, typical efficiencies for some combinations of capture and control devices are presented in Table 4.2.2.7-1. It is important to note that these control system efficiencies are applicable only to emissions that occur within the areas served by the systems. Emissions from such sources as process wastewater or discarded waste coatings may not be controlled at all.

In cases where emission estimates from the mixing area alone are desired, a slightly different approach is necessary. Here, uncontrolled emissions will be only that portion of total solvent that evaporates during the mixing process. A liquid material balance across the mixing area (i. e., solvent entering minus solvent content of coating applied) would provide a good estimate. In the absence of any measured value, it may be assumed that approximately 10 percent of the total solvent entering the mixing area is emitted during the mixing process, but this can vary widely. When an estimate of uncontrolled mixing area emissions has been made, the controlled emission rate can be calculated as discussed previously. Table 4.2.2.7-1 lists typical overall control efficiencies for coating mix preparation equipment.

Solvent storage tanks of the size typically found in this industry are regulated by only a few States and localities. Tank emissions are generally small (< 125 kg/yr [275 lb/yr]). If an estimate of emissions is desired, it can be computed using the equations, tables, and figures provided in Chapter 7.

References For Section 4.2.2.7

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4.2.2.8 Automobile And Light Duty Truck Surface Coating Operations[1-4]

4.2.2.8.1 General

Surface coating of an automobile body is a multistep operation carried out on an assembly line conveyor system. Such a line operates at a speed of 3 to 8 meters (9 to 25 feet) per minute and usually produces 30 to 70 units per hour. An assembly plant may operate up to 2 8-hour production shifts per day, with a third shift used for cleanup and maintenance. Plants may stop production for a vacation of one-and-a-half weeks at Christmas through New Year's Day and may stop for several weeks in summer for model changeover.

Although finishing processes vary from plant to plant, they have some common characteristics. Major steps of such processes are:

Solvent[a] wipe
Phosphating treatment
Application of prime coat
Curing of prime coat
Application of guide coat
Curing of guide coat
Application of topcoat(s)
Curing of topcoat(s)
Final repair operations

A general diagram of these consecutive steps is presented in Figure 4.2.2.8-1. Application of a coating takes place in a dip tank or spray booth, and curing occurs in the flashoff area and bake oven. The typical structures for application and curing are contiguous, to prevent exposure of the wet body to the ambient environment before the coating is cured.

The automobile body is assembled from a number of welded metal sections. The body and the parts to be coated all pass through the same metal preparation process.

First, surfaces are wiped with solvent to eliminate traces of oil and grease. Second, a phosphating process prepares surfaces for the primer application. Since iron and steel rust readily, phosphate treatment is necessary to retard such. Phosphating also improves the adhesion of the primer and the metal. The phosphating process occurs in a multistage washer, with detergent cleaning, rinsing, and coating of the metal surface with zinc phosphate. The parts and bodies pass through a water spray cooling process. If solventborne primer is to be applied, they are then oven dried.

A primer is applied to protect the metal surface from corrosion and to ensure good adhesion of subsequent coatings. Approximately half of all assembly plants use solventborne primers with a combination of manual and automatic spray application. The rest use waterborne primers. As new plants are constructed and existing plants modernized, the use of waterborne primers is expected to increase.

Waterborne primer is most often applied in an electrodeposition (EDP) bath. The composition of the bath is about 5 to 15 volume percent solids, 2 to 10 percent solvent, and the rest water. The solvents used are typically organic compounds of higher molecular weight and low volatility, like ethylene glycol monobutyl ether.

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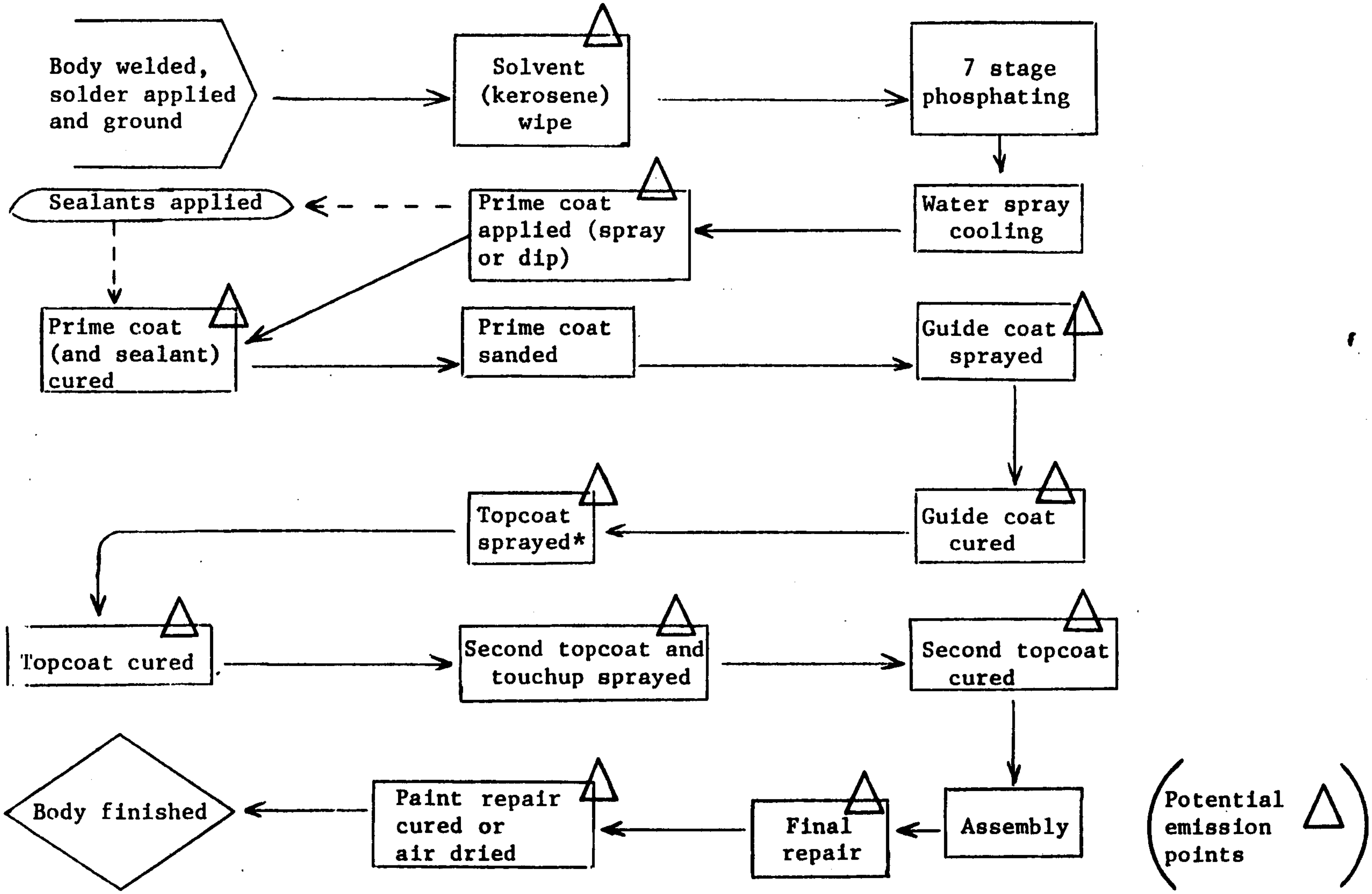
[a] The term "solvent" here means organic solvent.



*To get sufficient film build, for two colors or a base coat/clear coat, there may be multiple topcoats.

Figure 4.2.2.8-1. Typical automobile and light duty truck surface coating line.

When EDP is used, a guide coat (also called a primer surfacer) is applied between the primer and the topcoat to build film thickness, to fill in surface imperfections, and to permit sanding between the primer and topcoat. Guide coats are applied by a combination of manual and automatic spraying and can be solventborne or waterborne. Powder guide coat is used at one light duty truck plant.

The topcoat provides the variety of colors and surface appearance to meet customer demand. Topcoats are applied in 1 to 3 steps to ensure sufficient coating thickness. An oven bake may follow each topcoat application, or the coating may be applied wet on wet. At a minimum, the final topcoat is baked in a high-temperature oven.

Topcoats in the automobile industry traditionally have been solventborne lacquers and enamels. Recent trends have been to higher solids content. Powder topcoats have been tested at several plants.

The current trend in the industry is toward base coat/clear coat (BC/CC) topcoating systems, consisting of a relatively thin application of highly pigmented metallic base coat followed by a thicker clear coat. These BC/CC topcoats have more appealing appearance than do single coat metallic topcoats, and competitive pressures are expected to increase their use by U. S. manufacturers.

The VOC content of most BC/CC coatings in use today is higher than that of conventional enamel topcoats. Development and testing of lower VOC content (higher solids) BC/CC coatings are being done, however, by automobile manufacturers and coating suppliers.

Following the application of the topcoat, the body goes to the trim operation area, where vehicle assembly is completed. The final step of the surface coating operation is generally the final repair process, in which damaged coating is repaired in a spray booth and is air dried or baked in a low temperature oven to prevent damage of heat sensitive plastic parts added in the trim operation area.

4.2.2.8.2 Emissions And Controls

Volatile organic compounds (VOC) are the major pollutants from surface coating operations. Potential VOC emitting operations are shown in Figure 4.2.2.8-1. The application and curing of the prime coat, guide coat, and topcoat account for 50 to 80 percent of the VOC emitted from assembly plants. Final topcoat repair, cleanup, and miscellaneous sources such as the coating of small component parts and application of sealants, account for the remaining 20 percent. Approximately 75 to 90 percent of the VOC emitted during the application and curing process is emitted from the spray booth and flashoff area, and 10 to 25 percent from the bake oven. This emissions split is heavily dependent on the types of solvents used and on transfer efficiency. With improved transfer efficiencies and the newer coatings, it is expected that the percent of VOC emitted from the spray booth and the flashoff area will decrease, and the percent of VOC emitted from the bake oven will remain fairly constant. Higher solids coatings, with their slower solvents, will tend to have a greater fraction of emissions from the bake oven.

Several factors affect the mass of VOC emitted per vehicle from surface coating operations in the automotive industry. Among these are:

VOC content of coatings (pounds of coating, less water)
Volume solids content of coating
Area coated per vehicle

Film thickness
Transfer efficiency

The greater the quantity of VOC in the coating composition, the greater will be the emissions. Lacquers having 12 to 18 volume percent solids are higher in VOCs than enamels having 24 to 33 volume percent solids. Emissions are also influenced by the area of the parts being coated, the coating thickness, the configuration of the part, and the application technique.

The transfer efficiency (fraction of the solids in the total consumed coating that remains on the part) varies with the type of application technique. Transfer efficiency for typical air atomized spraying ranges from 30 to 50 percent. The range for electrostatic spraying, an application method that uses an electrical potential to increase transfer efficiency of the coating solids, is from 60 to 95 percent. Both air atomized and electrostatic spray equipment may be used in the same spray booth.

Several types of control techniques are available to reduce VOC emissions from automobile and light duty truck surface coating operations. These methods can be broadly categorized as either control devices or new coating and application systems. Control devices reduce emissions by either recovering or destroying VOC before it is discharged into the ambient air. Such techniques include thermal and catalytic incinerators on bake ovens, and carbon absorbers on spray booths. New coatings with relatively low VOC levels can be used in place of high-VOC-content coatings. Such coating systems include electrodeposition of waterborne prime coatings, and for top coats, air spray of waterborne enamels and air or electrostatic spray of high solids, solventborne enamels and powder coatings. Improvements in the transfer efficiency decrease the amount of coating which must be used to achieve a given film thickness, thereby reducing emissions of VOC to the ambient air.

Calculation of VOC emissions for representative conditions provides the emission factors in Table 4.2.2.8-1. The factors were calculated with the typical value of parameters present in Tables 4.2.2.8-2 and 4.2.2.8-3. The values for the various parameters for automobiles and light duty trucks represent average conditions existing in the automobile and light duty truck industry in 1980. A more accurate estimate of VOC emissions can be calculated with the equation in Table 4.2.2.8-1 and with site-specific values for the various parameters.

Emission factors are not available for final topcoat repair, cleanup, coating of small parts, and application of sealants.

Table 4.2.2.8-1 (Metric And English Units). EMISSION FACTORS FOR AUTOMOBILE AND LIGHT DUTY TRUCK SURFACE COATING OPERATIONS[a]

EMISSION FACTOR RATING: C

Coating	Automobile kg (lb) Of VOC		Light Duty Truck kg (lb) Of VOC	
	Per Vehicle	Per Hour[b]	Per Vehicle	Per Hour[c]
Prime Coat				
Solventborne spray	6.61 (14.54)	363 (799)	19.27 (42.39)	732 (1611)
Cathodic electrodeposition	0.21 (0.45)	12 (25)	0.27 (0.58)	10 (22)
Guide Coat				
Solventborne spray	1.89 (4.16)	104 (229)	6.38 (14.04)	243 (534)
Waterborne spray	0.68 (1.50)	38 (83)	2.3 (5.06)	87 (192)
Topcoat				
Lacquer	21.96 (48.31)	1208 (2657)	NA	NA
Dispersion lacquer	14.50 (31.90)	798 (1755)	NA	NA
Enamel	7.08 (15.58)	390 (857)	17.71 (38.96)	673 (1480)
Basecoat/clear coat	6.05 (13.32)	333 (732)	18.91 (41.59)	719 (1581)
Waterborne	2.25 (4.95)	124 (273)	7.03 (15.47)	267 (588)

[a] All nonmethane VOC. Factors are calculated using the following equation and the typical values of parameters presented in Tables 4.2.2.8-2 and 4.2.2.8-3. NA = not applicable.

$$E_v = \frac{A_v\, c_1\, T_f\, V_c\, c_2}{S_c\, e_T}$$

Table 4.2.2.8-1 (cont.).

where:

E_v = emission factor for VOC, mass per vehicle (lb/vehicle) (exclusive of any add-on control devices)
A_v = area coated per vehicle (ft^2/vehicle)
c_1 = conversion factor: 1 ft/12,000 mil
T_f = thickness of the dry coating film (mil)
V_c = VOC (organic solvent) content of coating as applied, less water (lb VOC/gal coating, less water)
c_2 = conversion factor: 7.48 gal/ft^3
S_c = solids in coating as applied, volume fraction (gal solids/gal coating)
e_T = transfer efficiency fraction (fraction of total coating solids used that remains on coated parts)

Example: The VOC emissions per automobile from a cathodic electrodeposited prime coat.

$$E_v \text{ mass of VOC} = \frac{(850 \text{ ft}^2)\ (1/12000)\ (0.6 \text{ mil})\ (1.2 \text{ lb/gal}-H_2O)\ (7.58 \text{ gal/ft}^3)}{(0.84 \text{ gal/gal})\ (1.00)}$$

$$= 0.45 \text{ lb VOC/vehicle } (0.21 \text{ kg VOC/vehicle})$$

[b] Based on an average line speed of 55 automobiles/hr.
[c] Based on an average line speed of 38 light duty trucks/hr.

Table 4.2.2.8-2 (English Units). PARAMETERS FOR THE AUTOMOBILE SURFACE COATING INDUSTRY[a]

Application	Area Coated Per Vehicle, ft^2	Film Thickness, mil	VOC Content, lb/gal-H_2O	Volume Fraction Solids, gal/gal-H_2O	Transfer Efficiency, %
Prime coat					
Solventborne spray	450 (220-570)	0.8 (0.3-2.5)	5.7 (4.2-6.0)	0.22 (0.20-0.35)	40 (35-50)
Cathodic electrodeposition	850 (660-1060)	0.6 (0.5-0.8)	1.2 (1.2-1.5)	0.84 (0.84-0.87)	100 (85-100)
Guide coat					
Solventborne spray	200 (170-280)	0.8 (0.5-1.5)	5.0 (3.0-5.6)	0.30 (0.25-0.55)	40 (35-65)
Waterborne spray	200 (170-280)	0.8 (0.5-2.0)	2.8 (2.6-3.0)	0.62 (0.60-0.65)	30 (25-40)
Topcoat					
Solventborne spray					
Lacquer	240 (170-280)	2.5 (1.0-3.0)	6.2 (5.8-6.6)	0.12 (0.10-0.13)	40 (30-65)
Dispersion lacquer	240 (170-280)	2.5 (1.0-3.0)	5.8 (4.9-5.8)	0.17 (0.17-0.27)	40 (30-65)
Enamel	240 (170-280)	2.5 (1.0-3.0)	5.0 (3.0-5.6)	0.30 (0.25-0.55)	40 (30-65)
Base coat/clear coat[b]	240	2.5	4.7	0.33	40
Base coat	240 (170-280)	1.0 (0.8-1.0)	5.6 (3.4-6.4)	0.20 (0.13-0.48)	40 (30-50)
Clear coat	240 (170-280)	1.5 (1.2-1.5)	4.0 (3.0-5.1)	0.42 (0.30-0.54)	40 (30-65)
Waterborne spray	240 (170-280)	2.2 (1.0-2.5)	2.8 (2.6-3.0)	0.62 (0.60-0.65)	30 (25-40)

[a] All values for coatings as applied except for VOC content and volume fraction solids that are for coatings as applied minus water. Ranges in parentheses. Low VOC content (high solids) base coat/clear coats are still undergoing testing and development.

[b] Composite of base coat and clear coat.

Table 4.2.2.8-3 (English Units). PARAMETERS FOR THE LIGHT DUTY TRUCK SURFACE COATING INDUSTRY[a]

Application	Area Coated Per Vehicle, ft^2	Film Thickness, mil	VOC Content, $lb/gal-H_2O$	Volume Fraction Solids, $gal/gal-H_2O$	Transfer Efficiency, %
Prime coat					
Solventborne spray	875 (300-1000)	1.2 (0.7-1.7)	5.7 (4.2-6.0)	0.22 (0.20-0.35)	40 (35-50)
Cathodic electrodeposition	1100 (850-1250)	0.6 (0.5-0.8)	1.2 (1.2-1.5)	0.84 (0.84-0.87)	100 (85-100)
Guide coat					
Solventborne spray	675 (180-740)	0.8 (0.7-1.7)	5.0 (3.0-5.6)	0.30 (0.25-0.55)	40 (35-65)
Waterborne spray	675 (180-740)	0.8 (0.5-2.0)	2.8 (2.6-3.0)	0.62 (0.60-0.65)	30 (25-40)
Topcoat					
Solventborne spray					
Enamel	750 (300-900)	2.0 (1.0-2.5)	5.0 (3.0-5.6)	0.30 (0.25-0.55)	40 (30-65)
Base coat/clear coat[b]	750	2.5	4.7	0.33	40
Base coat	750 (300-900)	1.0 (0.8-1.0)	5.6 (3.4-6.4)	0.20 (0.13-0.48)	40 (30-50)
Clear coat	750 (300-900)	1.5 (1.2-1.5)	4.0 (3.0-5.1)	0.42 (0.30-0.54)	40 (30-65)
Waterborne spray	750 (300-900)	2.2 (1.0-2.5)	2.8 (2.6-3.0)	0.62 (0.60-0.65)	30 (25-40)

[a] All values for coatings as applied, except for VOC content and volume fraction solids that are for coatings as applied minus water. Ranges in parentheses. Low VOC content (high solids) base coat/clear coats are still undergoing testing and development.

[b] Composite of typical base coat and clear coat.

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4.2.2.9 Pressure Sensitive Tapes And Labels

4.2.2.9.1 General[1-5]

The coating of pressure sensitive tapes and labels (PSTL) is an operation in which some backing material (paper, cloth, or film) is coated to create a tape or label product that sticks on contact. The term "pressure sensitive" indicates that the adhesive bond is formed on contact, without wetting, heating, or adding a curing agent.

The products manufactured by the PSTL surface coating industry may have several different types of coatings applied to them. The 2 primary types of coatings are adhesives and releases. Adhesive coating is a necessary step in the manufacture of almost all PSTL products. It is generally the heaviest coating (typically 0.051 kg/m^2, or 0.011 lb/ft^2 and therefore has the highest level of solvent emissions (generally 85 to 95 percent of total line emissions).

Release coatings are applied to the backside of tape or to the mounting paper of labels. The function of release coating is to allow smooth and easy unrolling of a tape or removal of a label from mounting paper. Release coatings are applied in a very thin coat (typically 0.00081 kg/m^2, or 0.00017 lb/ft^2). This thin coating produces less emissions than does a comparable size adhesive coating line.

Five basic coating processes can be used to apply both adhesive and release coatings:

solvent base coating
waterborne (emulsion) coating
100 percent solids (hot melt) coating
calender coating
prepolymer coating

A solvent base coating process is used to produce 80 to 85 percent of all products in the PSTL industry, and essentially all of the solvent emissions from the industry result from solvent base coating. Because of its broad application and significant emissions, solvent base coating of PSTL products is discussed in greater detail.

4.2.2.9.2 Process Description[1-2,5]

Solvent base surface coating is conceptually a simple process. A continuous roll of backing material (called the web) is unrolled, coated, dried, and rolled again. A typical solvent base coating line is shown in Figure 4.2.2.9-1. Large lines in this industry have typical web widths of 152 centimeters (60 in.), while small lines are generally 48 centimeters (24 in.). Line speeds vary substantially, from 3 to 305 meters per minute (10 to 1000 ft/min). To initiate the coating process the continuous web material is unwound from its roll. It travels to a coating head, where the solvent base coating formulation is applied. These formulations have specified levels of solvent and coating solids by weight. Solvent base adhesive formulations contain approximately 67 weight percent solvent and 33 weight percent coating solids. Solvent base releases average about 95 weight percent solvent and 5 weight percent coating solids. Solvents used include toluene, xylene, heptane, hexane, and methyl ethyl ketone. The coating solids portion of the formulations consists of elastomers (natural rubber, styrene-butadiene rubber, polyacrylates), tackifying resins (polyterpenes, rosins, petroleum

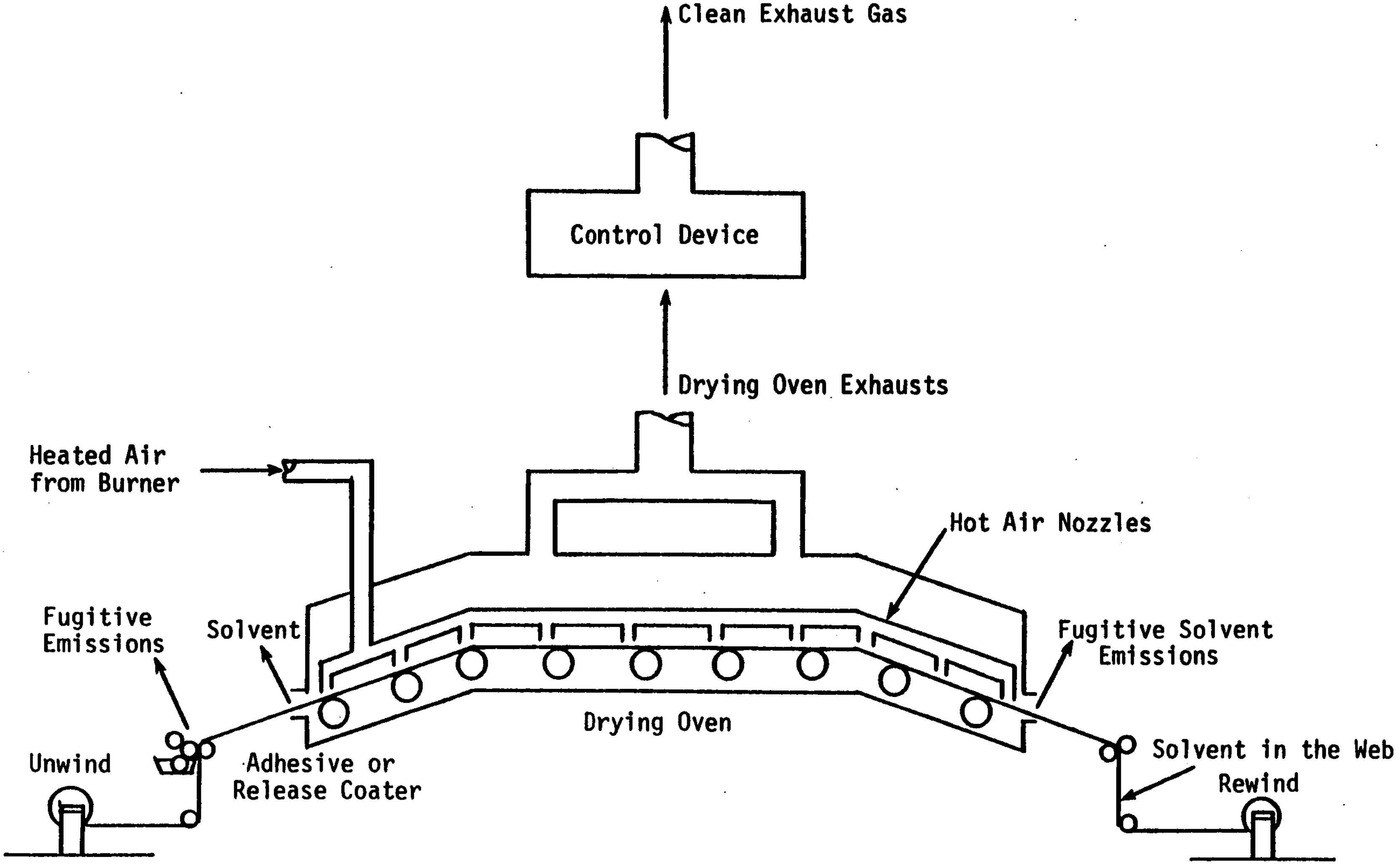

Figure 4.2.2.9-1. Diagram of a pressure sensitive tape and label coating line.

hydrocarbon resins, asphalts), plasticizers (phthalate esters, polybutenes, mineral oil), and fillers (zinc oxide, silica, clay).

The order of application is generally release coat, primer coat (if any), and adhesive coat. A web must always have a release coat before the adhesive can be applied. Primer coats are not required on all products, generally being applied to improve the performance of the adhesive.

Three basic categories of coating heads are used in the PSTL industry. The type of coating head used has a great effect on the quality of the coated product, but only a minor effect on overall emissions. The first type operates by applying coating to the web and scraping excess off to a desired thickness. Examples of this type of coater are the knife coater, blade coater, and metering rod coater. The second category of coating head meters on a specific amount of coating. Gravure and reverse roll coaters are the most common examples. The third category of coating head does not actually apply a surface coating, but rather it saturates the web backing. The most common example in this category is the dip and squeeze coater.

After solvent base coatings have been applied, the web moves into the drying oven where the solvents are evaporated from the web. The important characteristics of the drying oven operation are:

source of heat
temperature profile
residence time
allowable hydrocarbon concentration in the dryer
oven air circulation

Two basic types of heating are used in conventional drying ovens, direct and indirect. Direct heating routes the hot combustion gases (blended with ambient air to the proper temperature) directly into the drying zone. With indirect heating, the incoming oven air stream is heated in a heat exchanger with steam or hot combustion gases but does not physically mix with them. Direct-fired ovens are more common in the PSTL industry because of their higher thermal efficiency. Indirect heated ovens are less energy efficient in both the production of steam and the heat transfer in the exchanger.

Drying oven temperature control is an important consideration in PSTL production. The oven temperature must be above the boiling point of the applied solvent. However, the temperature profile must be controlled by using multizoned ovens. Coating flaws known as "craters" or "fish eyes" will develop if the initial drying proceeds too quickly. These ovens are physically divided into several sections, each with its own hot air supply and exhaust. By keeping the temperature of the first zone low, and then gradually increasing it in subsequent zones, uniform drying can be accomplished without flaws. After exiting the drying oven, the continuous web is wound on a roll, and the coating process is complete.

4.2.2.9.3 Emissions[1,6-10]

The only pollutants emitted in significant quantities from solvent base coating of pressure sensitive tapes and labels are volatile organic compounds (VOC) from solvent evaporation. In an uncontrolled facility, essentially all of the solvent used in the coating formulation is emitted to the atmosphere. Of these uncontrolled emissions, 80 to 95 percent are emitted with the drying oven exhaust. Some solvent (from zero to 5 percent) can remain in the final coated product, although this solvent will eventually evaporate into the atmosphere. The remainder of applied solvent is lost from a number of small sources as fugitive emissions. The major VOC emission points in a PSTL surface coating operation are indicated in Figure 4.2.2.9-1.

There are also VOC losses from solvent storage and handling, equipment cleaning, miscellaneous spills, and coating formulation mixing tanks. These emissions are not addressed here, as these sources have a comparatively small quantity of emissions.

Fugitive solvent emissions during the coating process come from the evaporative loss of solvent around the coating head and from the exposed wet web prior to its entering the drying oven. The magnitude of these losses is determined by the width of the web, the line speed, the volatility and temperature of the solvent, and the air turbulence in the coating area.

Two factors that directly determine total line emissions are the weight (thickness) of the applied coating on the web and the solvent/solids ratio of the coating formulations. For coating formulations with a constant solvent/solids ratio during coating, any increases in coating weight would produce higher levels of VOC emissions. The solvent/solids ratio in coating formulations is not constant industrywide. This ratio varies widely among products. If a coating weight is constant, greater emissions will be produced by increasing the weight percent solvent of a particular formulation.

These 2 operating parameters, combined with line speed, line width, and solvent volatility, produce a number of potential mass emission situations. Table 4.2.2.9-1 presents emission factors for controlled and uncontrolled PSTL surface coating operations. The potential amount of VOC emissions from the coating process is equal to the total amount of solvent applied at the coating head.

4.2.2.9.4 Controls[1,6-18]

The complete air pollution control system for a modern pressure sensitive tape or label surface coating facility consists of 2 sections, the solvent vapor capture system and the emission control device. The capture system collects VOC vapors from the coating head, the wet web, and the drying oven. The captured vapors are directed to a control device to be either recovered (as liquid solvent) or destroyed. As an alternate emission control technique, the PSTL industry is also using low-VOC content coatings to reduce their VOC emissions. Waterborne and hot melt coatings and radiation-cured prepolymers are examples of these low-VOC-content coatings. Emissions of VOC from such coatings are negligible or zero. Low-VOC-content coatings are not universally applicable to the PSTL industry, but about 25 percent of the production in this industry is presently using these innovative coatings.

4.2.2.9.4.1 Capture Systems -

In a typical PSTL surface coating facility, 80 to 95 percent of VOC emissions from the coating process is captured in the coating line drying ovens. Fans are used to direct drying oven emissions to a control device. In some facilities, a portion of the drying oven exhaust is recirculated into the oven instead of to a control device. Recirculation is used to increase the VOC concentration of the drying oven exhaust gases going to the control device.

Another important aspect of capture in a PSTL facility involves fugitive VOC emissions. Three techniques can be used to collect fugitive VOC emissions from PSTL coating lines. The first involves the use of floor sweeps and/or hooding systems around the coating head and exposed coated web. Fugitive emissions collected in the hoods can be directed into the drying oven and on to a control device, or they can be sent directly to the control device. The second capture technique involves enclosing the entire coating line or the coating application and flashoff areas. By

Table 4.2.2.9-1 (Metric And English Units). EMISSION FACTORS FOR PRESSURE SENSITIVE TAPE AND LABEL SURFACE COATING OPERATIONS

EMISSION FACTOR RATING: C

Emission Points	Nonmethane VOC[a]		
	Uncontrolled, kg/kg (lb/lb)	85% Control, kg/kg (lb/lb)	90% Control, kg/kg (lb/lb)
Drying oven exhaust[b]	0.80 - 0.95	—	—
Fugitives[c]	0.01 - 0.15	0.01 - 0.095	0.0025 - 0.0425
Product retention[d]	0.01 - 0.05	0.01 - 0.05	0.01 - 0.05
Control device[e]	—	0.045	0.0475
Total emissions[f]	1.0	0.15	0.10

[a] Expressed as the mass of volatile organic compounds (VOC) emitted per mass of total solvent used. Solvent is assumed to consist entirely of VOC.

[b] References 1,6-7,9. Dryer exhaust emissions depend on coating line operating speed, frequency of line downtime, coating composition, and oven design.

[c] Determined by difference between total emissions and other point sources. Magnitude is determined by size of the line equipment, line speed, volatility and temperature of the solvents, and air turbulence in the coating area.

[d] References 6-8. Solvent in the product eventually evaporates into the atmosphere.

[e] References 1,10,17-18. Emissions are residual content in captured solvent-laden air vented after treatment. Controlled coating line emissions are based on an overall reduction efficiency which is equal to capture efficiency times control device efficiency. For 85% control, capture efficiency is 90% with a 95% efficient control device. For 90% control, capture efficiency is 95% with a 95% efficient control device.

[f] Values assume that uncontrolled coating lines eventually emit 100% of all solvents used.

maintaining a slight negative pressure within the enclosure, a capture efficiency of 100 percent is theoretically possible. The captured emissions are directed by fans into the oven or to a control device. The third capture technique is an expanded form of total enclosure. The entire building or structure which houses the coating line acts as an enclosure. The entire room air is vented to a control device. The maintenance of a slight negative pressure ensures that very few emissions escape the room.

The efficiency of any vapor capture system is highly dependent on its design and its degree of integration with the coating line equipment configuration. The design of any system must allow safe and adequate access to the coating line equipment for maintenance. The system must also be designed to protect workers from exposure to unhealthy concentrations of the organic solvents used in the surface coating processes. The efficiency of a well-designed combined dryer exhaust and fugitive capture system is 95 percent.

4.2.2.9.4.2 Control Devices -

The control devices and/or techniques that may be used to control captured VOC emissions can be classified into 2 categories, solvent recovery and solvent destruction. Fixed-bed carbon adsorption is the primary solvent recovery technique used in this industry. In fixed-bed adsorption, the solvent vapors are adsorbed onto the surface of activated carbon, and the solvent is regenerated by steam. Solvent recovered in this manner may be reused in the coating process or sold to a reclaimer. The efficiency of carbon adsorption systems can reach 98 percent, but a 95 percent efficiency is more characteristic of continuous long term operation.

The primary solvent destruction technique used in the PSTL industry is thermal incineration, which can be as high as 99 percent efficient. However, operating experience with incineration devices has shown that 95 percent efficiency is more characteristic. Catalytic incineration could be used to control VOC emissions with the same success as thermal incineration, but no catalytic devices have been found in the industry.

The efficiencies of carbon adsorption and thermal incineration control techniques on PSTL coating VOC emissions have been determined to be equal. Control device emission factors presented in Table 4.2.2.9-1 represent the residual VOC content in the exhaust air after treatment.

The overall emission reduction efficiency for VOC emission control systems is equal to the capture efficiency times the control device efficiency. Emission factors for 2 control levels are presented in Table 4.2.2.9-1. The 85 percent control level represents 90 percent capture with a 95 percent efficient control device. The 90 percent control level represents 95 percent capture with a 95 percent efficient control device.

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4.2.2.10 Metal Coil Surface Coating

4.2.2.10.1 General[1-2]

Metal coil surface coating (coil coating) is the linear process by which protective or decorative organic coatings are applied to flat metal sheet or strip packaged in rolls or coils. Although the physical configurations of coil coating lines differ from one installation to another, the operations generally follow a set pattern. Metal strip is uncoiled at the entry to a coating line and is passed through a wet section, where the metal is thoroughly cleaned and is given a chemical treatment to inhibit rust and to promote coatings adhesion to the metal surface. In some installations, the wet section contains an electrogalvanizing operation. Then the metal strip is dried and sent through a coating application station, where rollers coat one or both sides of the metal strip. The strip then passes through an oven where the coatings are dried and cured. As the strip exits the oven, it is cooled by a water spray and again dried. If the line is a tandem line, there is first the application of a prime coat, followed by another of top or finish coat. The second coat is also dried and cured in an oven, and the strip is again cooled and dried before being rewound into a coil and packaged for shipment or further processing. Most coil coating lines have accumulators at the entry and exit that permit continuous metal strip movement through the coating process while a new coil is mounted at the entry or a full coil removed at the exit. Figure 4.2.2.10-1 is a flow diagram of a coil coating line.

Coil coating lines process metal in widths ranging from a few centimeters to 183 centimeters (72 inches), and in thicknesses of from 0.018 to 0.229 centimeters (0.007 to 0.090 inches). The speed of the metal strip through the line is as high as 3.6 meters per second (700 feet per minute [ft/min]) on some of the newer lines.

A wide variety of coating formulations is used by the coil coating industry. The more prevalent coating types include polyesters, acrylics, polyfluorocarbons, alkyds, vinyls and plastisols. About 85 percent of the coatings used are organic solvent base and have solvent contents ranging from near 0 to 80 volume percent, with the prevalent range being 40 to 60 volume percent. Most of the remaining 15 percent of coatings are waterborne, but they contain organic solvent in the range of 2 to 15 volume percent. High solids coatings, in the form of plastisols, organosols, and powders, are also used to some extent by the industry, but the hardware is different for powder applications.

The solvents most often used in the coil coating industry include xylene, toluene, methyl ethyl ketone (MEK), Cellosolve Acetate™ , butanol, diacetone alcohol, Cellosolve™, Butyl Cellosolve™, Solvesso 100 and 150™, isophorone, butyl carbinol, mineral spirits, ethanol, nitropropane, tetrahydrofuran, Panasolve™, methyl isobutyl ketone, Hisol 100™, Tenneco T-125™, isopropanol, and diisoamyl ketone.

Coil coating operations can be classified in 1 of 2 operating categories, toll coaters and captive coaters. The toll coater is a service coater who works for many customers according to the needs and specifications of each. The coated metal is delivered to the customer, who forms the end products. Toll coaters use many different coating formulations and normally use mostly organic solvent-base coatings. Major markets for toll coating operations include the transportation industry, the construction industry, and appliance, furniture, and container manufacturers. The captive coater is normally 1 operation in a manufacturing process. Many steel and aluminum companies have their own coil coating operations, where the metal they produce is coated and then formed into end

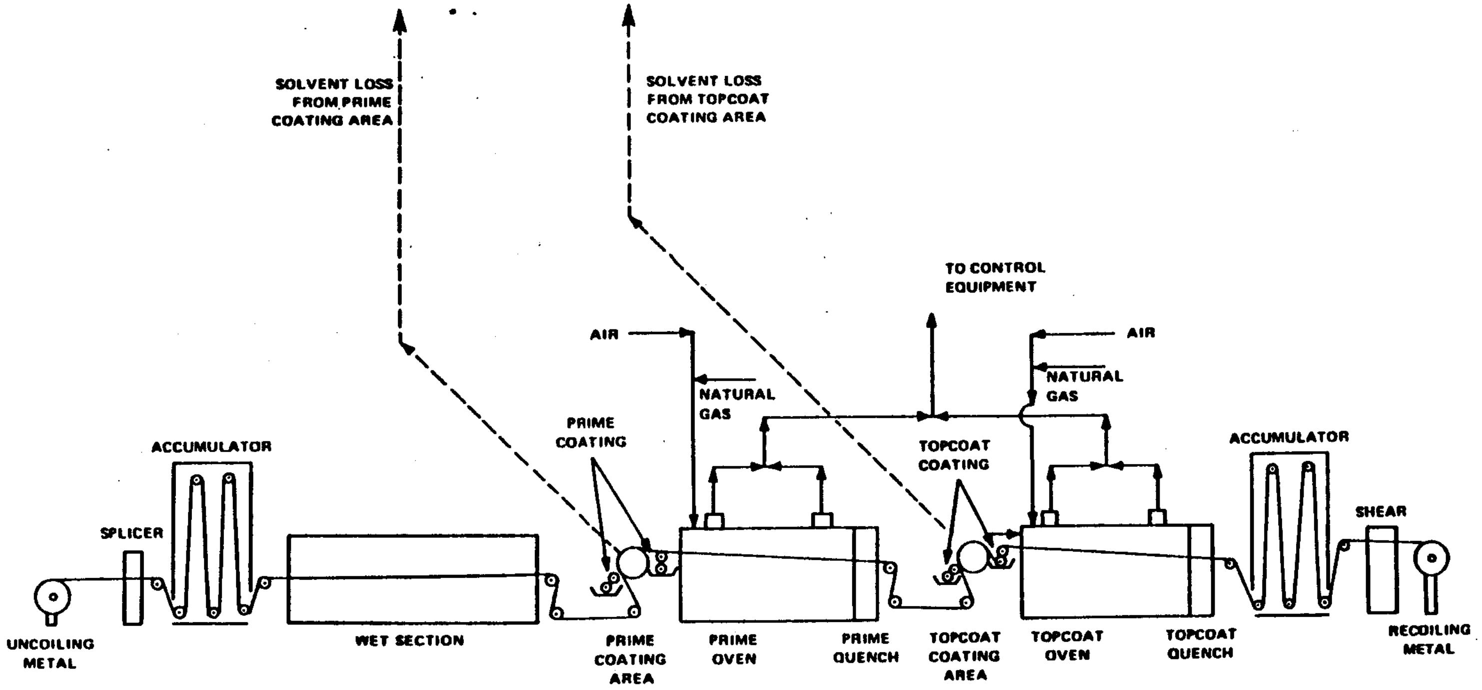

Figure 4.2.2.10-1. Flow diagram of model coil coating line.

products. Captive coaters are much more likely to use water-base coatings because the metal coated is often used for only a few end products. Building products such as aluminum siding are one of the more important uses of waterborne metal coatings.

4.2.2.10.2 Emissions And Controls[1-12]

Volatile organic compounds (VOC) are the major pollutants emitted from metal coil surface coating operations. Specific operations that emit VOC are the coating application station, the curing oven and the quench area. These are identified in Figure 4.2.2.10-1. VOC emissions result from the evaporation of organic solvents contained in the coating. The percentage of total VOC emissions given off at each emission point varies from one installation to another, but, on the average, about 8 percent is given off at the coating application station, 90 percent the oven and 2 percent the quench area. On most coating lines, the coating application station is enclosed or hooded to capture fugitive emissions and to direct them into the oven. The quench is an enclosed operation located immediately adjacent to the exit end of the oven so that a large fraction of the emissions given off at the quench is captured and directed into the oven by the oven ventilating air. In operations such as these, approximately 95 percent of the total emissions are exhausted by the oven, and the remaining 5 percent escape as fugitive emissions.

The rate of VOC emissions from individual coil coating lines may vary widely from one installation to another. Factors that affect the emission rate include VOC content of coatings as applied, VOC density, area of metal coated, solids content of coatings as applied, thickness of the applied coating and number of coats applied. Because the coatings are applied by roller coating, transfer efficiency is generally considered to approach 100 percent and therefore does not affect the emission rate.

Two emission control techniques are widespread in the coil coating industry, incineration and use of low-VOC-content coatings. Incinerators may be either thermal or catalytic, both of which have been demonstrated to achieve consistently a VOC destruction efficiency of 95 percent or greater. When used with coating rooms or hoods to capture fugitive emissions, incineration systems can reduce overall emissions by 90 percent or more.

Waterborne coatings are the only low-VOC-content coating technology that is used to a significant extent in the coil coating industry. These coatings have substantially lower VOC emissions than most of the organic solventborne coatings. Waterborne coatings are used as an emission control technique most often by installations that coat metal for only a few products, such as building materials. Many such coaters are captive to the firm that produces and sells the products fabricated from the coated coil. Because waterborne coatings have not been developed for many coated metal coil uses, most toll coaters use organic solventborne coatings and control their emissions by incineration. Most newer incinerator installations use heat recovery to reduce the operating cost of an incineration system.

Emission factors for coil coating operations and the equations used to compute them are presented in Table 4.2.2.10-1. The values presented therein represent maximum, minimum, and average emissions from small, medium, and large coil coating lines. An average film thickness and an average solvent content are assumed to compute the average emission factor. Values for the VOC content near the maximum and minimum used by the industry are assumed for the calculations of maximum and minimum emission factors.

The emission factors in Table 4.2.2.10-1 are useful in estimating VOC emissions for a large sample of coil coating sources, but they may not be applicable to individual plants. To estimate the emissions from a specific plant, operating parameters of the coil coating line should be obtained and used in the equation given in the footnote to Table 4.2.2.10-1. If different coatings are used for prime and topcoats, separate calculations must be made for each coat. Operating parameters on which the emission factors are based are presented in Table 4.2.2.10-2.

Table 4.2.2.10-1 (Metric And English Units). VOC EMISSION FACTORS FOR COIL COATING[a]

EMISSION FACTOR RATING: C

Coatings	kg/hr (lb/hr)		kg/m^2 (lb/ft^2)	
	Average	Normal Range	Average	Normal Range
Solventborne				
Uncontrolled	303 (669)	50 - 1,798 (110 - 3,964)	0.060 (0.012)	0.027 - 0.160 (0.006 - 0.033)
Controlled[b]	30 (67)	5 - 180 (11 - 396)	0.0060 (0.0012)	0.0027 - 0.0160 (0.0006 - 0.0033)
Waterborne	50 (111)	3 - 337 (7 - 743)	0.0108 (0.0021)	0.0011 - 0.0301 (0.0003 - 0.0062)

[a] All nonmethane VOC. Factors are calculated using the following equations and the operating parameters given in Table 4.2.2.10-2.

$$E = \frac{0.623\ ATVD}{S} \qquad (1)$$

where:

E = Mass of VOC emissions per hour (lb/hr)
A = Area of metal coated per hour (ft^2)
= Line speed (ft/min) x strip width (ft) x 60 min/hr
T = Total dry film thickness of coatings applied (in.).
V = VOC content of coatings (fraction by volume)
D = VOC density (assumed to be 7.36 lb/gal)
S = Solids content of coatings (fraction by volume)

The constant 0.623 represents conversion factors of 7.48 gal/ft^3 divided by the conversion factor of 12 in./ft.

$$M = \frac{E}{A} \qquad (2)$$

where:

M = Mass of VOC emissions per unit area coated.

[b] Computed by assuming a 90% overall control efficiency (95% capture and 95% removal by the control device).

Table 4.2.2.10-2 (English Units). OPERATING PARAMETERS FOR SMALL, MEDIUM, AND LARGE COIL COATING LINES[a]

Line Size	Line Speed (ft/min)	Strip Width (ft)	Total Dry Film Thickness[b] (in.)	VOC Content[c] (fraction)	Solids Content[c] (fraction)	VOC Density[b] (lb/gal)
Solventborne coatings						
Small	200	1.67	0.0018	0.40	0.60	7.36
Medium	300	3	0.0018	0.60	0.40	7.36
Large	500	4	0.0018	0.80	0.20	7.36
Waterborne coatings						
Small	200	1.67	0.0018	0.02	0.50	7.36
Medium	300	3	0.0018	0.10	0.40	7.36
Large	500	4	0.0018	0.15	0.20	7.36

[a] Obtained from Reference 3.

[b] Average value assumed for emission factor calculations. Actual values should be used to estimate emissions from individual sources.

[c] All three values of VOC content and solids content were used in the calculation of emission factors for each plant size to give maximum, minimum, and average emission factors.

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4.2.2.11 Large Appliance Surface Coating

4.2.2.11.1 General[1]

Large appliance surface coating is the application of protective or decorative organic coatings to preformed large appliance parts. For this discussion, large appliances are defined as any metal range, oven, microwave oven, refrigerator, freezer, washing machine, dryer, dishwasher, water heater, or trash compactor.

Regardless of the appliance, similar manufacturing operations are involved. Coiled or sheet metal is cut and stamped into the proper shapes, and the major parts are welded together. The welded parts are cleaned with organic degreasers or a caustic detergent (or both) to remove grease and mill scale accumulated during handling, and the parts are then rinsed in one or more water rinses. This is often followed by a process to improve the grain of the metal before treatment in a phosphate bath. Iron or zinc phosphate is commonly used to deposit a microscopic matrix of crystalline phosphate on the surface of the metal. This process provides corrosion resistance and increases the surface area of the part, thereby allowing superior coating adhesion. Often the highly reactive metal is protected with a rust inhibitor to prevent rusting prior to painting.

Two separate coatings have traditionally been applied to these prepared appliance parts: a protective prime coating that also covers surface imperfections and contributes to total coating thickness, and a final, decorative topcoat. Single-coat systems, where only a prime coat or only a topcoat is applied, are becoming more common. For parts not exposed to customer view, a prime coat alone may suffice. For exposed parts, a protective coating may be formulated and applied so as to act as the topcoat. There are many different application techniques in the large appliance industry, including manual, automatic, and electrostatic spray operations, and several dipping methods. Selection of a particular method depends largely upon the geometry and use of the part, the production rate, and the type of coating being used. Typical application of these coating methods is shown in Figure 4.2.2.11-1.

A wide variety of coating formulations is used by the large appliance industry. The prevalent coating types include epoxies, epoxy/acrylics, acrylics, and polyester enamels. Liquid coatings may use either an organic solvent or water as the main carrier for the paint solids.

Waterborne coatings are of 3 major classes: water solutions, water emulsions, and water dispersions. All of the waterborne coatings, however, contain a small amount (up to 20 volume percent) of organic solvent that acts as a stabilizing, dispersing or emulsifying agent. Waterborne systems offer some advantages over organic solvent systems. They do not exhibit as great an increase in viscosity with increasing molecular weight of solids, they are nonflammable, and they have limited toxicity. But because of the relatively slow evaporation rate of water, it is difficult to achieve a smooth finish with waterborne coatings. A bumpy "orange peel" surface often results. For this reason, their main use in the large appliance industry is as prime coats.

While conventional organic solventborne coatings also are used for prime coats, they predominate as topcoats. This is due in large part to the controllability of the finish and the amenability of these materials to application by electrostatic spray techniques. The most common organic solvents are ketones, esters, ethers, aromatics, and alcohols. To obtain or maintain certain application characteristics, solvents are often added to coatings at the plant. The use of powder

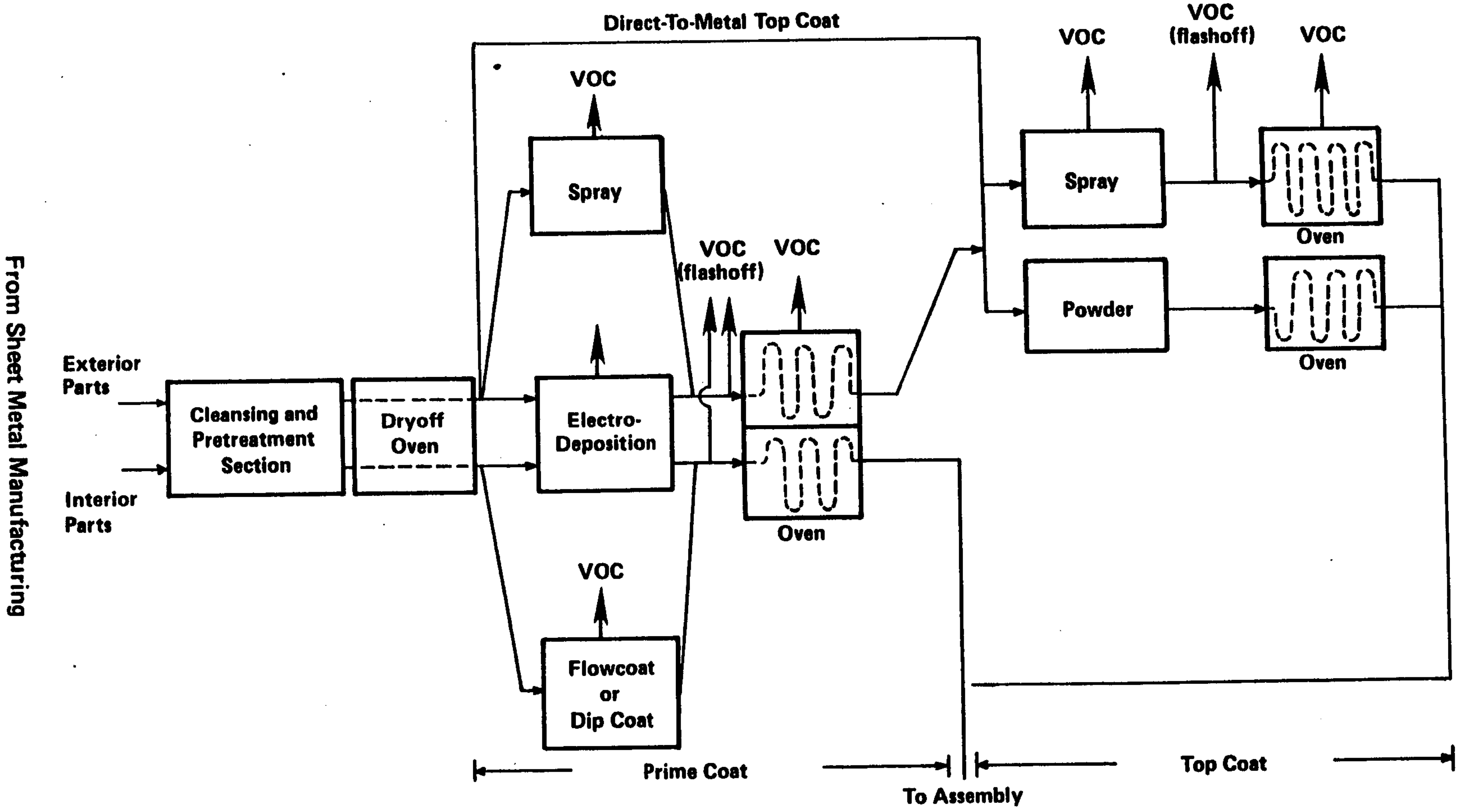

Figure 4.2.2.11-1. Typical coating application methods in the large appliance industry.

coatings for topcoats is gaining acceptance in the industry. These coatings, which are applied as a dry powder and then fused into a continuous coating film through the use of heat, yield negligible emissions.

4.2.2.11.2 Emissions And Controls[1-2]

Volatile organic compounds (VOC) are the major pollutants emitted from large appliance surface coating operations. VOC from evaporation of organic solvents contained in the coating are emitted in the application station, the flashoff area and the oven. An estimated 80 percent of total VOC emissions is given off in the application station and flashoff area. The remaining 20 percent occurs in the oven. Because the emissions are widely dispersed, the use of capture systems and control devices is not an economically attractive means of controlling emissions. While both incinerators and carbon adsorbers are technically feasible, none is known to be used in production, and none is expected. Improvements in coating formulation and application efficiency are the major means of reducing emissions.

Factors that affect the emission rate include the volume of coating used, the coating's solids content, the coating's VOC content, and the VOC density. The volume of coating used is a function of 3 additional variables: (1) the area coated, (2) the coating thickness, and (3) the application efficiency.

While a reduction in coating VOC content will reduce emissions, the transfer efficiency with which the coating is applied (i. e., the volume required to coat a given surface area) also has a direct bearing on the emissions. A transfer efficiency of 60 percent means that 60 percent of the coating solids consumed is deposited usefully onto appliance parts. The other 40 percent is wasted overspray. With a specified VOC content, an application system with a high transfer efficiency will have lower emission levels than will a system with a low transfer efficiency, because a smaller volume of coating will coat the same surface area. Since not every application method can be used with all parts and types of coating, transfer efficiencies in this industry range from 40 to over 95 percent.

Although waterborne prime coats are becoming common, the trend for topcoats appears to be toward use of "high solids" solventborne material, generally 60 volume percent or greater solids. As different types of coatings are required to meet different performance specifications, a combination of reduced coating VOC content and improved transfer efficiency is the most common means of emission reduction.

In the absence of control systems that remove or destroy a known fraction of the VOC prior to emission to the atmosphere, a material balance provides the quickest and most accurate emissions estimate. An equation to calculate emissions is presented below. To the extent that the parameters of this equation are known or can be determined, its use is encouraged. In the event that both a prime coat and a topcoat are used, the emissions from each must be calculated separately and added to estimate total emissions. Because of the diversity of product mix and plant sizes, it is difficult to provide emission factors for "typical" facilities. Approximate values for several of the variables in the equation are provided, however.

$$E = \frac{(6.234 \times 10^{-4})\ P\ A\ t\ V_o\ D_o}{V_s\ T} + L_d\ D_d$$

where:

E = mass of VOC emissions per unit time (lb/unit time)
P = units of production per unit time
A = area coated per unit of production (ft^2) (see Table 4.2.2.11-2)
t = dry coating thickness (mils) (see Table 4.2.2.11-2)
V_o = proportion of VOC in the coating (volume fraction), as received[a]
D_o = density of VOC solvent in the coating (lb/gal), as received[a]
V_s = proportion of solids in the coating (volume fraction), as received[a]
T = transfer efficiency (fraction: the ratio of coating solids deposited onto appliance parts to the total amount of coating solids used. See Table 4.2.2.11-1.)
L_d = volume of VOC solvent added to the coating per unit time (gal/unit time)
D_d = density of VOC solvent added (lb/gal)

The constant 6.234×10^{-4} is the product of 2 conversion factors:

$$\frac{8.333 \times 10^{-5} \text{ ft}}{\text{mil}} \quad \text{and} \quad \frac{7.481 \text{ gal}}{\text{ft}^3}$$

If all the data are not available to complete the above equation, the following may be used as approximations:

$V_o = 0.38$
$D_o = 7.36$ lb/gal
$V_s = 0.62$
$L_d = 0$ (assumes no solvent added at the plant)

In the absence of all operating data, an emission estimate of 49.9 Mg (55 tons) of VOC per year may be used for the average appliance plant. Because of the large variation in emissions among plants (from less than 10 to more than 225 Mg [10 to 250 tons] per year), caution is advised when this estimate is used for anything except approximations for a large geographical area. Most of the known large appliance plants are in localities considered nonattainment areas for achieving the national ambient air quality standard (NAAQS) for ozone. The 49.9-Mg-per-year (55-ton-per-year) average is based on an emission limit of 2.8 lb of VOC per gallon of coating (minus water), which is the limit recommended by the Control Techniques Guideline (CTG) applicable in those areas. For a plant operating in an area where there are no emission limits, the emissions may be 4 times greater than from an identical plant subject to the CTG-recommended limit.

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[a] If known, V_o, D_o, and V_s for the coating as applied (i. e., diluted) may be used in lieu of the values for the coating as received, and the term L_d D_d deleted.

Table 4.2.2.11-1. TRANSFER EFFICIENCIES

Application Method	Transfer Efficiency (T)
Air atomized spray	0.40
Airless spray	0.45
Manual electrostatic spray	0.60
Flow coat	0.85
Dip coat	0.85
Nonrotational automatic electrostatic spray	0.85
Rotating head automatic electrostatic spray	0.90
Electrodeposition	0.95
Powder	0.95

Table 4.2.2.11-2 (Metric And English Units). AREAS COATED AND COATING THICKNESS[a]

Appliance	Prime Coat		Topcoat	
	A (ft^2)	t (mils)	A (ft^2)	t (mils)
Compactor	20	0.5	20	0.8
Dishwasher	10	0.5	10	0.8
Dryer	90	0.6	30	1.2
Freezer	75	0.5	75	0.8
Microwave oven	8	0.5	8	0.8
Range	20	0.5	30	0.8
Refrigerator	75	0.5	75	0.8
Washing machine	70	0.6	25	1.2
Water heater	20	0.5	20	0.8

[a] A = area coated per unit of production. t = dry coating thickness.

References For Section 4.2.2.11

1. *Industrial Surface Coating: Appliances—Background Information For Proposed Standards*, EPA-450/3-80-037a, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 1980.

2. *Industrial Surface Coating: Large Appliances—Background Information For Promulgated Standards*, EPA 450/3-80-037b, U. S. Environmental Protection Agency, Research Triangle Park, NC, 27711, October 1982.

4.2.2.12 Metal Furniture Surface Coating

4.2.2.12.1 General

The metal furniture surface coating process is a multistep operation consisting of surface cleaning, coatings application, and curing. Items such as desks, chairs, tables, cabinets, bookcases, and lockers are normally fabricated from raw material to finished product in the same facility. The industry uses primarily solventborne coatings, applied by spray, dip, or flow coating processes. Spray coating is the most common application technique used. The components of spray coating lines vary from plant to plant, but generally consist of the following:

3- to 5-stage washer
Dryoff oven
Spray booth
Flashoff area
Bake oven

Items to be coated are first cleaned in the washer to remove any grease, oil, or dirt from the surface. The washer generally consists of an alkaline cleaning solution, a phosphate treatment to improve surface adhesion characteristics, and a hot water rinse. The items are then dried in an oven and conveyed to the spray booth, where the surface coating is applied. After this application, the items are conveyed through the flashoff area to the bake oven, where the surface coating is cured. A diagram of these consecutive steps is presented in Figure 4.2.2.12-1. Although most metal furniture products receive only 1 coat of paint, some facilities apply a prime coat before the topcoat to improve the corrosion resistance of the product. In these cases, a separate spray booth and bake oven for application of the prime coat are added to the line, following the dryoff oven.

The coatings used in the industry are primarily solventborne resins, including acrylics, amines, vinyls, and cellulosics. Some metallic coatings are also used on office furniture. The solvents used are mixtures of aliphatics, xylene, toluene, and other aromatics. Typical coatings that have been used in the industry contain 65 volume percent solvent and 35 volume percent solids. Other types of coatings now being used in the industry are waterborne, powder, and solventborne high solids coatings.

4.2.2.12.2 Emissions And Controls

Volatile organic compounds (VOC) from the evaporation of organic solvents in the coatings are the major pollutants from metal furniture surface coating operations. Specific operations that emit VOC are the coating application process, the flashoff area and the bake oven. The percentage of total VOC emissions given off at each emission point varies from one installation to another, but on the average spray coating line, about 40 percent is given off at the application station, 30 percent in the flashoff area, and 30 percent in the bake oven.

Factors affecting the quantity of VOC emitted from metal furniture surface coating operations are the VOC content of the coatings applied, the solids content of coatings as applied, and the transfer efficiency. Knowledge of both the VOC content and solids content of coatings is necessary in cases where the coating contains other components, such as water.

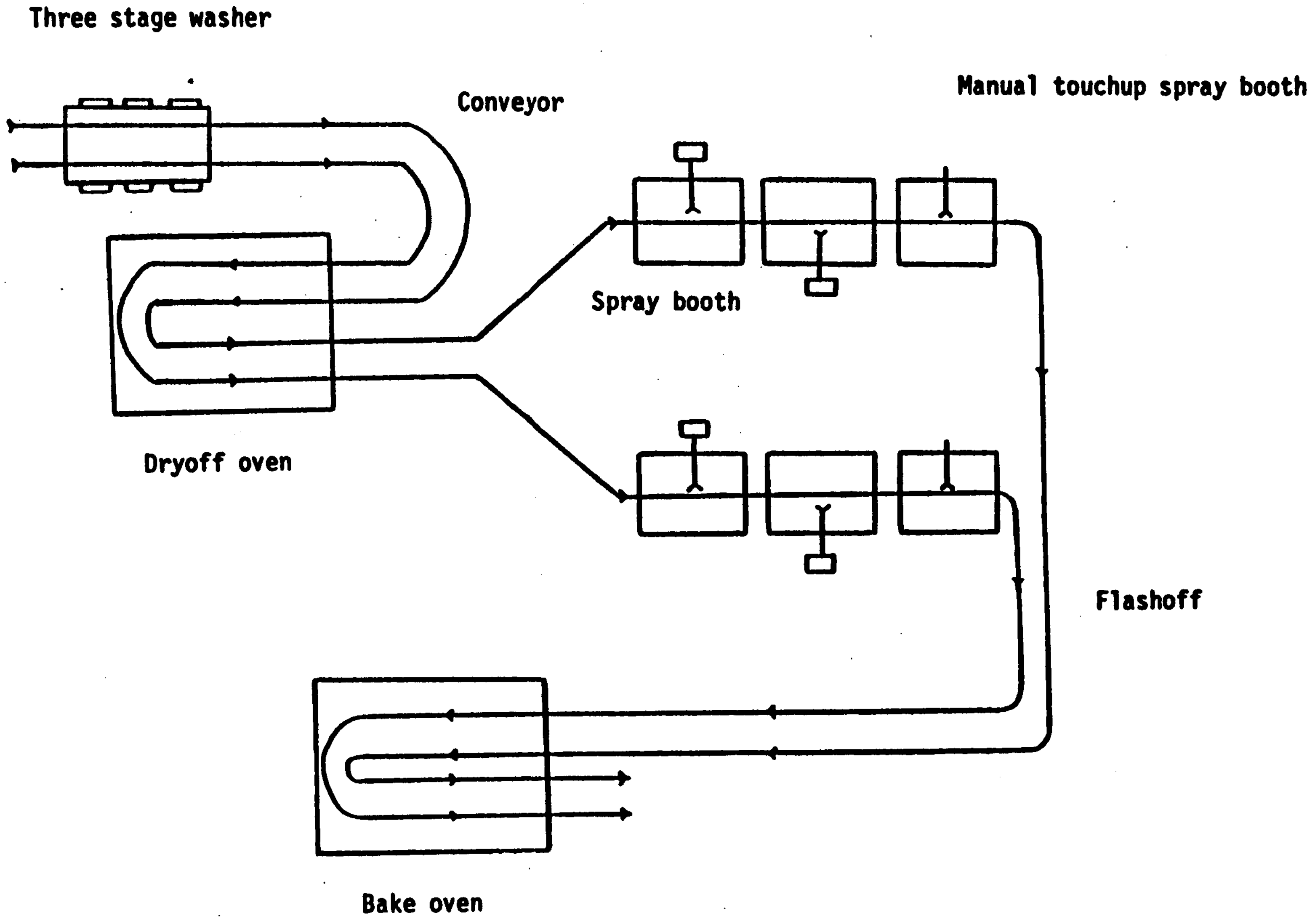

Figure 4.2.2.12-1. Example automated spray coating lines, with manual touchup.

The transfer efficiency (volume fraction of the solids in the total consumed coating that remains on the part) varies with the application technique. Transfer efficiency for standard (or ordinary) spraying ranges from 25 to 50 percent. The range for electrostatic spraying, a method that uses an electrical potential to increase transfer efficiency of the coating solids, is from 50 to 95 percent, depending on part size and shape. Powder coating systems normally capture and recirculate overspray material and, therefore, are considered in terms of a "utilization rate" rather than a transfer efficiency. Most facilities achieve a powder utilization rate of 90 to 95 percent.

Typical values for transfer efficiency with various application devices are in Table 4.2.2.12-1.

Table 4.2.2.12-1. COATING METHOD TRANSFER EFFICIENCIES

Application Methods	Transfer Efficiency (Te)
Air atomized spray	0.25
Airless spray	0.25
Manual electrostatic spray	0.60
Nonrotational automatic electrostatic spray	0.70
Rotating head electrostatic spray (manual and automatic)	0.80
Dip coat and flow coat	0.90
Electrodeposition	0.95

Two types of control techniques are available to reduce VOC emissions from metal furniture surface coating operations. The first technique makes use of control devices such as carbon absorbers and thermal or catalytic incinerators to recover or destroy VOC before it is discharged into the ambient air. These control methods are seldom used in the industry, however, because the large volume of exhaust air and low concentrations of VOC in the exhaust reduce their efficiency. The more prevalent control technique involves reducing the total amount of VOC likely to be evaporated and emitted. This is accomplished by use of low VOC content coatings and by improvements in transfer efficiency. New coatings with relatively low VOC levels can be used instead of the traditional high VOC content coatings. Examples of these new systems include waterborne coatings, powder coatings, and higher solids coatings. Improvements in coating transfer efficiency decrease the amount that must be used to achieve a given film thickness, thereby reducing emissions of VOC to the ambient air. By using a system with increased transfer efficiency (such as electrostatic spraying) and lower VOC content coatings, VOC emission reductions can approach those achieved with control devices.

The data presented in Tables 4.2.2.12-2 and 4.2.2.12-3 are representative of values which might be obtained from existing plants with similar operating characteristics. Each plant has its own combination of coating formulations, application equipment, and operating parameters. It is recommended that, whenever possible, plant-specific values be obtained for all variables when calculating emission estimates.

Table 4.2.2.12-2 (Metric Units). OPERATING PARAMETERS FOR COATING OPERATIONS

Plant Size	Operating Schedule (hr/yr)	Number Of Lines	Line Speed[a] (m/min)	Surface Area Coated/yr (m^2)	Liters Of Coating Used[b]
Small	2,000	1 (1 spray booth)	2.5	45,000	5,000
Medium	2,000	3 (3 booths/line	2.4	780,000	87,100
Large	2,000	10 (3 booths/line)	4.6	4,000,000	446,600

[a] Line speed is not used to calculate emissions, only to characterize plant operations.

[b] Using 35 volume % solids coating, applied by electrostatic spray at 65% transfer efficiency.

Table 4.2.2.12-3 (Metric Units). EMISSION FACTORS FOR VOC FROM SURFACE COATING OPERATIONS[a,b]

Plant Size And Control Techniques	VOC Emissions		
	kg/m^2 Coated	kg/yr	kg/hr
Small			
Uncontrolled emissions	0.064	2,875	1.44
65 Volume % high solids coating	0.019	835	0.42
Waterborne coating	0.012	520	0.26
Medium			
Uncontrolled emissions	0.064	49,815	24.90
65 Volume % high solids coating	0.019	14,445	7.22
Waterborne coating	0.012	8,970	4.48
Large			
Uncontrolled emissions	0.064	255,450	127.74
65 Volume % high solids coating	0.019	74,080	37.04
Waterborne coating	0.012	46,000	23.00

[a] Calculated using the parameters given in Table 4.2.2.12-2 and the following equation. Values have been rounded off.

$$E = \frac{0.0254\ ATVD}{S\ Te}$$

where:

E = Mass of VOC emitted per hour (kg)
A = Surface area coated per hour (m^2)
T = Dry film thickness of coating applied (mils)

Table 4.2.2.12-3 (cont.).

V = VOC content of coating, including dilution solvents added at the plant (fraction by volume)
D = VOC density (assumed to be 0.88 kg/L)
S = Solids content of coating (fraction by volume)
T_e = Transfer efficiency (fraction)

The constant 0.0254 converts the volume of dry film applied per m^2 to liters.

Example: The VOC emission from a medium size plant applying 35 volume % solids coatings and the parameters given in Table 4.2.2.12-3.

$$E_{\text{kilograms of VOC/hr}} = \frac{(0.0254)\ (390\ \text{m}^2/\text{hr})\ (1\ \text{mil})\ (0.65)\ (0.88\ \text{kg/L})}{(0.35)\ (0.65)}$$

$$= 24.9\ \text{kilograms of VOC/hr}$$

[b] Nominal values of T, V, S, and Te:

T = 1 mil (for all cases)
V = 0.65 (uncontrolled), 0.35 (65 volume % solids), 0.117 (waterborne)
S = 0.35 (uncontrolled), 0.65 (65 volume % solids), 0.35 (waterborne)
Te = 0.65 (for all cases)

Another method that also may be used to estimate emissions for metal furniture coating operations involves a material balance approach. By assuming that all VOC in the coatings applied are evaporated at the plant site, an estimate of emissions can be calculated using only the coating formulation and data on the total quantity of coating used in a given time period. The percentage of VOC solvent in the coating, multiplied by the quantity of coating used yields the total emissions. This method of emissions estimation avoids the requirement to use variables such as coating thickness and transfer efficiency, which are often difficult to define precisely.

Reference For Section 4.2.2.12

1. *Surface Coating Of Metal Furniture—Background Information For Proposed Standards*, EPA-450/3-80-007a, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1980.

4.2.2.13 Magnetic Tape Manufacturing[1-9]

Magnetic tape manufacturing is a subcategory of industrial paper coating, which includes coating of foil and plastic film. In the manufacturing process, a mixture of magnetic particles, resins, and solvents is coated on a thin plastic film or "web". Magnetic tape is used largely for audio and video recording and computer information storage. Other uses include magnetic cards, credit cards, bank transfer ribbons, instrumentation tape, and dictation tape. The magnetic tape coating industry is included in two Standard Industrial Classification codes, 3573 (Electronic Computing Equipment) and 3679 (Electronic Components Not Elsewhere Classified).

4.2.2.13.1 Process Description[1-2]

The process of manufacturing magnetic tape consists of:

1. mixing the coating ingredients (including solvents)
2. conditioning the web
3. applying the coating to the web
4. orienting the magnetic particles
5. drying the coating in a drying oven
6. finishing the tape by calendering, rewinding, slitting, testing,and packaging

Figure 4.2.2.13-1 shows a typical magnetic tape coating operation, indicating volatile organic compound (VOC) emission points. Typical plants have from 5 to 12 horizontal or vertical solvent storage tanks, ranging in capacity from 3,800 to 75,700 liters (1,000 to 20,000 gallons), that are operated at or slightly above atmospheric pressure. Coating preparation equipment includes the mills, mixers, polishing tanks, and holding tanks used to prepare the magnetic coatings before application. Four types of coaters are used in producing magnetic tapes: extrusion (slot die), gravure, knife, and reverse roll (3- and 4-roll). The web may carry coating on 1 or both sides. Some products receive a nonmagnetic coating on the back. After coating, the web is guided through an orientation field, in which an electromagnet or permanent magnet aligns the individual magnetic particles in the intended direction. Webs from which flexible disks are to be produced do not go through the orientation process. The coated web then passes through a drying oven, where the solvents in the coating evaporate. Typically, air flotation ovens are used, in which the web is supported by jets of drying air. For safe operation, the concentration of solvent vapors is held between 10 and 40 percent of the lower explosive limit. The dry coated web may be passed through several calendering rolls to compact the coating and to smooth the surface finish. Nondestructive testing is performed on up to 100 percent of the final product, depending on the level of precision required of the final product. The web may then be slit into the desired tape widths. Flexible disks are punched from the finished web with a die. The final product is then packaged. Some plants ship the coated webs in bulk to other facilities for slitting and packaging.

High performance tapes require very clean production conditions, especially in the coating application and drying oven areas. Air supplied to these areas is conditioned to remove dust particles and to adjust the temperature and humidity. In some cases, "clean room" conditions are rigorously maintained.

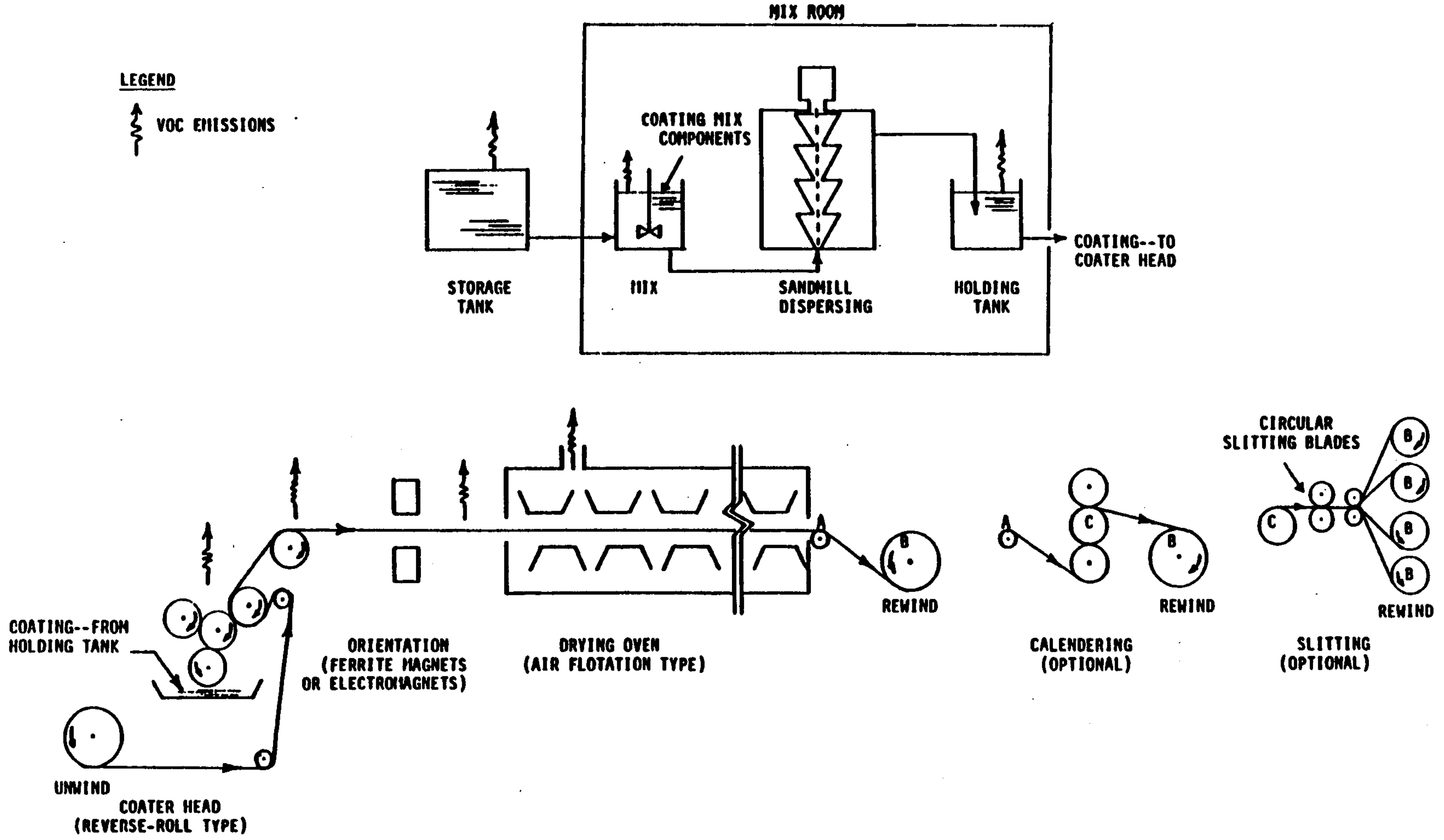

Figure 4.2.2.13-2. Schematic drawing of a magnetic tape coating plant.[1]

4.2.2.13.2 Emissions And Controls[1-8]

The significant VOC emission sources in a magnetic tape manufacturing plant include the coating preparation equipment, the coating application and flashoff area, and the drying ovens. Emissions from the solvent storage tanks and the cleanup area are generally only a negligible percentage of total emissions.

In the mixing or coating preparation area, VOCs are emitted from the individual pieces of equipment during the following operations: filling of mixers and tanks; transfer of the coating; intermittent activities, such as changing the filters in the holding tanks; and mixing (if mix equipment is not equipped with tightly fitting covers). Factors affecting emissions in the mixing areas include the capacity of the equipment, the number of pieces of equipment, solvent vapor pressure, throughput, and the design and performance of equipment covers. Emissions will be intermittent or continuous, depending on whether the preparation method is batch or continuous.

Emissions from the coating application area result from the evaporation of solvent during use of the coating application equipment and from the exposed web as it travels from the coater to the drying oven (flashoff). Factors affecting emissions are the solvent content of the coating, line width and speed, coating thickness, volatility of the solvent(s), temperature, distance between coater and oven, and air turbulence in the coating area.

Emissions from the drying oven are of the remaining solvent that is driven off in the oven. Uncontrolled emissions at this point are determined by the solvent content of the coating when it reaches the oven. Because the oven evaporates all the remaining solvent from the coating, there are no process VOC emissions after oven drying.

Solvent type and quantity are the common factors affecting emissions from all operations in a magnetic tape coating facility. The rate of evaporation or drying depends on solvent vapor pressure at a given temperature and concentration. The most commonly used organic solvents are toluene, methyl ethyl ketone (MEK), cyclohexanone, tetrahydrofuran, and methyl isobutyl ketone. Solvents are selected for their cost, solvency, availability, desired evaporation rate, ease of use after recovery, compatibility with solvent recovery equipment, and toxicity.

Of the total uncontrolled VOC emissions from the mixing area and coating operation (application/flashoff area and drying oven), approximately 10 percent is emitted from the mixing area, and 90 percent from the coating operation. Within the coating operation, approximately 10 percent occurs in the application/flashoff area, and 90 percent in the drying oven.

A control system for evaporative emissions consists of 2 components, a capture device and a control device. The efficiency of the control system is determined by the efficiencies of the 2 components.

A capture device is used to contain emissions from a process operation and direct them to a stack or to a control device. Room ventilation systems, covers, and hoods are possible capture devices from coating preparation equipment. Room ventilation systems, hoods, and partial and total enclosures are typical capture devices used in the coating application area. A drying oven can be considered a capture device, because it both contains and directs VOC process emissions. The efficiency of a capture device or a combination of capture devices is variable and depends on the quality of design and the levels of operation and maintenance.

A control device is any equipment that has as its primary function the reduction of emissions to the atmosphere. Control devices typically used in this industry are carbon adsorbers, condensers, and incinerators. Tightly fitting covers on coating preparation equipment may be considered both capture and control devices, because they can be used either to direct emissions to a desired point outside the equipment or to prevent potential emissions from escaping.

Carbon adsorption units use activated carbon to adsorb VOCs from a gas stream, after which the VOCs are desorbed and recovered from the carbon. Two types of carbon adsorbers are available, fixed-bed and fluidized-bed. Fixed-bed carbon adsorbers are designed with a steam-stripping technique to recover the VOCs and to regenerate the activated carbon. The fluidized-bed units used in this industry are designed to use nitrogen for VOC vapor recovery and carbon regeneration. Both types achieve typical VOC control efficiencies of 95 percent when properly designed, operated, and maintained.

Condensers control VOC emissions by cooling the solvent-laden gas to the dew point of the solvent(s) and then collecting the droplets. There are 2 condenser designs commercially available, nitrogen (inert gas) atmosphere and air atmosphere. These systems differ in the design and operation of the drying oven (i. e., use of nitrogen or air in the oven) and in the method of cooling the solvent-laden air (i. e., liquified nitrogen or refrigeration). Both design types can achieve VOC control efficiencies of 95 percent.

Incinerators control VOC emissions by oxidation of the organic compounds into carbon dioxide and water. Incinerators used to control VOC emissions may be of thermal or catalytic design and may use primary or secondary heat recovery to reduce fuel costs. Thermal incinerators operate at approximately 890°C (1600°F) to ensure oxidation of the organic compounds. Catalytic incinerators operate in the range of 400° to 540°C (750° to 1000°F) while using a catalyst to achieve comparable oxidation of VOCs. Both design types achieve a typical VOC control efficiency of 98 percent.

Tightly fitting covers control VOC emissions from coating preparation equipment by reducing evaporative losses. The parameters affecting the efficiency of these controls are solvent vapor pressure, cyclic temperature change, tank size, and product throughput. A good system of tightly fitting covers on coating preparation equipment reduces emissions by as much as 40 percent. Control efficiencies of 95 or 98 percent can be obtained by venting the covered equipment to an adsorber, condenser, or incinerator.

When the efficiencies of a capture device and control device are known, the efficiency of the control system can be computed by the following equation:

$$\begin{matrix}\text{capture} \\ \text{efficiency}\end{matrix} \;\text{x}\; \begin{matrix}\text{control device} \\ \text{efficiency}\end{matrix} = \begin{matrix}\text{control system} \\ \text{efficiency}\end{matrix}$$

The terms of this equation are fractional efficiencies rather than percentages. For instance, a system of hoods delivering 60 percent of VOC emissions to a 90 percent efficient carbon adsorber would have a control system efficiency of 54 percent (0.60 x 0.90 = 0.54). Table 4.2.2.13-1 summarizes control system efficiencies, which may be used to estimate emissions in the absence of measured data on equipment and coating operations.

Table 4.2.2.13-1. TYPICAL OF CONTROL EFFICIENCIES[a]

Control Technology	Control Efficiency %[b]
Coating Preparation Equipment	
Uncontrolled	0
Tightly fitting covers	40
Sealed covers with carbon adsorber/condenser	95
Coating Operation[c]	
Local ventilation with carbon adsorber/condenser	83
Partial enclosure with carbon adsorber/condenser	87
Total enclosure with carbon adsorber/condenser	93
Total enclosure with incinerator	95

[a] Reference 1.

[b] To be applied to uncontrolled emissions from indicated process area, not from entire plant.

[c] Includes coating application/flashoff area and drying oven.

4.2.2.13.3 Emission Estimation Techniques[1,3-9]

In this industry, realistic emission estimates require solvent consumption data. The variations found in coating formulations, line speeds, and products mean that no reliable inferences can be made otherwise.

In uncontrolled plants and in those where VOCs are recovered for reuse or sale, plantwide emissions can be estimated by performing a liquid material balance based on the assumption that all solvent purchased replaces that which has been emitted. Any identifiable and quantifiable side streams should be subtracted from this total. The liquid material balance may be performed using the following general formula:

$$\begin{matrix}\text{solvent}\\\text{purchased}\end{matrix} - \begin{matrix}\text{quantifiable}\\\text{solvent output}\end{matrix} = \begin{matrix}\text{VOC}\\\text{emitted}\end{matrix}$$

The first term encompasses all solvent purchased, including thinners, cleaning agents, and any solvent directly used in coating formulation. From this total, any quantifiable solvent outputs are subtracted. Outputs may include reclaimed solvent sold for use outside the plant or solvent contained in waste streams. Reclaimed solvent that is reused at the plant is not subtracted.

The advantages of this method are that it is based on data that are usually readily available, it reflects actual operations rather than theoretical steady state production and control conditions, and it includes emissions from all sources at the plant. Care should be taken not to apply this method over too short a time span. Solvent purchase, production, and waste removal occur in cycles that may not coincide exactly.

Occasionally, a liquid material balance may be possible on a scale smaller than the entire plant. Such an approach may be feasible for a single coating line or group of lines, if served by a dedicated mixing area and a dedicated control and recovery system. In this case, the computation begins with total solvent metered to the mixing area, instead of with solvent purchased. Reclaimed solvent is subtracted from this volume, whether or not it is reused on the site. Of course, other solvent input and output streams must be accounted for, as previously indicated. The difference between total solvent input and total solvent output is then taken to be the quantity of VOCs emitted from the equipment in question.

Frequently, the configuration of meters, mixing areas, production equipment, and controls will make the liquid material balance approach impossible. In cases where control devices destroy potential emissions, or where a liquid material balance is inappropriate for other reasons, plantwide emissions can be estimated by summing the emissions calculated for specific areas of the plant. Techniques for these calculations are presented below.

Estimating VOC emissions from a coating operation (application/flashoff area and drying oven) starts with the assumption that the uncontrolled emission level is equal to the quantity of solvent contained in the coating applied. In other words, all the VOC in the coating evaporates by the end of the drying process.

Two factors are necessary to calculate the quantity of solvent applied: solvent content of the coating and the quantity of coating applied. Coating solvent content can be either directly measured using EPA Reference Method 24 or estimated using coating formulation data usually available from the plant owner/operator. The amount of coating applied may be directly metered. If it is not, it must be determined from production data. These data should be available from the plant owner/operator. Care should be taken in developing these 2 factors to ensure that they are in compatible units. In cases where plant-specific data cannot be obtained, the information in Table 4.2.2.13-2 may be useful in approximating the quantity of solvent applied.

When an estimate of uncontrolled emissions is obtained, the controlled emissions level is computed by applying a control system efficiency factor:

$$(\text{uncontrolled VOC}) \times (1 - \text{control system efficiency}) = (\text{VOC emitted})$$

As previously explained, the control system efficiency is the product of the efficiencies of the capture device and of the control device. If these values are not known, typical efficiencies for some combinations of capture and control devices are presented in Table 4.2.2.13-1. It is important to note that these control system efficiencies apply only to emissions that occur within the areas serviced by the systems. Emissions from sources such as process wastewater or discarded waste coatings may not be controlled at all.

In cases where emission estimates from the mixing area alone are desired, a slightly different approach is necessary. Here, uncontrolled emissions will consist of only that portion of total solvent that evaporates during the mixing process. A liquid material balance across the mixing area (i. e., solvent entering minus solvent content of coating applied) would provide a good estimate. In the absence of any measured value, it may be assumed, very approximately, that 10 percent of the total solvent entering the mixing area is emitted during the mixing process. When an estimate of uncontrolled mixing area emissions has been made, the controlled emission rate can be calculated as discussed previously. Table 4.2.2.13-1 lists typical overall control efficiencies for coating mix preparation equipment.

Solvent storage tanks of the size typically found in this industry are regulated by only a few states and localities. Tank emissions are generally small (130 kilograms [285 lb] per year or less). If an emissions estimate is desired, it can be computed using the equations, tables, and figures provided in Chapter 7.

Table 4.2.2.13-2 (Metric And English Units). SELECTED COATING MIX PROPERTIES[a]

Parameter	Unit	Range
Solids	weight % volume %	15 - 50 10 - 26
VOC	weight % volume %	50 - 85 74 - 90
Density of Coating	kg/L lb/gal	1.0 - 1.2 8 - 10
Density of Coating Solids	kg/L lb/gal	2.8 - 4.0 23 - 33
Resins/binder	weight % of solids	15 - 21
Magnetic particles	weight % of solids	66 - 78
Density of magnetic material	kg/L lb/gal	1.2 - 4.8 10 - 40
Viscosity	Pa•s $lb_f \cdot s/ft^2$	2.7 - 5.0 0.06 - 0.10
Coating thickness		
Wet	µm mil	3.8 - 54 0.15 - 2.1
Dry	µm mil	1.0 - 11 0.04 - 0.4

[a] Reference 9. To be used when plant-specific data are unavailable.

References For Section 4.2.2.13

1. *Magnetic Tape Manufacturing Industry—Background Information For Proposed Standards*, EPA-450/3-85-029a, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1985.

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3. C. Beall, "*Distribution Of Emissions Between Coating Mix Preparation Area And The Coating Line*", Memorandum file, Midwest Research Institute, Raleigh, NC, June 22, 1984.

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4.2.2.14 Surface Coating Of Plastic Parts For Business Machines

4.2.2.14.1 General[1-2]

Surface coating of plastic parts for business machines is defined as the process of applying coatings to plastic business machine parts to improve the appearance of the parts, to protect the parts from physical or chemical stress, and/or to attenuate electromagnetic interference/radio frequency interference (EMI/RFI) that would otherwise pass through plastic housings. Plastic parts for business machines are synthetic polymers formed into panels, housings, bases, covers, or other business machine components. The business machines category includes items such as typewriters, electronic computing devices, calculating and accounting machines, telephone and telegraph equipment, photocopiers, and miscellaneous office machines.

The process of applying an exterior coating to a plastic part can include surface preparation, spray coating, and curing, with each step possibly being repeated several times. Surface preparation may involve merely wiping off the surface, or it could involve sanding and puttying to smooth the surface. The plastic parts are placed on racks or trays, or are hung on racks or hooks from an overhead conveyor track for transport among spray booths, flashoff areas, and ovens. Coatings are sprayed onto parts in partially enclosed booths. An induced air flow is maintained through the booths to remove overspray and to keep solvent concentrations in the room air at safe levels. Although low-temperature bake ovens (60°C [140°F] or less) are often used to speed up the curing process, coatings also may be partially or completely cured at room temperature.

Dry filters or water curtains (in water wash spray booths) are used to remove overspray particles from the booth exhaust. In waterwash spray booths, most of the insoluble material is collected as sludge, but some of this material is dispersed in the water along with the soluble overspray components. Figure 4.2.2.14-1 depicts a typical dry filter spray booth, and Figure 4.2.2.14-2 depicts a typical water wash spray booth.

Many surface coating plants have only 1 manually operated spray gun per spray booth, and they interchange spray guns according to what type of coating is to be applied to the plastic parts. However, some larger surface coating plants operate several spray guns (manual or robotic) per spray booth, because coating a large volume of similar parts on conveyor coating lines makes production more efficient.

Spray coating systems commonly used in this industry fall into 3 categories, 3-coat, 2-coat, and single-coat. The 3-coat system is the most common, applying a prime coat, a color or base coat, and a texture coat. Typical dry film thickness for the 3-coat system ranges from 1 to 3 mils for the prime coat, 1 to 2 mils for the color coat, and 1 to 5 mils for the texture coat. Figure 4.2.2.14-3 depicts a typical conveyorized coating line using the 3-coat system. The conveyor line consists of 3 separate spray booths, each followed by a flashoff (or drying) area, all of which is followed by a curing oven. A 2-coat system applies a color or base coat, then a texture coat. Typical dry film thickness for the 2-coat system is 2 mils for the color (or base) coat, and 2 to 5 mils for the texture coat. The rarely used single-coat system applies only a thin color coat, either to protect the plastic substrate or to improve color matching between parts whose color and texture are molded in. Less coating solids are applied with the single-coat system than with the other systems. The dry film thickness applied for the single-coat system depends on the function of the coating. If protective properties are desired, the dry film thickness must be at least 1 mil (0.001 inches). For purposes of

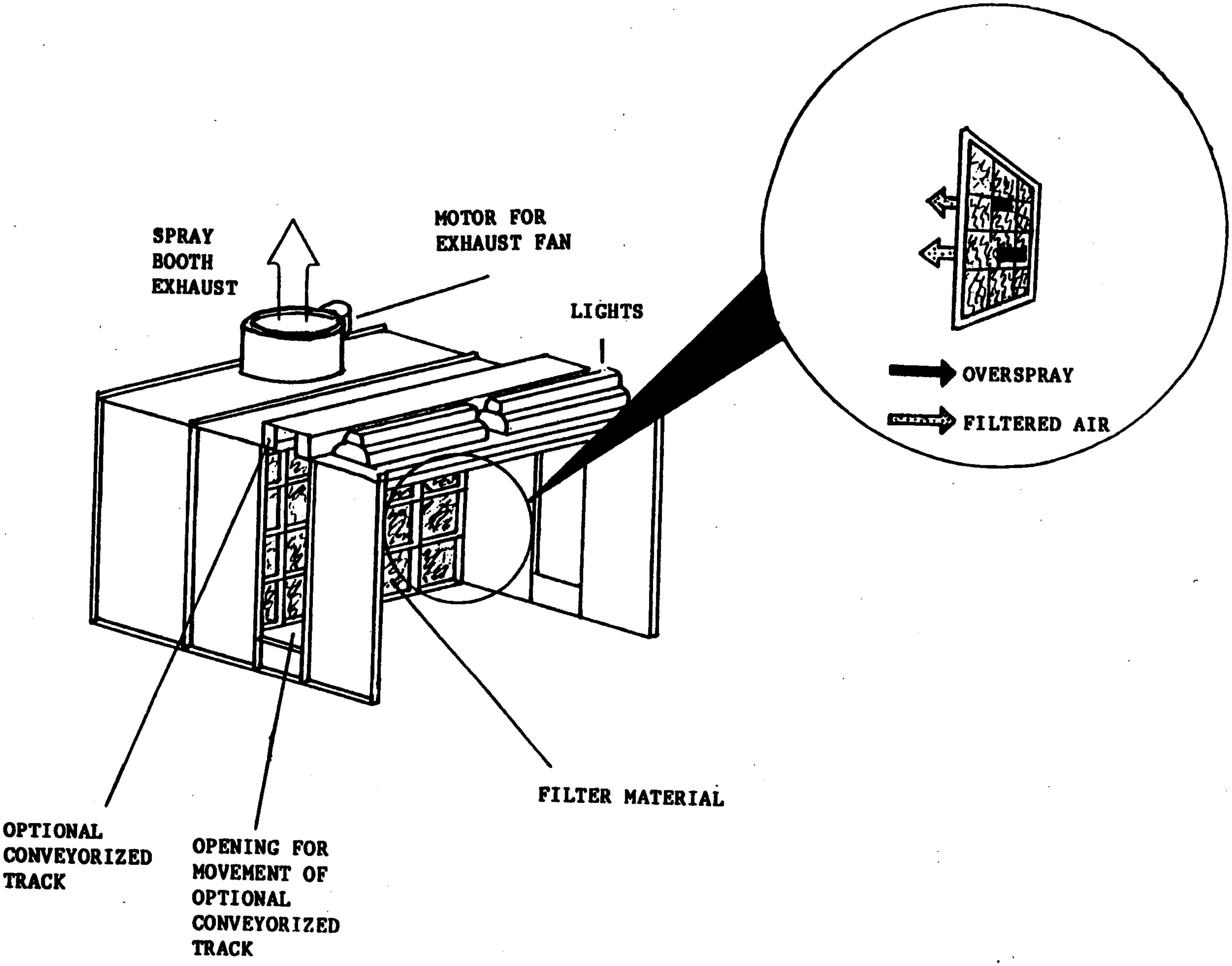

Figure 4.2.2.14-1. Typical dry filter spray booth.[3-4]

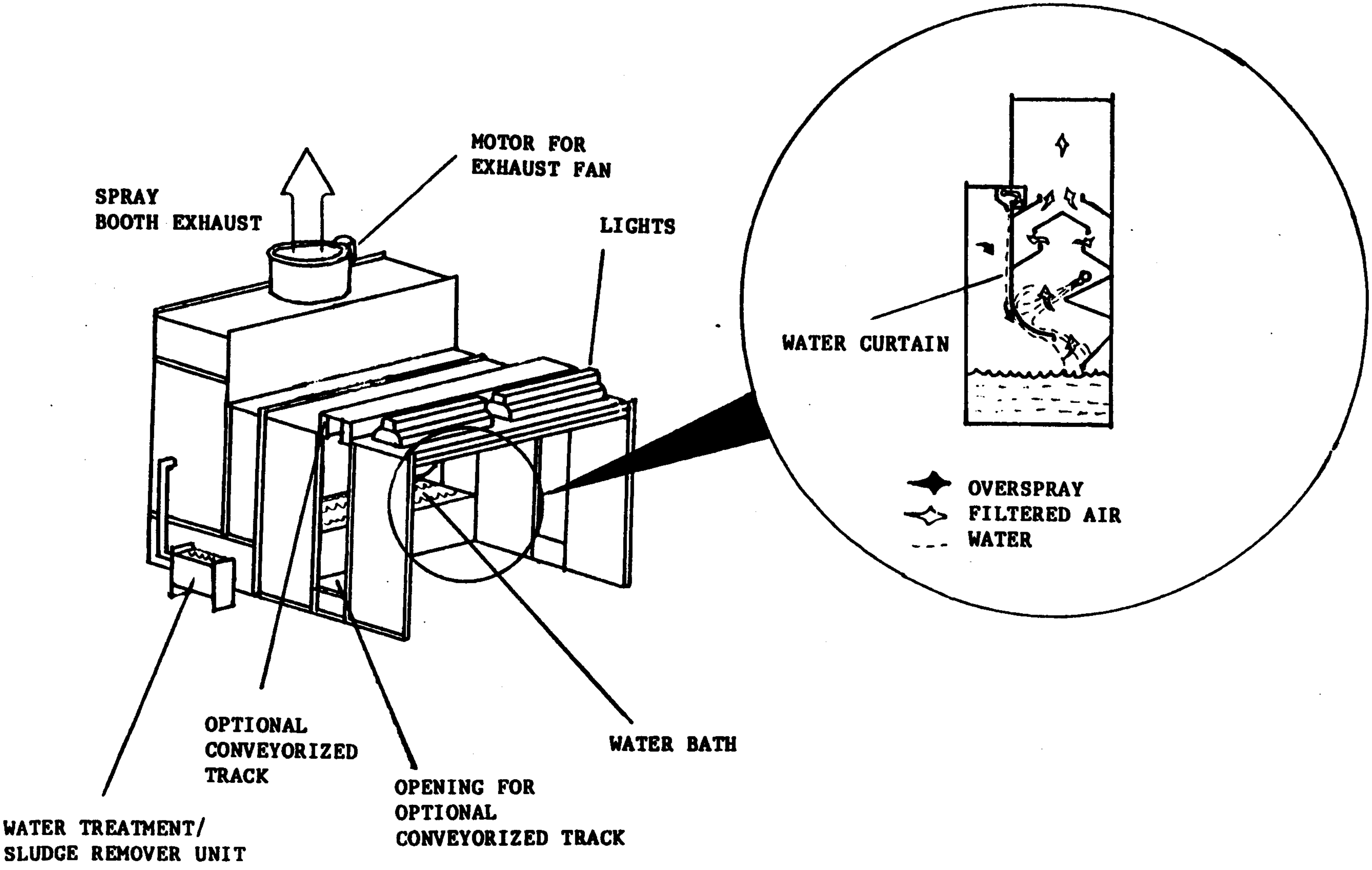

Figure 4.2.2.14-2. Typical water wash spray booth.[3]

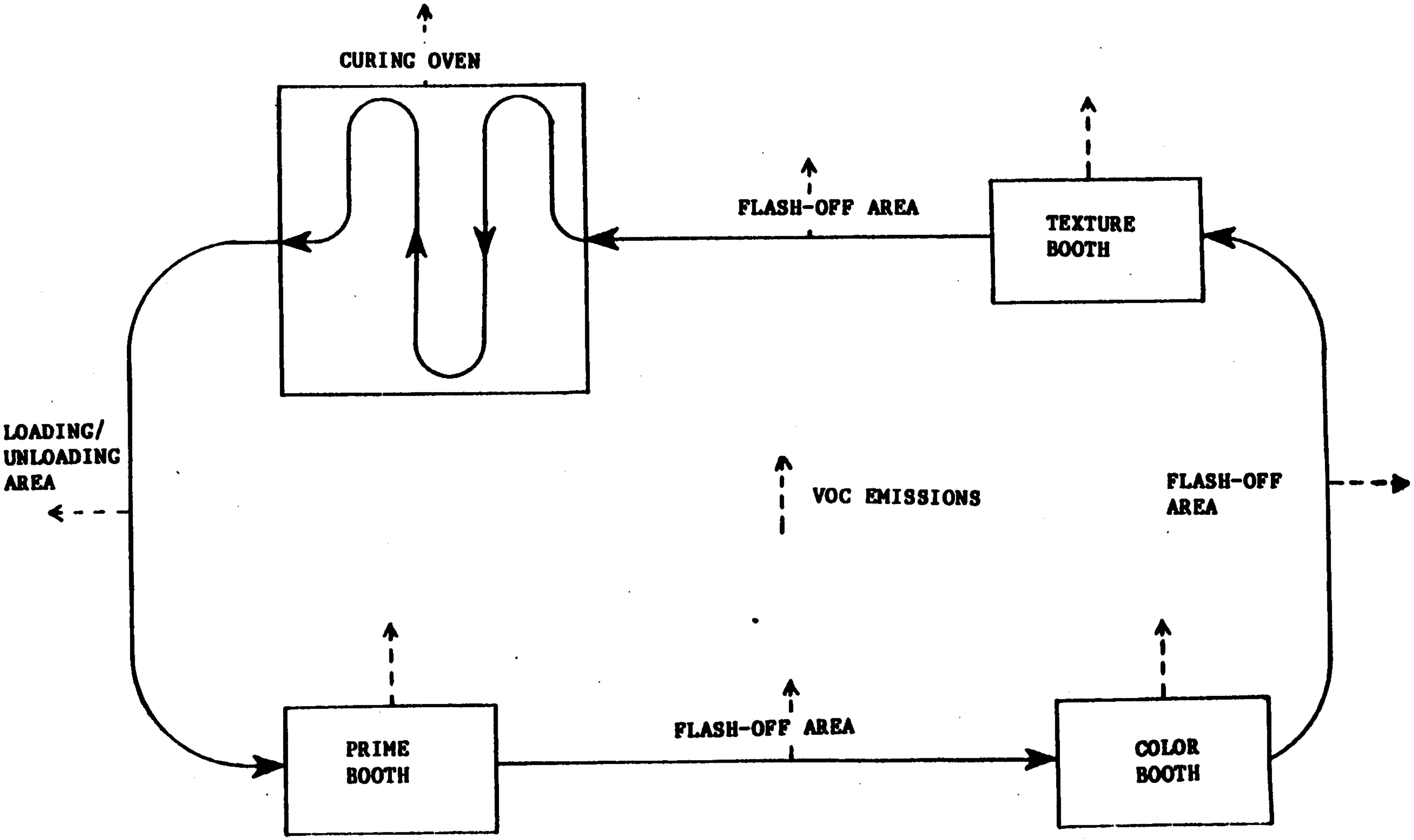

Figure 4.2.2.14-3. Typical conveyor line for 3-coat system.

color matching among parts having molded-in color and texture, a dry film thickness of 0.5 mils or less is needed to avoid masking the molded-in texture. The process of applying 0.5 mils of coating or less for color matching is commonly known as "fog coating", "mist coating", or "uniforming".

The 3 basic spray methods used in this industry to apply decorative/exterior coatings are air-atomized spray, air-assisted airless spray, and electrostatic air spray. Air-atomized spray is the most widely used coating technique for plastic business machine parts. Air-assisted airless spray is growing in popularity but is still not frequently found. Electrostatic air spray is rarely used, because plastic parts are not conductive. It has been used to coat parts that have been either treated with a conductive sensitizer or plated with a thin film of metal.

Air-atomized spray coating uses compressed air, which may be heated and filtered, to atomize the coating and to direct the spray. Air-atomized spray equipment is compatible with all coatings commonly found on plastic parts for business machines.

Air-assisted airless spray is a variation of airless spray, a spray technique used in other industries. In airless spray coating, the coating is atomized without air by forcing the liquid coating through specially designed nozzles, usually at pressures of 7 to 21 megapascals (MPa) (1,000 to 3,000 pounds per square inch [psi]). Air-assisted airless spray atomizes the coating by the same mechanism as airless spray, but at lower fluid pressures (under 7 MPa [1,000 psi]). After atomizing, air is then used to atomize the coating further and to help shape the spray pattern, reducing overspray to levels lower than those achieved with airless atomization alone. Figure 4.2.2.14-4 depicts a typical air-assisted airless spray gun. Air-assisted airless spray has been used to apply prime and color coats but not texture coats, because the larger size of the sprayed coating droplet (relative to that achieved by conventional air atomized spray) makes it difficult to achieve the desired surface finish quality for a texture coat. A touch-up coating step with air atomized equipment is sometimes necessary to apply color to recessed and louvered areas missed by air-assisted airless spray.

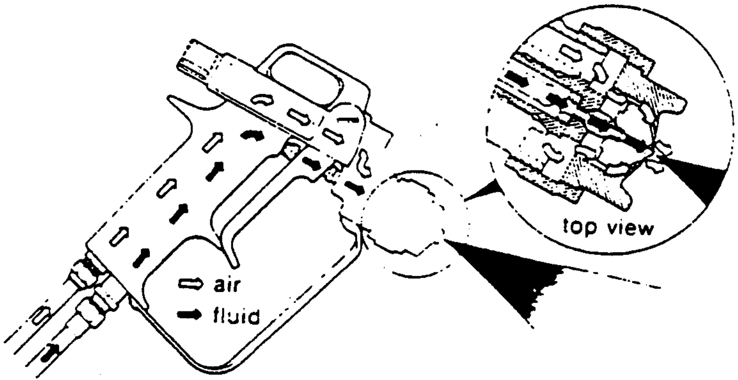

Figure 4.2.2.14-4. Typical air-assisted airless spray gun.[5]

In electrostatic air spray, the coating is usually charged electrically, and the parts being coated are grounded to create an electric potential between the coating and the parts. The atomized coating is attracted to the part by electrostatic force. Because plastic is an insulator, it is necessary to provide a conductive surface that can bleed off the electrical charge to maintain the ground potential of the part as the charged coating particles accumulate on the surfaces. Electrostatic air spray has been demonstrated for application of prime and color coats and has been used to apply texture coats, but this technique does not function well with the large-size particles generated for the texture coat, and it offers no substantial improvement over air-atomized spray for texture coating. A touch-up coating step with air-atomized spray is sometimes necessary to apply color and texture to recessed and louvered areas missed by electrostatic spray.

The coatings used for decorative/exterior coats are generally solvent-based and waterborne coatings. Solvents used include toluene, methyl ethyl ketone, methylene chloride, xylene, acetone, and isopropanol. Typically, organic solvent-based coatings used for decorative/exterior coats are 2 types of 2-component catalyzed urethanes. The solids contents of these coatings are from 30 to 35 volume percent (low solids) and 40 to 54 volume percent (medium solids) at the spray gun (i. e., at the point of application, or as applied). Waterborne decorative/exterior coatings typically contain no more than 37 volume percent solids at the gun. Other decorative/exterior coatings being used by the industry include solvent-based high solids coatings (i. e., equal to or greater than 60 volume percent solids) and 1-component low solids and medium solids coatings.

The application of an EMI/RFI shielding coat is done in a variety of ways. About 45 percent of EMI/RFI shielding applied to plastic parts is done by zinc-arc spraying, a process that does not emit volatile organic compounds (VOC). About 45 percent is done using organic solvent-based and waterborne metal-filled coatings, and the remaining EMI/RFI shielding is achieved by a variety of techniques involving electroless plating, and vacuum metallizing or sputtering (defined below), and use of conductive plastics, and metal inserts.

Zinc-arc spraying is a 2-step process in which the plastic surface (usually the interior of a housing) is first roughened by sanding or grit blasting and then sprayed with molten zinc. Grit blasting and zinc-arc spraying are performed in separate booths specifically equipped for those activities. Both the surface preparation and the zinc-arc spraying steps currently are performed manually, but robot systems have recently become available. Zinc-arc spraying requires a spray booth, a special spray gun, pressurized air, and zinc wire. The zinc-arc spray gun mechanically feeds 2 zinc wires into the tip of the spray gun, where they are melted by an electric arc. A high pressure air nozzle blows the molten zinc particles onto the surface of the plastic part. The coating thickness usually ranges from 1 to 4 mils, depending on product requirements.

Conductive coatings can be applied with most conventional spray equipment used to apply exterior coatings. Conductive coatings are usually applied manually with air spray guns, although air-assisted airless spray guns are sometimes used. Electrostatic spray methods cannot be used because of the high conductivity of EMI/RFI shielding coatings.

Organic solvent-based conductive coatings contain particles of nickel, silver, copper, or graphite, in either an acrylic or urethane resin. Nickel-filled acrylic coatings are the most frequently used, because of their shielding ability and their lower cost. Nickel-filled acrylics and urethanes contain from 15 to 25 volume percent solids at the gun. Waterborne nickel-filled acrylics with between 25 and 34 volume percent solids at the gun (approximately 50 to 60 volume percent solids, minus water) are less frequently used than are organic solvent-based conductive coatings.

The application of a conductive coating usually involves 3 steps: surface preparation, coating application, and curing. Although the first step can be eliminated if parts are kept free of mold-release agents and dirt, part surfaces are usually cleaned by wiping with organic solvents or detergent solutions and then roughened by light sanding. Coatings are usually applied to the interior surface of plastic housings, at a dry film thickness of 1 to 3 mils. Most conductive coatings can be cured at room temperature, but some must be baked in an oven.

Electroless plating is a dip process in which a film of metal is deposited in aqueous solution onto all exposed surfaces of the part. In the case of plastic business machine housings, both sides of a housing are coated. No VOC emissions are associated with the plating process itself. However, coatings applied before the plating step, so that only selected areas of the parts are plated, may emit VOCs. Waste water treatment may be necessary to treat the spent plating chemicals.

Vacuum metallizing and sputtering are similar techniques in which a thin film of metal (usually aluminum) is deposited from the vapor phase onto the plastic part. Although no VOC emissions occur during the actual metallizing process, prime coats often applied to ensure good adhesion and top coats to protect the metal film may both emit VOCs.

Conductive plastics are thermoplastic resins that contain conductive flakes or fibers of materials such as aluminum, steel, metallized glass, or carbon. Resin types currently available with conductive fillers include acrylonitrile butadiene styrene, acrylonitrile butadiene styrene/polycarbonate blends, polyphenylene oxide, nylon 6/6, polyvinyl chloride, and polybutyl terephthalate. The conductivity, and therefore the EMI/RFI shielding effectiveness, of these materials relies on contact or near-contact between the conductive particles within the resin matrix. Conductive plastic parts usually are formed by straight injection molding. Structural foam injection molding can reduce the EMI/RFI shield effectiveness of these materials because air pockets in the foam separate the conductive particles.

4.2.2.14.2 Emissions And Controls

The major pollutants from surface coating of plastic parts for business machines are VOC emissions from evaporation of organic solvents in the coatings used, and from reaction byproducts when the coatings cure. VOC sources include spray booth(s), flashoff area(s), and oven(s) or drying area(s). The relative contribution of each to total VOC emissions vary from plant to plant, but for an average coating operation, about 80 percent is emitted from the spray booth(s), 10 percent from the flashoff area(s), and 10 percent from the oven(s) or drying area(s).

Factors affecting the quantity of VOC emitted are the VOC content of the coatings applied, the solids content of coatings as applied, film build (thickness of the applied coating), and the transfer efficiency (TE) of the application equipment. To determine of VOC emissions when waterborne coatings are used, it is necessary to know the amounts of VOC, water, and solids in the coatings.

The TE is the fraction of the solids sprayed that remains on a part. TE varies with application technique and with type of coating applied. Table 4.2.2.14-1 presents typical TE values for various application methods.

Volatile organic compound emissions can be reduced by using low VOC content coatings (i. e., high solids or waterborne coatings), using surface finishing techniques that do not emit VOC, improving TE, and/or adding controls. Lower VOC content decorative/exterior coatings include high solids content (i. e., at least 60 volume percent solids at the spray gun), 2-component catalyzed urethane coatings, and waterborne coatings (i. e., 37 volume percent solids and 12.6 volume percent VOC at the spray gun). Both of these types of exterior/decorative coatings contain less VOC than conventional urethane coatings, which are typically 32 volume percent solids at the gun. Lower VOC content EMI/RFI shielding coatings include organic solvent-based acrylic or urethane conductive coatings containing at least 25 volume percent solids at the spray gun and waterborne conductive coatings containing 30 to 34 volume percent solids at the gun. Use of lower VOC content coatings reduces emissions of VOCs both by reducing the volume of coating needed to cover the part(s) and by reducing the amount of VOC in the coatings that are sprayed.

The major technique which provides an attractive exterior/decorative finish on plastic parts for business machines without emitting VOCs is the use of molded-in color and texture. VOC-free techniques for EMI/RFI shielding include zinc-arc spraying, electroless plating, the use of conductive plastics or metal inserts, and in some cases, vacuum metallizing and sputtering.

Table 4.2.2.14-1. TRANSFER EFFICIENCIES[a]

Application Methods	Transfer Efficiency (%)	Type Of Coating
Air-atomized spray	25	Prime, color, texture, touchup, and fog coats
Air-assisted airless spray	40	Prime, color coats
Electrostatic air spray	40	Prime, color coats

[a] As noted in the promulgated standards, values are presented solely to aid in determining compliance with the standards and may not reflect actual TE at a given plant. For this reason, table should be used with caution for estimating VOC emissions from any new facility. For a more exact estimate of emissions, the actual TE from specific coating operations at a given plant should be used. Reference 1.

Transfer efficiency can be improved by using air-assisted airless or electrostatic spray equipment, which are more efficient than the common application technique (air atomized). More efficient equipment can reduce VOC emissions by as much as 37 percent over conventional air atomized spray equipment, through reducing the amount of coating that must be sprayed to achieve a given film thickness.

Add-on controls applied to VOC emissions in other surface coating industries include thermal and catalytic incinerators, carbon adsorbers, and condensers. However, these control technologies have not been used in the surface coating of plastic parts because the large volume of exhaust air and the low concentrations of VOC in the exhaust reduce their efficiency.

The operating parameters in Tables 4.2.2.14-2 and 4.2.2.14-3 and the emissions factors in Tables 4.2.2.14-4 and 4.2.2.14-5 are representative of conditions at existing plants with similar operating characteristics. The 3 general sizes of surface coating plants presented in these tables (small, medium, and large) are given to assist in making a general estimate of VOC emissions. However, each plant has its own combination of coating formulations, application equipment, and operating parameters. Thus, it is recommended that, whenever possible, plant-specific values be obtained for all variables when calculating emission estimates.

A material balance may be used to provide a more accurate estimate of VOC emissions from the surface coating of plastic parts for business machines. An emissions estimate can be calculated using coating composition data (as determined by EPA Reference Method 24), and data on coating and solvent quantities used in a given time period by a surface coating operation. Using this approach, emissions are calculated as follows:

$$M_T = \sum_{i=1}^{n} L_{ci} D_{ci} W_{oi}$$

where:

M_T = total mass of VOC emitted (kg)
L_c = volume of each coating consumed, as sprayed (L)
D_c = density of each coating consumed, as sprayed (kg/L)
W_o = the proportion of VOC in each coating, as sprayed (including dilution solvent added at plant) (weight fraction)
n = number of coatings applied

Table 4.2.2.14-2 (Metric Units). REPRESENTATIVE PARAMETERS FOR SURFACE COATING OPERATIONS TO APPLY DECORATIVE/EXTERIOR COATINGS[a]

Plant Size	Operating Schedule (hr/yr)	Number Of Spray Booths		Surface Area Coated/yr (m² Of Plastic)	Coating Option/Control Techniques	Coating Sprayed (L/yr)
		Dry Filter	Water Wash			
Small	4,000	2	0	9,711	Baseline coating mix[b]	16,077[c]
					Low solids SB coating[d]	18,500[c]
					Medium solids SB coating[e]	11,840[c]
					High solids SB coating[f]	9,867[c]/6,167[g]
					WB coating[h]	16,000[c]
Medium	4,000	5[i]	0	77,743	Baseline coating mix[b]	128,704[c]
					Low solids SB coating[d]	148,100[c]
					Medium solids SB coating[e]	94,784[c]
					High solids SB coating[f]	78,987[c]/49,367[g]
					WB coating[h]	128,086[c]
Large	4,000	6[j]	3[k]	194,370	Baseline coating mix[b]	321,760[c]
					Low solids SB coating[d]	370,275[c]
					Medium solids SB coating[e]	236,976[c]
					High solids SB coating[f]	197,480[c]/123,425[g]
					WB coating[h]	320,238[c]

[a] Does not address EMI/RFI shielding coatings. SB = solventborne. WB = waterborne.

[b] Assumes baseline decorative/exterior coating consumption consists of a mix of coatings as follows:

64.8% = Solvent base 2-component catalyzed urethane containing 32 volume % solids at the gun.
23.5% = Solvent base two-component catalyzed urethane containing 50 volume % solids at the gun.
11.7% = Waterborne acrylic containing 37 volume % solids and 12.6 volume % organic solvent at the gun.

[c] Assumes 25% transfer efficiency (TE) based on the use of air-atomized spray equipment.

[d] Assumes use of a solvent base coating containing 32 volume % solids at the gun.

[e] Assumes use of a solvent base coating containing 50 volume % solids at the gun.

[f] Assumes the use of solvent base 2-component catalyzed urethane coating containing 60 volume % solids at the gun.

[g] Assumes 40% TE based on the use of air-assisted airless spray equipment, as required by new source performance standards.

[h] Assumes the use of a waterborne coating containing 37 volume % solids and 12.6 volume % organic solvent at the gun.

[i] Assumes 2 spray booths are for batch surface coating operations and remaining 3 booths are on a conveyor line.

[j] Assumes 2 spray booths are for batch surface coating operations and remaining 4 booths are on a conveyor line.

[k] Assumes that 3 spray booths are on a conveyor line.

Table 4.2.2.14-3 (Metric Units). REPRESENTATIVE PARAMETERS FOR SURFACE COATING OPERATIONS TO APPLY EMI/RFI SHIELDING COATINGS[a]

Plant Size	Operating Schedule (hr/yr)	Number Of Spray Booths		Surface Area Coated/yr (m^2 Of Plastic)	Coating Option/Control Technique	Coating Sprayed (L/yr)[b]
		Grit Blasting[a]	Zinc Arc Spray[a]			
Small	4,000	0	0	4,921	Low solids SB EMI/RFI shielding coating[c,d]	3,334
					Higher solids SB EMI/RFI shielding coating[d,e]	2,000
					WB EMI/RFI shielding coating[d,f]	1,515
					Zinc arc spray[g-i]	750
Medium	4,000	2	2	109,862	Low solids SB EMI/RFI shielding coating[c,d]	74,414
					Higher solids SB EMI/RFI shielding coating[d,e]	44,648
					WB EMI/RFI shielding coating[d,f]	33,824
					Zinc arc spray[g-i]	16,744
Large	4,000	4	4	239,239	Low solids SB EMI/RFI shielding coating[c,d]	162,040
					Higher solids SB EMI/RFI shielding coating[d,e]	97,224
					WB EMI/RFI shielding coating[d,f]	73,654
					Zinc arc spray[g-i]	34,460

[a] Includes sprayed conductive coatings using the dry filter and water wash spray booths listed in Table 4.2.2.14-2. SB = solventborne. WB = waterborne.

[b] Assumes 50% transfer efficiency (TE).

[c] Assumes use of solvent base EMI/RFI shielding coating containing 15 volume % solids at the gun.

[d] Applied at a 2 mil thickness (standard industry practice).

[e] Assumes use of a solvent base EMI/RFI shielding coating containing 25 volume % solids at the gun.

[f] Assumes use of a waterborne EMI/RFI shielding coating containing 33 volume % solids and 18.8 volume % organic solvent at the gun.

[g] Assumes use of zinc-arc spray shielding.

[h] Applied at a 3 mil thickness (standard industry practice).

[i] Based on amount of zinc wire sprayed per year (kg/yr) and zinc density of 6.32 g/mL.

Table 4.2.2.14-4 (Metric Units). EMISSION FACTORS FOR VOC FROM SURFACE COATING OPERATIONS TO APPLY DECORATIVE/EXTERIOR COATINGS[a,b]

Plant Configuration And Control Technique	kg/m^2 Coated	Volatile Organics	
		kg/yr	kg/hr
Small			
Baseline coating mix[c]	0.84	8,122	2.0
Low solids SB coating[d]	1.14	11,096	2.8
Medium solids SB coating[e]	0.54	5,221	1.3
High solids SB coating[f]	0.36 - 0.22	3,481 - 2,176	0.87 - 0.54
WB coating[g]	0.18	1,778	0.44
Medium			
Baseline coating mix[c]	0.84	64,986	16.2
Low solids SB coating[d]	1.14	88,825	22.2
Medium solids SB coating[e]	0.54	41,800	10.4
High solids SB coating[f]	0.36 - 0.22	27,867 - 17,417	7.0 - 4.4
WB coating[g]	0.18	14,234	3.6
Large			
Baseline coating mix[c]	0.84	162,463	40.6
Low solids SB coating[d]	1.14	222,076	55.5
Medium solids SB coating[e]	0.54	104,506	26.1
High solids SB coating[f]	0.36 - 0.22	69,671 - 43,544	17.4 - 10.9
WB coating[g]	0.18	35,589	8.9

[a] Assumes values given in Table 4.2.2.14-2, using the following equation: E = LDV
where:

E = VOC emission factors from surface coating operations (kg/yr)
L = Volume of coating sprayed (L)
D = Density coating sprayed (kg/L)
V = Volatile content of coating, including dilution solvents added at plant (weight fraction)

[b] Assumes all VOC present is emitted. Values have been rounded off. Does not address EMI/RFI shielding coatings. Assumes annual operating schedule of 4,000 hours. SB = solventborne. WB = waterborne.

[c] Based on use of the baseline coating mix in Table 4.2.2.14-2.

[d] Based on use of a solvent base coating containing 32 volume % solids at the gun.

[e] Based on use of a solvent base coating containing 50 volume % solids at the gun.

[f] Based on use of a solvent base coating containing 60 volume % solids at the gun.

[g] Based on use of a waterborne coating containing 37 volume % solids and 12.6 volume % organic solvent at the gun.

Table 4.2.2.14-5 (Metric Units). EMISSION FACTORS FOR VOC FROM SURFACE COATING OPERATIONS TO APPLY EMI/RFI SHIELDING COATINGS[a,b]

Plant Configuration And Control Technique	kg/m^2 Coated	Volatile Organics	
		kg/yr	kg/hr
Small			
Low solids SB EMI/RFI shielding coating[c]	0.51	2,500	0.62
Higher solids SB EMI/RFI shielding coating[d]	0.27	1,323	0.33
WB EMI/RFI shielding coating[e]	0.05	251	0.063
Zinc-arc spray[f]	0	0	0
Medium			
Low solids SB EMI/RFI shielding coating[c]	0.51	55,787	13.9
Higher solids SB EMI/RFI shielding coating[d]	0.27	29,535	7.4
WB EMI/RFI shielding coating[e]	0.05	5,609	1.4
Zinc-arc spray[f]	0	0	0
Large			
Low solids SB EMI/RFI shielding coating[c]	0.51	121,484	30.4
Higher solids SB EMI/RFI shielding coating[d]	0.27	64,314	16.1
WB EMI/RFI shielding coating[e]	0.05	12,214	3.1
Zinc-arc spray[f]	0	0	0

[a] Assumes values given in Table 4.2.2.14-3, using the following equation: E = LDV where:

E = VOC emission factors from surface coating operations (kg/yr)
L = Volume of coating sprayed (L)
D = Density coating sprayed (kg/L)
V = Volatile content of coating, including dilution solvents added at plant (fraction by weight)

[b] Assumes all VOC present is emitted. Values have been rounded off. Does not address EMI/RFI shielding coatings. Assumes annual operating schedule of 4,000 hours. SB = solventborne. WB = waterborne.

[c] Assumes use of solvent base EMI/RFI shielding coating containing 15 volume % solids at the gun.

[d] Assumes use of a solvent base EMI/RFI shielding coating containing 25 volume % solids at the gun.

[e] Assumes use of a waterborne EMI/RFI shielding coating containing 33 volume % solids and 18.8 volume % organic solvent at the gun.

[f] Assumes use of a zinc-arc spray shielding.

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4.3 Waste Water Collection, Treatment And Storage

4.3.1 General

Many different industries generate waste water streams that contain organic compounds. Nearly all of these streams undergo collection, contaminant treatment, and/or storage operations before they are finally discharged into either a receiving body of water or a municipal treatment plant for further treatment. During some of these operations, the waste water is open to the atmosphere, and volatile organic compounds (VOC) may be emitted from the waste water into the air.

Industrial waste water operations can range from pretreatment to full-scale treatment processes. In a typical pretreatment facility, process and/or sanitary waste water and/or storm water runoff is collected, equalized, and/or neutralized and then discharged to a municipal waste water plant, also known as a publicly owned treatment works (POTWs), where it is then typically treated further by biodegradation.

In a full-scale treatment operation, the waste water must meet Federal and/or state quality standards before it is finally discharged into a receiving body of water. Figure 4.3-1 shows a generic example of collection, equalization, neutralization, and biotreatment of process waste water in a full-scale industrial treatment facility. If required, chlorine is added as a disinfectant. A storage basin contains the treated water until the winter months (usually January to May), when the facility is allowed to discharge to the receiving body of water. In the illustration, the receiving body of water is a slow-flowing stream. The facility is allowed to discharge in the rainy season when the facility waste water is diluted.

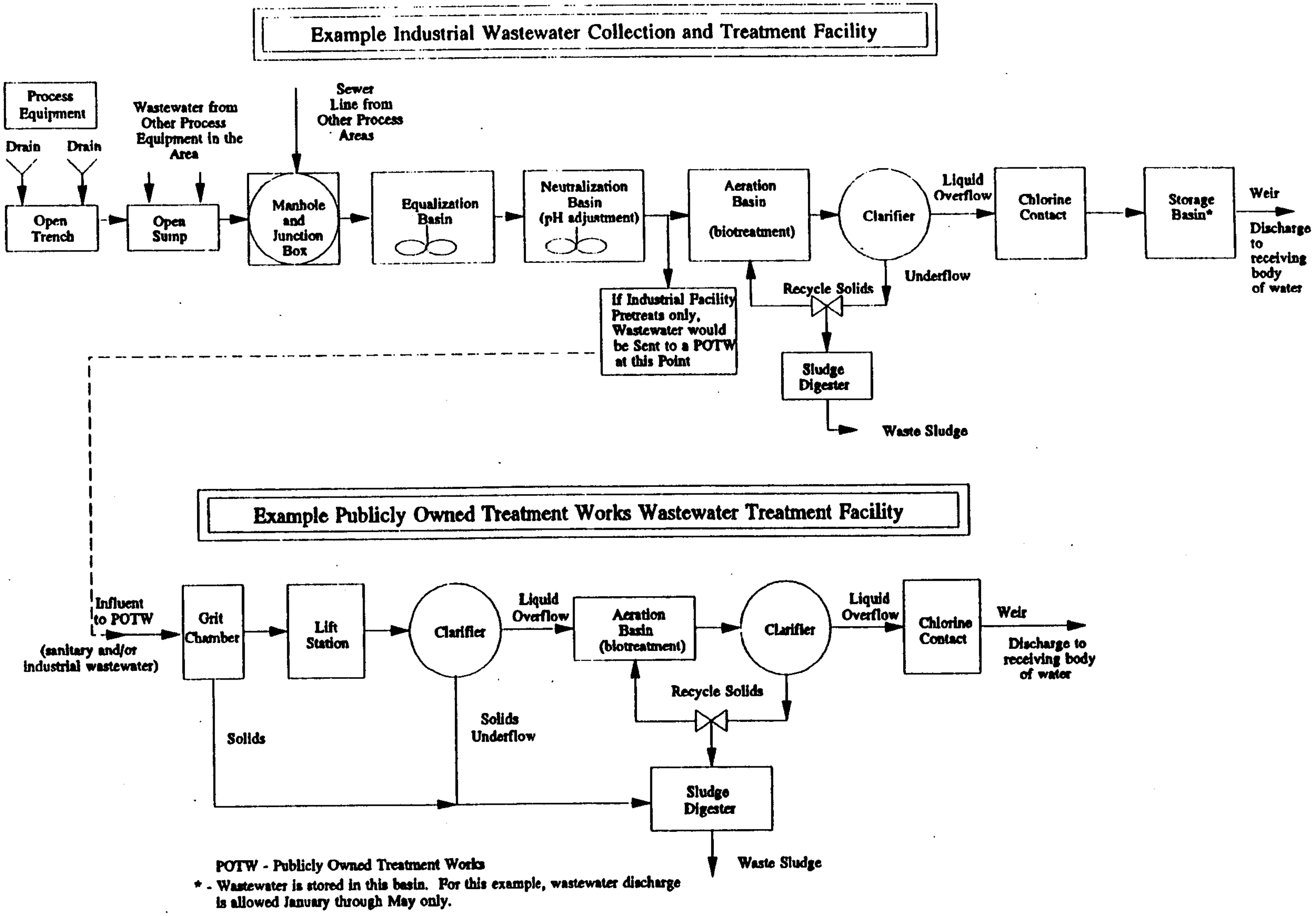
Figure 4.3-1 also presents a typical treatment system at a POTW waste water facility. Industrial waste water sent to POTWs may be treated or untreated. POTWs may also treat waste water from residential, institutional, and commercial facilities; from infiltration (water that enters the sewer system from the ground); and/or storm water runoff. These types of waste water generally do not contain VOCs. A POTW usually consists of a collection system, primary settling, biotreatment, secondary settling, and disinfection.

Collection, treatment, and storage systems are facility-specific. All facilities have some type of collection system, but the complexity will depend on the number and volume of waste water streams generated. As mentioned above, treatment and/or storage operations also vary in size and degree of treatment. The size and degree of treatment of waste water streams will depend on the volume and degree of contamination of the waste water and on the extent of contaminant removal desired.

4.3.1.1 Collection Systems -

There are many types of waste water collection systems. In general, a collection system is located at or near the point of waste water generation and is designed to receive 1 or more waste water streams and then to direct these streams to treatment and/or storage systems.

A typical industrial collection system may include drains, manholes, trenches, junction boxes, sumps, lift stations, and/or weirs. Waste water streams from different points throughout the industrial facility normally enter the collection system through individual drains or trenches connected to a main sewer line. The drains and trenches are usually open to the atmosphere. Junction boxes, sumps,



Example Industrial Wastewater Collection and Treatment Facility

Example Publicly Owned Treatment Works Wastewater Treatment Facility

POTW - Publicly Owned Treatment Works

* - Wastewater is stored in this basin. For this example, wastewater discharge is allowed January through May only.

Figure 4.3.1. Typical waste water collection and treatment systems for industrial and municipal facilities.

trenches, lift stations, and weirs will be located at points requiring waste water transport from 1 area or treatment process to another.

A typical POTW facility collection system will contain a lift station, trenches, junction boxes, and manholes. Waste water is received into the POTW collection system through open sewer lines from all sources of influent waste water. As mentioned previously, these sources may convey sanitary, pretreated or untreated industrial, and/or storm water runoff waste water.

The following paragraphs briefly describe some of the most common types of waste water collection system components found in industrial and POTW facilities. Because the arrangement of collection system components is facility-specific, the order in which the collection system descriptions are presented is somewhat arbitrary.

Waste water streams normally are introduced into the collection system through individual or area drains, which can be open to the atmosphere or sealed to prevent waste water contact with the atmosphere. In industry, individual drains may be dedicated to a single source or piece of equipment. Area drains will serve several sources and are located centrally among the sources or pieces of equipment that they serve.

Manholes into sewer lines permit service, inspection, and cleaning of a line. They may be located where sewer lines intersect or where there is a significant change in direction, grade, or sewer line diameter.

Trenches can be used to transport industrial waste water from point of generation to collection units such as junction boxes and lift station, from 1 process area of an industrial facility to another, or from 1 treatment unit to another. POTWs also use trenches to transport waste water from 1 treatment unit to another. Trenches are likely to be either open or covered with a safety grating.

Junction boxes typically serve several process sewer lines, which meet at the junction box to combine multiple waste water streams into 1. Junction boxes normally are sized to suit the total flow rate of the entering streams.

Sumps are used typically for collection and equalization of waste water flow from trenches or sewer lines before treatment or storage. They are usually quiescent and open to the atmosphere.

Lift stations are usually the last collection unit before the treatment system, accepting waste water from 1 or several sewer lines. Their main function is to lift the collected waste water to a treatment and/or storage system, usually by pumping or by use of a hydraulic lift, such as a screw.

Weirs can act as open channel dams, or they can be used to discharge cleaner effluent from a settling basin, such as a clarifier. When used as a dam, the weir's face is normally aligned perpendicular to the bed and walls of the channel. Water from the channel usually flows over the weir and falls to the receiving body of water. In some cases, the water may pass through a notch or opening in the weir face. With this type of weir, flow rate through the channel can be measured. Weir height, generally the distance the water falls, is usually no more than 2 meters (6 feet). A typical clarifier weir is designed to allow settled waste water to overflow to the next treatment process. The weir is generally placed around the perimeter of the settling basin, but it can also be towards the middle. Clarifier weir height is usually only about 0.1 meters (4 inches).

4.3.1.2 Treatment And/Or Storage Systems -

These systems are designed to hold liquid wastes or waste water for treatment, storage, or disposal. They are usually composed of various types of earthen and/or concrete-lined basins, known as surface impoundments. Storage systems are used typically for accumulating waste water before its ultimate disposal, or for temporarily holding batch (intermittent) streams before treatment.

Treatment systems are divided into 3 categories: primary, secondary, or tertiary, depending on their design, operation, and application. In primary treatment systems, physical operations remove floatable and settleable solids. In secondary treatment systems, biological and chemical processes remove most of the organic matter in the waste water. In tertiary treatment systems, additional processes remove constituents not taken out by secondary treatment.

Examples of primary treatment include oil/water separators, primary clarification, equalization basins, and primary treatment tanks. The first process in an industrial waste water treatment plant is often the removal of heavier solids and lighter oils by means of oil/water separators. Oils are usually removed continuously with a skimming device, while solids can be removed with a sludge removal system.

In primary treatment, clarifiers are usually located near the beginning of the treatment process and are used to settle and remove settleable or suspended solids contained in the influent waste water. Figure 4.3-2 presents an example design of a clarifier. Clarifiers are generally cylindrical and are sized according to both the settling rate of the suspended solids and the thickening characteristics of the sludge. Floating scum is generally skimmed continuously from the top of the clarifier, while sludge is typically removed continuously from the bottom of the clarifier.

Equalization basins are used to reduce fluctuations in the waste water flow rate and organic content before the waste is sent to downstream treatment processes. Flow rate equalization results in a more uniform effluent quality in downstream settling units such as clarifiers. Biological treatment performance can also benefit from the damping of concentration and flow fluctuations, protecting biological processes from upset or failure from shock loadings of toxic or treatment-inhibiting compounds.

In primary treatment, tanks are generally used to alter the chemical or physical properties of the waste water by, for example, neutralization and the addition and dispersion of chemical nutrients. Neutralization can control the pH of the waste water by adding an acid or a base. It usually precedes biotreatment, so that the system is not upset by high or low pH values. Similarly, chemical nutrient addition/dispersion precedes biotreatment, to ensure that the biological organisms have sufficient nutrients.

An example of a secondary treatment process is biodegradation. Biological waste treatment usually is accomplished by aeration in basins with mechanical surface aerators or with a diffused air system. Mechanical surface aerators float on the water surface and rapidly mix the water. Aeration of the water is accomplished through splashing. Diffused air systems, on the other hand, aerate the water by bubbling oxygen through the water from the bottom of the tank or device. Figure 4.3-3 presents an example design of a mechanically aerated biological treatment basin. This type of basin is usually an earthen or concrete-lined pond and is used to treat large flow rates of waste water. Waste waters with high pollutant concentrations, and in particular high-flow sanitary waste waters, are typically treated using an activated sludge system where biotreatment is followed by secondary clarification. In this system, settled solids containing biomass are recycled from clarifier sludge to the biotreatment system. This creates a high biomass concentration and therefore allows biodegradation to occur over a shorter residence time. An example of a tertiary treatment process is nutrient

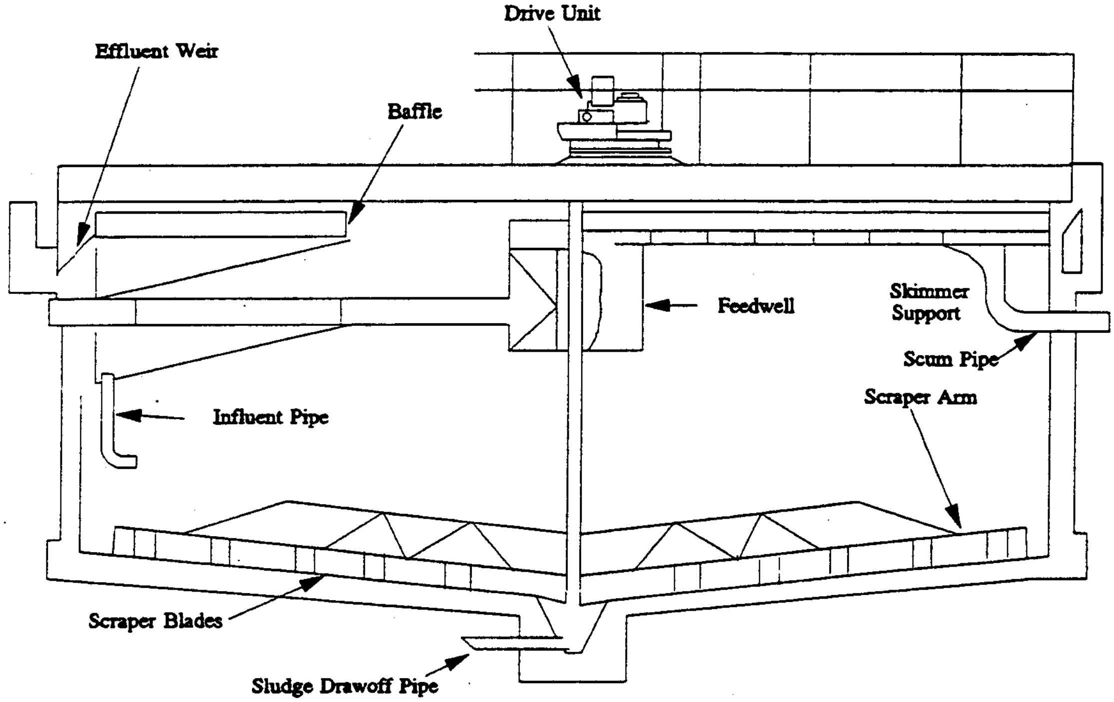


Figure 4.3-2. Example clarifier configuration.

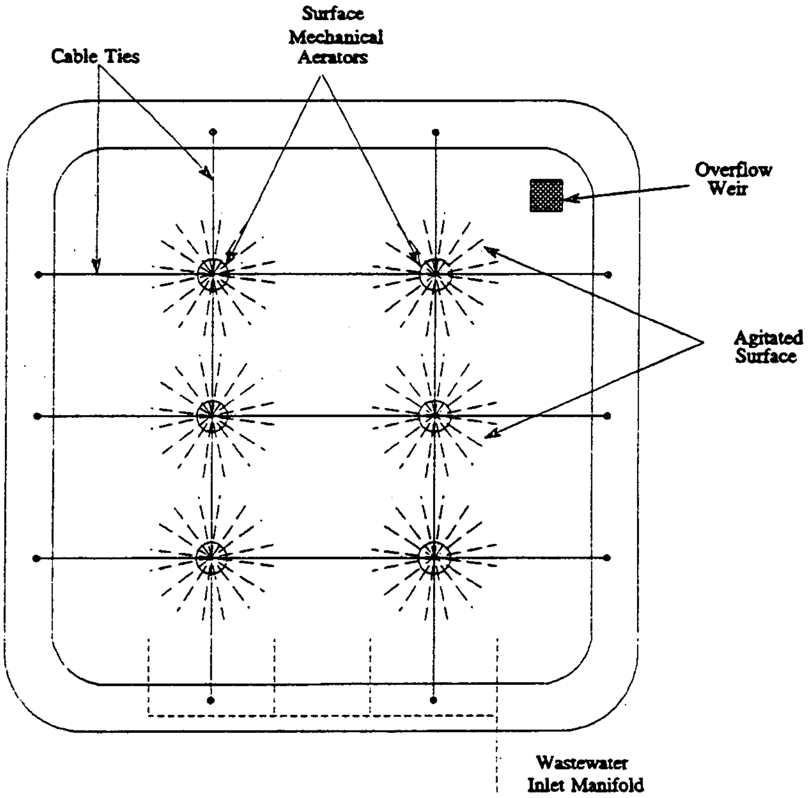


Figure 4.3-3. Example aerated biological treatment basin.

removal. Nitrogen and phosphorus are removed after biodegradation as a final treatment step before waste water is discharged to a receiving body of water.

4.3.1.3 Applications -

As previously mentioned, waste water collection, treatment, and storage are common in many industrial categories and in POTW. Most industrial facilities and POTW collect, contain, and treat waste water. However, some industries do not treat their waste water, but use storage systems for temporary waste water storage or for accumulation of waste water for ultimate disposal. For example, the Agricultural Industry does little waste water treatment but needs waste water storage systems, while the Oil and Gas Industry also has a need for waste water disposal systems.

The following are waste water treatment and storage applications identified by type of industry:

1. Mining And Milling Operations - Storage of various waste waters such as acid mine water, solvent wastes from solution mining, and leachate from disposed mining wastes. Treatment operations include settling, separation, washing, sorting of mineral products from tailings, and recovery of valuable minerals by precipitation.

2. Oil And Gas Industry - One of the largest sources of waste water. Operations treat brine produced during oil extraction and deep-well pressurizing operations, oil-water mixtures, gaseous fluids to be separated or stored during emergency conditions, and drill cuttings and drilling muds.

3. Textile And Leather Industry - Treatment and sludge disposal. Organic species treated or disposed of include dye carriers such as halogenated hydrocarbons and phenols. Heavy metals treated or disposed of include chromium, zinc, and copper. Tanning and finishing wastes may contain sulfides and nitrogenous compounds.

4. Chemical And Allied Products Industry - Process waste water treatment and storage, and sludge disposal. Waste constituents are process-specific and include organics and organic phosphates, fluoride, nitrogen compounds, and assorted trace metals.

5. Other Industries - Treatment and storage operations are found at petroleum refining, primary metals production, wood treating, and metal finishing facilities. Various industries store and/or treat air pollution scrubber sludge and dredging spoils sludge (i. e., settled solids removed from the floor of a surface impoundment).

4.3.2 Emissions

VOCs are emitted from waste water collection, treatment, and storage systems through volatilization of organic compounds at the liquid surface. Emissions can occur by diffusive or convective mechanisms, or both. Diffusion occurs when organic concentrations at the water surface are much higher than ambient concentrations. The organics volatilize, or diffuse into the air, in an attempt to reach equilibrium between aqueous and vapor phases. Convection occurs when air flows over the water surface, sweeping organic vapors from the water surface into the air. The rate of volatilization relates directly to the speed of the air flow over the water surface.

Other factors that can affect the rate of volatilization include waste water surface area, temperature, and turbulence; waste water retention time in the system(s); the depth of the waste water in the system(s); the concentration of organic compounds in the waste water and their physical properties, such as volatility and diffusivity in water; the presence of a mechanism that inhibits volatilization, such as an oil film; or a competing mechanism, such as biodegradation.

The rate of volatilization can be determined by using mass transfer theory. Individual gas phase and liquid phase mass transfer coefficients (k_g and k_ℓ, respectively) are used to estimate overall mass transfer coefficients (K, K_{oil}, and K_D) for each VOC.[1-2] Figure 4.3-4 presents a flow diagram to assist in determining the appropriate emissions model for estimating VOC emissions from various types of waste water treatment, storage, and collection systems. Tables 4.3-1 and 4.3-2, respectively, present the emission model equations and definitions.

VOCs vary in their degree of volatility. The emission models presented in this section can be used for high-, medium-, and low-volatility organic compounds. The Henry's law constant (HLC) is often used as a measure of a compound's volatility, or the diffusion of organics into the air relative to diffusion through liquids. High-volatility VOCs are HLC $> 10^{-3}$ atm-m^3/gmol; medium-volatility VOCs are $10^{-3} <$ HLC $< 10^{-5}$ atm-m^3/gmol; and low-volatility VOCs are HLC $< 10^{-5}$ atm-m^3/ gmol.[1]

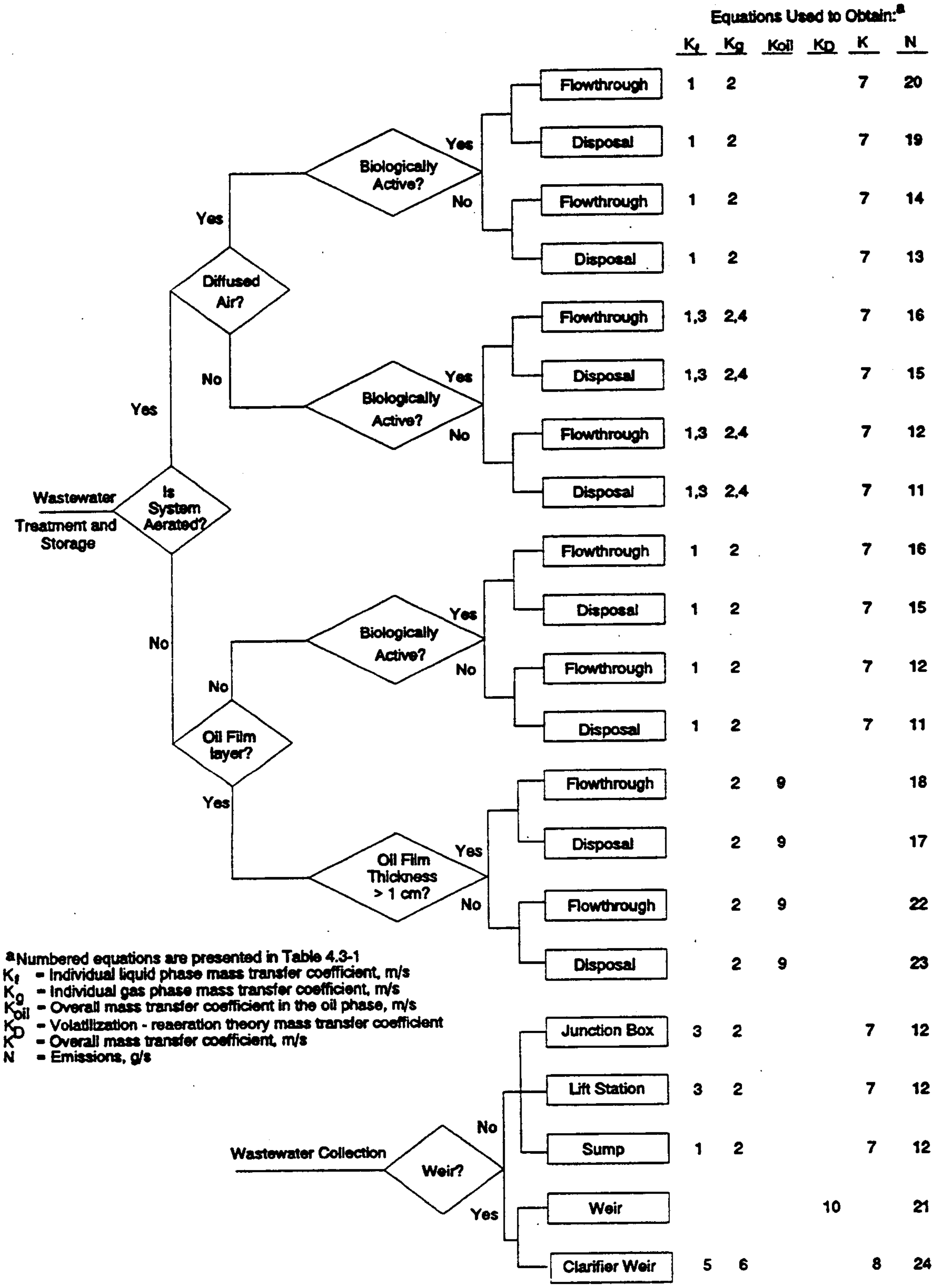
The design and arrangement of collection, treatment, and storage systems are facility-specific; therefore the most accurate waste water emissions estimate will come from actual tests of a facility (i. e., tracer studies or direct measurement of emissions from openings). If actual data are unavailable, the emission models provided in this section can be used.

Emission models should be given site-specific information whenever it is available. The most extensive characterization of an actual system will produce the most accurate estimates from an emissions model. In addition, when addressing systems involving biodegradation, the accuracy of the predicted rate of biodegradation is improved when site-specific compound biorates are input. Reference 3 contains information on a test method for measuring site-specific biorates, and Table 4.3-4 presents estimated biorates for approximately 150 compounds.

To estimate an emissions rate (N), the first step is to calculate individual gas phase and liquid phase mass transfer coefficients k_g and k_ℓ. These individual coefficients are then used to calculate the overall mass transfer coefficient, K. Exceptions to this procedure are the calculation of overall mass transfer coefficients in the oil phase, K_{oil}, and the overall mass transfer coefficient for a weir, K_D. K_{oil} requires only k_g, and K_D does not require any individual mass transfer coefficients. The overall mass transfer coefficient is then used to calculate the emissions rates. The following discussion describes how to use Figure 4.3-4 to determine an emission rate. An example calculation is presented in Part 4.3.2.1 below.

Figure 4.3-4 is divided into 2 sections: waste water treatment and storage systems, and waste water collection systems. Waste water treatment and storage systems are further segmented into aerated/nonaerated systems, biologically active systems, oil film layer systems, and surface impoundment flowthrough or disposal. In flowthrough systems, waste water is treated and discharged to a POTW or a receiving body of water, such as a river or stream. All waste water collection systems are by definition flowthrough. Disposal systems, on the other hand, do not discharge any waste water.

Figure 4.3-4 includes information needed to estimate air emissions from junction boxes, lift stations, sumps, weirs, and clarifier weirs. Sumps are considered quiescent, but junction boxes, lift stations, and weirs are turbulent in nature. Junction boxes and lift stations are turbulent because incoming flow is normally above the water level in the component, which creates some splashing.



Equations Used to Obtain:[a]

	K_ℓ	K_g	K_{oil}	K_D	K	N
Flowthrough	1	2			7	20
Disposal	1	2			7	19
Flowthrough	1	2			7	14
Disposal	1	2			7	13
Flowthrough	1,3	2,4			7	16
Disposal	1,3	2,4			7	15
Flowthrough	1,3	2,4			7	12
Disposal	1,3	2,4			7	11
Flowthrough	1	2			7	16
Disposal	1	2			7	15
Flowthrough	1	2			7	12
Disposal	1	2			7	11
Flowthrough		2	9			18
Disposal		2	9			17
Flowthrough		2	9			22
Disposal		2	9			23
Junction Box	3	2			7	12
Lift Station	3	2			7	12
Sump	1	2			7	12
Weir				10		21
Clarifier Weir	5	6			8	24

[a] Numbered equations are presented in Table 4.3-1

K_ℓ = Individual liquid phase mass transfer coefficient, m/s
K_g = Individual gas phase mass transfer coefficient, m/s
K_{oil} = Overall mass transfer coefficient in the oil phase, m/s
K_D = Volatilization - reaeration theory mass transfer coefficient
K = Overall mass transfer coefficient, m/s
N = Emissions, g/s

Figure 4.3.4. Flow diagram for estimating VOC emissions from waste water collection, treatment, and storage systems.

Table 4.3-1. MASS TRANSFER CORRELATIONS AND EMISSIONS EQUATIONS[a]

Equation No.	Equation
Individual liquid (k_ℓ) and gas (k_g) phase mass transfer coefficients	
1	$k_\ell \text{ (m/s)} = (2.78 \times 10^{-6})(D_w/D_{ether})^{2/3}$ For: $0 < U_{10} < 3.25$ m/s and all F/D ratios $k_\ell \text{ (m/s)} = [(2.605 \times 10^{-9})(F/D) + (1.277 \times 10^{-7})](U_{10})^2(D_w/D_{ether})^{2/3}$ For: $U_{10} > 3.25$ m/s and $14 < F/D < 51.2$ $k_\ell \text{ (m/s)} = (2.61 \times 10^{-7})(U_{10})^2(D_w/D_{ether})^{2/3}$ For: $U_{10} > 3.25$ m/s and $F/D > 51.2$ $k_\ell \text{ (m/s)} = 1.0 \times 10^{-6} + 144 \times 10^{-4} (U^*)^{2.2} (Sc_L)^{-0.5}; U^* < 0.3$ $k_\ell \text{ (m/s)} = 1.0 \times 10^{-6} + 34.1 \times 10^{-4} U^* (Sc_L)^{-0.5}; U^* > 0.3$ For: $U_{10} > 3.25$ m/s and $F/D < 14$ where: $U^* \text{ (m/s)} = (0.01)(U_{10})(6.1 + 0.63(U_{10}))^{0.5}$ $Sc_L = \mu_L/(\rho_L D_w)$ $F/D = 2\,(A/\pi)^{0.5}$
2	$k_g \text{ (m/s)} = (4.82 \times 10^{-3})(U_{10})^{0.78} (Sc_G)^{-0.67} (d_e)^{-0.11}$ where: $Sc_G = \mu_a/(\rho_a D_a)$ $d_e\text{(m)} = 2(A/\pi)^{0.5}$
3	$k_\ell \text{ (m/s)} = [(8.22 \times 10^{-9})(J)(POWR)(1.024)^{(T-20)}(O_t)(10^6) * (MW_L)/(Va_v \rho_L)](D_w/D_{O2,w})^{0.5}$ where: POWR (hp) = (total power to aerators)(V) $Va_v(\text{ft}^2)$ = (fraction of area agitated)(A)
4	$k_g \text{ (m/s)} = (1.35 \times 10^{-7})(Re)^{1.42} (P)^{0.4} (Sc_G)^{0.5} (Fr)^{-0.21}(D_a\ MW_a/d)$ where: $Re = d^2\, w\, \rho_a/\mu_a$ $P = [(0.85)(POWR)(550 \text{ ft-lb}_f\text{/s-hp})/N_I]\ g_c/(\rho_L (d^*)^5 w^3)$ $Sc_G = \mu_a/(\rho_a D_a)$ $Fr = (d^*)w^2/g_c$
5	$k_\ell \text{ (m/s)} = (f_{air,\ell})(Q)/[3600 \text{ s/min } (h_c)(\pi d_c)]$ where: $f_{air,\ell} = 1 - 1/r$ $r = \exp\,[0.77(h_c)^{0.623}(Q/\pi d_c)^{0.66}(D_w/D_{O2,w})^{0.66}]$
6	$k_g \text{ (m/s)} = 0.001 + (0.0462(U^{**})(Sc_G)^{-0.67})$ where: $U^{**} \text{ (m/s)} = [6.1 + (0.63)(U_{10})]^{0.5}(U_{10}/100)$ $Sc_G = \mu_a/(\rho_a D_a)$

Table 4.3-1 (cont.).

Equation No.	Equation
Overall mass transfer coefficients for water (K) and oil (K_{oil}) phases and for weirs (K_D)	
7	$K = (k_\ell \, Keq \, k_g)/(Keq \, k_g + k_\ell)$ where: $Keq = H/(RT)$
8	$K \, (m/s) = [[MW_L/(k_{\ell\rho L}{*}(100 \, cm/m)] + [MW_a/(k_g \rho_a H{*}$ $55{,}555(100 \, cm/m))]]^{-1} \, MW_L/[(100 \, cm/m)\rho_L]$
9	$K_{oil} = k_g Keq_{oil}$ where: $Keq_{oil} = P^* \rho_a MW_{oil}/(\rho_{oil} \, MW_a \, P_o)$
10	$K_D = 0.16h \, (D_w/D_{O2,w})^{0.75}$
Air emissions (N)	
11	$N(g/s) = (1 - Ct/Co) \, V \, Co/t$ where: $Ct/Co = \exp[-K \, A \, t/V]$
12	$N(g/s) = K \, C_L \, A$ where: $C_L(g/m^3) = Q \, Co/(KA + Q)$
13	$N(g/s) = (1 - Ct/Co) \, V \, Co/t$ where: $Ct/Co = \exp[-(KA + KeqQ_a)t/V]$
14	$N(g/s) = (KA + Q_a Keq)C_L$ where: $C_L(g/m^3) = QCo/(KA + Q + Q_a Keq)$
15	$N(g/s) = (1 - Ct/Co) \, KA/(KA + Kmax \, b_i \, V/K_s) \, V \, Co/t$ where: $Ct/Co = \exp[-Kmax \, b_i \, t/K_s - K \, A \, t/V]$
16	$N(g/s) = K \, C_L \, A$ where: $C_L(g/m^3) = [-b + (b^2 - 4ac)^{0.5}]/(2a)$ and: $a = KA/Q + 1$ $b = K_s(KA/Q + 1) + Kmax \, b_i \, V/Q - Co$ $c = -K_s Co$

Table 4.3-1 (cont.).

Equation No.	Equation
17	$N(g/s) = (1 - Ct_{oil}/Co_{oil})V_{oil}Co_{oil}/t$ where: $Ct_{oil}/Co_{oil} = \exp[-K_{oil}\ t/D_{oil}]$ and: $Co_{oil} = Kow\ Co/[1 - FO + FO(Kow)]$ $V_{oil} = (FO)(V)$ $D_{oil} = (FO)(V)/A$
18	$N(g/s) = K_{oil}C_{L,oil}A$ where: $C_{L,oil}(g/m^3) = Q_{oil}Co_{oil}/(K_{oil}A + Q_{oil})$ and: $Co_{oil} = Kow\ Co/[1 - FO + FO(Kow)]$ $Q_{oil} = (FO)(Q)$
19	$N(g/s) = (1 - Ct/Co)(KA + Q_aKeq)/(KA + Q_aKeq + Kmax\ b_i\ V/K_s)\ V\ Co/t$ where: $Ct/Co = \exp[-(KA + KeqQ_a)t/V - Kmax\ b_i\ t/K_s]$
20	$N(g/s) = (KA + Q_aKeq)C_L$ where: $C_L(g/m^3) = [-b + (b^2 - 4ac)^{0.5}]/(2a)$ and: $a = (KA + Q_aKeq)/Q + 1$ $b = K_s[(KA + Q_aKeq)/Q + 1] + Kmax\ b_i\ V/Q - Co$ $c = -K_sCo$
21	$N\ (g/s) = (1 - \exp[-K_D])Q\ Co$
22	$N(g/s) = K_{oil}C_{L,oil}A$ where: $C_{L,oil}(g/m^3) = Q_{oil}(Co_{oil}^*)/(K_{oil}A + Q_{oil})$ and: $Co_{oil}^* = Co/FO$ $Q_{oil} = (FO)(Q)$
23	$N(g/s) = (1 - Ct_{oil}/Co_{oil}^*)(V_{oil})(Co_{oil}^*)/t$ where: $Ct_{oil}/Co_{oil}^* = \exp[-K_{oil}\ t/D_{oil}]$ and: $Co_{oil}^* = Co/FO$ $V_{oil} = (FO)(V)$ $D_{oil} = (FO)(V)/A$
24	$N\ (g/s) = (1 - \exp[-K\ \pi\ d_c\ h_c/Q])Q\ Co$

[a] All parameters in numbered equations are defined in Table 4.3-2.

Table 4.3-2. PARAMETER DEFINITIONS FOR MASS TRANSFER CORRELATIONS AND EMISSIONS EQUATIONS

Parameter	Definition	Units	Code^{a}
A	Waste water surface area	m^2 or ft^2	A
b_i	Biomass concentration (total biological solids)	g/m^3	B
C_L	Concentration of constituent in the liquid phase	g/m^3	D
$C_{L,oil}$	Concentration of constituent in the oil phase	g/m^3	D
Co	Initial concentration of constituent in the liquid phase	g/m^3	A
Co_{oil}	Initial concentration of constituent in the oil phase considering mass transfer resistance between water and oil phases	g/m^3	D
Co_{oil}^{*}	Initial concentration of constituent in the oil phase considering no mass transfer resistance between water and oil phases	g/m^3	D
Ct	Concentration of constituent in the liquid phase at time = t	g/m^3	D
Ct_{oil}	Concentration of constituent in the oil phase at time = t	g/m^3	D
d	Impeller diameter	cm	B
D	Waste water depth	m or ft	A,B
d^{*}	Impeller diameter	ft	B
D_a	Diffusivity of constituent in air	cm^2/s	C
d_c	Clarifier diameter	m	B
d_e	Effective diameter	m	D
D_{ether}	Diffusivity of ether in water	cm^2/s	$(8.5x10^{-6})^{b}$
$D_{O2,w}$	Diffusivity of oxygen in water	cm^2/s	$(2.4x10^{-5})^{b}$
D_{oil}	Oil film thickness	m	B
D_w	Diffusivity of constituent in water	cm^2/s	C
$f_{air,\ell}$	Fraction of constituent emitted to the air, considering zero gas resistance	dimensionless	D
F/D	Fetch to depth ratio, d_e/D	dimensionless	D
FO	Fraction of volume which is oil	dimensionless	B
Fr	Froude number	dimensionless	D
g_c	Gravitation constant (a conversion factor)	$lb_m\text{-}ft/s^2\text{-}lb_f$	32.17

Table 4.3-2 (cont.).

Parameter	Definition	Units	Code[a]
h	Weir height (distance from the waste water overflow to the receiving body of water)	ft	B
h_c	Clarifier weir height	m	B
H	Henry's law constant of constituent	atm-m^3/gmol	C
J	Oxygen transfer rating of surface aerator	lb 02/(hr-hp)	B
K	Overall mass transfer coefficient for transfer of constituent from liquid phase to gas phase	m/s	D
K_D	Volatilization-reaeration theory mass transfer coefficient	dimensionless	D
Keq	Equilibrium constant or partition coefficient (concentration in gas phase/concentration in liquid phase)	dimensionless	D
Keq_{oil}	Equilibrium constant or partition coefficient (concentration in gas phase/concentration in oil phase)	dimensionless	D
k_g	Gas phase mass transfer coefficient	m/s	D
k_ℓ	Liquid phase mass transfer coefficient	m/s	D
Kmax	Maximum biorate constant	g/s-g biomass	A,C
K_{oil}	Overall mass transfer coefficient for transfer of constituent from oil phase to gas phase	m/s	D
Kow	Octanol-water partition coefficient	dimensionless	C
K_s	Half saturation biorate constant	g/m^3	A,C
MW_a	Molecular weight of air	g/gmol	29
MW_{oil}	Molecular weight of oil	g/gmol	B
MW_L	Molecular weight of water	g/gmol	18
N	Emissions	g/s	D
N_I	Number of aerators	dimensionless	A,B
O_t	Oxygen transfer correction factor	dimensionless	B
P	Power number	dimensionless	D
P^*	Vapor pressure of the constituent	atm	C
P_o	Total pressure	atm	A
POWR	Total power to aerators	hp	B
Q	Volumetric flow rate	m^3/s	A

Table 4.3-2 (cont.).

Parameter	Definition	Units	Code[a]
Q_a	Diffused air flow rate	m^3/s	B
Q_{oil}	Volumetric flow rate of oil	m^3/s	B
r	Deficit ratio (ratio of the difference between the constituent concentration at solubility and actual constituent concentration in the upstream and the downstream)	dimensionless	D
R	Universal gas constant	atm-m^3/gmol-K	8.21×10^{-5}
Re	Reynolds number	dimensionless	D
Sc_G	Schmidt number on gas side	dimensionless	D
Sc_L	Schmidt number on liquid side	dimensionless	D
T	Temperature of water	°C or Kelvin (K)	A
t	Residence time of disposal	s	A
U^*	Friction velocity	m/s	D
U^{**}	Friction velocity	m/s	D
U_{10}	Wind speed at 10 m above the liquid surface	m/s	B
V	Waste water volume	m^3 or ft^3	A
Va_v	Turbulent surface area	ft^2	B
V_{oil}	Volume of oil	m^3	B
w	Rotational speed of impeller	rad/s	B
ρ_a	Density of air	g/cm^3	$(1.2 \times 10^{-3})^b$
ρ_L	Density of water	g/cm^3 or lb/ft^3	1^b or 62.4^b
ρ_{oil}	Density of oil	g/m^3	B
μ_a	Viscosity of air	g/cm-s	$(1.81 \times 10^{-4})^b$
μ_L	Viscosity of water	g/cm-s	$(8.93 \times 10^{-3})^b$

[a] Code:
A = Site-specific parameter.
B = Site-specific parameter. For default values, see Table 4.3-3.
C = Parameter can be obtained from literature. See Attachment 1 for a list of ~150 compound chemical properties at T = 25°C (298°K).
D = Calculated value.

[b] Reported values at 25°C (298°K).

Table 4.3-3. SITE-SPECIFIC DEFAULT PARAMETERS[a]

Default Parameter[b]	Definition	Default Value
General		
T	Temperature of water	298°K
U_{10}	Windspeed	4.47 m/s
Biotreatment Systems		
b_i	Biomass concentration (for biologically active systems)	
	Quiescent treatment systems	50 g/m^3
	Aerated treatment systems	300 g/m^3
	Activated sludge units	4000 g/m^3
POWR	Total power to aerators	
	(for aerated treatment systems)	0.75 hp/1000 ft^3 (V)
	(for activated sludge)	2 hp/1000 ft^3 (V)
W	Rotational speed of impeller (for aerated treatment systems)	126 rad/s (1200 rpm)
$d(d^*)$	Impeller diameter (for aerated treatment systems)	61 cm (2 ft)
Va_v	Turbulent surface area	
	(for aerated treatment systems)	0.24 (A)
	(for activated sludge)	0.52 (A)
J	Oxygen transfer rating to surface aerator (for aerated treatment systems)	3 lb O_2/hp•hr
O_t	Oxygen transfer correction factor (for aerated treatment systems)	0.83
N_I	Number of aerators	POWR/75
Diffused Air Systems		
Q_a	Diffused air volumetric flow rate	0.0004(V) m^3/s
Oil Film Layers		
MW_{oil}	Molecular weight of oil	282 g/gmol
D_{oil}	Depth of oil layer	0.001 (V/A) m
V_{oil}	Volume of oil	0.001 (V) m^3
Q_{oil}	Volumetric flow rate of oil	0.001 (Q) m^3/s
ρ_{oil}	Density of oil	0.92 g/cm^3

Table 4.3-3 (cont.).

Default Parameter[b]	Definition	Default Value
FO	Fraction of volume which is oil[c]	0.001
Junction Boxes		
D	Depth of Junction Box	0.9 m
N_I	Number of aerators	1
Lift Station		
D	Depth of Lift Station	1.5 m
N_I	Number of aerators	1
Sump		
D	Depth of sump	5.9 m
Weirs		
d_c	Clarifier weir diameter[d]	28.5 m
h	Weir height	1.8 m
h_c	Clarifier weir height[e]	0.1 m

[a] Reference 1.
[b] As defined in Table 4.3-2.
[c] Reference 4.
[d] Reference 2.
[e] Reference 5.

Waste water falls or overflows from weirs and creates splashing in the receiving body of water (both weir and clarifier weir models). Waste water from weirs can be aerated by directing it to fall over steps, usually only the weir model.

Assessing VOC emissions from drains, manholes, and trenches is also important in determining the total waste water facility emissions. As these sources can be open to the atmosphere and closest to the point of waste water generation (i. e., where water temperatures and pollutant concentrations are greatest), emissions can be significant. Currently, there are no well-established emission models for these collection system types. However, work is being performed to address this need.

Preliminary models of VOC emissions from waste collection system units have been developed.[4] The emission equations presented in Reference 4 are used with standard collection system parameters to estimate the fraction of the constituents released as the waste water flows through each unit. The fractions released from several units are estimated for high-, medium-, and low-volatility compounds. The units used in the estimated fractions included open drains, manhole covers, open trench drains, and covered sumps.

The numbers in Figure 4.3-4 under the columns for k_ℓ, k_g, K_{oil}, K_D, K, and N refer to the appropriate equations in Table 4.3-1.[a] Definitions for all parameters in these equations are given in Table 4.3-2. Table 4.3-2 also supplies the units that must be used for each parameter, with codes to help locate input values. If the parameter is coded with the letter A, a site-specific value is required. Code B also requires a site-specific parameter, but defaults are available. These defaults are typical or average values and are presented by specific system in Table 4.3-3.

Code C means the parameter can be obtained from literature data. Table 4.3-4 contains a list of approximately 150 chemicals and their physical properties needed to calculate emissions from waste water, using the correlations presented in Table 4.3-1. All properties are at 25°C (77°F). A more extensive chemical properties data base is contained in Appendix C of Reference 1.) Parameters coded D are calculated values.

Calculating air emissions from waste water collection, treatment, and storage systems is a complex procedure, especially if several systems are present. Performing the calculations by hand may result in errors and will be time consuming. A personal computer program called the Surface Impoundment Modeling System (SIMS) is now available for estimating air emissions. The program is menu driven and can estimate air emissions from all surface impoundment models presented in Figure 4.3-4, individually or in series. The program requires for each collection, treatment, or storage system component, at a minimum, the waste water flow rate and component surface area. All other inputs are provided as default values. Any available site-specific information should be entered in place of these defaults, as the most fully characterized system will provide the most accurate emissions estimate.

The SIMS program with user's manual and background technical document can be obtained through state air pollution control agencies and through the U. S. Environmental Protection Agency's Control Technology Center in Research Triangle Park, NC, telephone (919) 541-0800. The user's manual and background technical document should be followed to produce meaningful results.

The SIMS program and user's manual also can be downloaded from EPA's Clearinghouse For Inventories and Emission Factors (CHIEF) electronic bulletin board (BB). The CHIEF BB is open to all persons involved in air emission inventories. To access this BB, one needs a computer, modem, and communication package capable of communicating at up to 14,400 baud, 8 data bits, 1 stop bit, and no parity (8-N-1). This BB is part of EPA's OAQPS Technology Transfer Network system and its telephone number is (919) 541-5742. First-time users must register before access is allowed.

Emissions estimates from SIMS are based on mass transfer models developed by Emissions Standards Division (ESD) during evaluations of TSDFs and VOC emissions from industrial waste water. As a part of the TSDF project, a Lotus® spreadsheet program called CHEMDAT7 was developed for estimating VOC emissions from waste water land treatment systems, open landfills, closed landfills, and waste storage piles, as well as from various types of surface impoundments. For more information about CHEMDAT7, contact the ESD's Chemicals And Petroleum Branch (MD 13), US EPA, Research Triangle Park, NC 27711.

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[a] All emission model systems presented in Figure 4.3-4 imply a completely mixed or uniform waste water concentration system. Emission models for a plug flow system, or system in which there is no axial, or horizontal mixing, are too extensive to be covered in this document. (An example of plug flow might be a high waste water flow in a narrow channel.) For information on emission models of this type, see Reference 1.

4.3.2.1 Example Calculation -

An example industrial facility operates a flowthrough, mechanically aerated biological treatment impoundment that receives waste water contaminated with benzene at a concentration of 10.29 g/m^3.

The following format is used for calculating benzene emissions from the treatment process:

I. Determine which emission model to use
II. User-supplied information
III. Defaults
IV. Pollutant physical property data and water, air, and other properties
V. Calculate individual mass transfer coefficient
VI. Calculate the overall mass transfer coefficients
VII. Calculate VOC emissions

I. Determine Which Emission Model To Use — Following the flow diagram in Figure 4.3-4, the emission model for a treatment system that is aerated, but not by diffused air, is biologically active, and is a flowthrough system, contains the following equations:

Parameter	Definition	Equation Nos. from Table 4.3-1
K	Overall mass transfer coefficient, m/s	7
k_ℓ	Individual liquid phase mass transfer coefficient, m/s	1,3
k_g	Individual gas phase mass transfer coefficient, m/s	2,4
N	VOC emissions, g/s	16

II. User-supplied Information — Once the correct emission model is determined, some site-specific parameters are required. As a minimum for this model, site-specific flow rate, waste water surface area and depth, and pollutant concentration should be provided. For this example, these parameters have the following values:

Q = Volumetric flow rate = 0.0623 m^3/s
D = Waste water depth = 1.97 m
A = Waste water surface area = 17,652 m^2
Co = Initial benzene concentration in the liquid phase = 10.29 g/m^3

III. Defaults — Defaults for some emission model parameters are presented in Table 4.3-3. Generally, site-specific values should be used when available. For this facility, all available general and biotreatment system defaults from Table 4.3-3 were used:

U_{10} = Wind speed at 10 m above the liquid surface = e = 4.47 m/s
T = Temperature of water = 25°C (298°K)
b_i = Biomass concentration for aerated treatment systems = 300 g/m^3
J = Oxygen transfer rating to surface aerator = 3 lb O_2/hp-hr
POWR = Total power to aerators = 0.75 hp/1,000 ft^3 (V)
O_t = Oxygen transfer correction factor = 0.83
Va_v = Turbulent surface area = 0.24 (A)
d = Impeller diameter = 61 cm

d^* = Impeller diameter = 2 ft
w = Rotational speed of impeller = 126 rad/s
N_I = Number of aerators = POWR/75 hp

IV. **Pollutant Physical Property Data, And Water, Air and Other Properties — For each pollutant, the specific physical properties needed by this model are listed in Table 4.3-4. Water, air, and other property values are given in Table 4.3-2.**

A. **Benzene (from Table 4.3-4)**

$D_{w,benzene}$ = Diffusivity of benzene in water = 9.8×10^{-6} cm^2/s
$D_{a,benzene}$ = Diffusivity of benzene in air = 0.088 cm^2/s
$H_{benzene}$ = Henry's law constant for benzene = 0.0055 atm- m^3/gmol
$Kmax_{benzene}$ = Maximum biorate constant for benzene = 5.28×10^{-6} g/g-s
$K_{s,benzene}$ = Half saturation biorate constant for benzene = 13.6 g/m^3

B. **Water, Air, and Other Properties (from Table 4.3-3)**

ρ_a = Density of air = 1.2×10^3 g/cm^3
ρ_L = Density of water = 1 g/cm^3 (62.4 lb_m/ft^3)
μ_a = Viscosity of air = 1.81×10^{-4} g/cm-s
$D_{O2,w}$ = Diffusivity of oxygen in water = 2.4×10^{-5} cm^2/s
D_{ether} = Diffusivity of ether in water = 8.5×10^{-6} cm^2/s
MW_L = Molecular weight of water = 18 g/gmol
MW_a = Molecular weight of air = 29 g/gmol
g_c = Gravitation constant = 32.17 lb_m-ft/lb_f-s^2
R = Universal gas constant = 8.21×10^{-5} atm-m^3/gmol

V. **Calculate Individual Mass Transfer Coefficients — Because part of the impoundment is turbulent and part is quiescent, individual mass transfer coefficients are determined for both turbulent and quiescent areas of the surface impoundment.**

<u>Turbulent area of impoundment</u> — Equations 3 and 4 from Table 4.3-1.

A. **Calculate the individual liquid mass transfer coefficient, k_ℓ:**

$$k_\ell(m/s) = [(8.22 \times 10^{-9})(J)(POWR)(1.024)^{(T-20)} * (O_t)(10^6)MW_L/(Va_v\rho_L)](D_w/D_{O2,w})^{0.5}$$

The total power to the aerators, POWR, and the turbulent surface area, Va_v, are calculated separately [Note: some conversions are necessary.]:

1. **Calculate total power to aerators, POWR (Default presented in III):**

$$POWR\ (hp) = 0.75\ hp/1{,}000\ ft^3\ (V)$$
$$V = \text{waste water volume, } m^3$$
$$V\ (m^3) = (A)(D) = (17{,}652\ m^2)(1.97\ m)$$
$$V = 34{,}774\ m^3$$
$$POWR = (0.75\ hp/1{,}000\ ft^3)(ft^3/0.028317\ m^3)(34{,}774\ m^3)$$
$$= 921\ hp$$

2. **Calculate turbulent surface area, Va_v (default presented in III):**

$$Va_v\ (ft^2) = 0.24\ (A)$$
$$= 0.24(17{,}652\ m^2)(10.758\ ft^2/m^2)$$
$$= 45{,}576\ ft^2$$

Now, calculate k_ℓ, using the above calculations and information from II, III, and IV:

$$\begin{aligned} k_\ell\ (\text{m/s}) &= [(8.22 \times 10^{-9})(3\ \text{lb O}_2/\text{hp-hr})(921\ \text{hp}) * \\ &\quad (1.024)^{(25-20)}(0.83)(10^6)(18\ \text{g/gmol})/ \\ &\quad ((45{,}576\ \text{ft}^2)(1\ \text{g/cm}^3))] * \\ &\quad [(9.8 \times 10^{-6}\ \text{cm}^2/\text{s})/(2.4 \times 10^{-5}\ \text{cm}^2/\text{s})]^{0.5} \\ &= (0.00838)(0.639) \\ k_\ell &= 5.35 \times 10^{-3}\ \text{m/s} \end{aligned}$$

B. Calculate the individual gas phase mass transfer coefficient, k_g:
$k_g\ (\text{m/s}) = (1.35 \times 10^{-7})(\text{Re})^{1.42}(\text{P})^{0.4}(\text{Sc}_G)^{0.5}(\text{Fr})^{-0.21}(D_a\ MW_a/d)$

The Reynolds number, Re, power number, P, Schmidt number on the gas side, Sc_G, and Froude's number Fr, are calculated separately:

1. Calculate Reynolds number, Re:

$$\begin{aligned} \text{Re} &= d^2\ w\ \rho_a/\mu_a \\ &= (61\ \text{cm})^2(126\ \text{rad/s})(1.2 \times 10^{-3}\ \text{g/cm}^3)/(1.81 \times 10^{-4}\ \text{g/cm-s}) \\ &= 3.1 \times 10^6 \end{aligned}$$

2. Calculate power number, P:

$$\begin{aligned} \text{P} &= [(0.85)(\text{POWR})(550\ \text{ft-lb}_f/\text{s-hp})/N_I]\ g_c/(\rho_L(d^*)^5\ w^3) \\ N_I &= \text{POWR}/75\ \text{hp (default presented in III)} \\ \text{P} &= (0.85)(75\ \text{hp})(\text{POWR}/\text{POWR})(550\ \text{ft-lb}_f/\text{s-hp}) * \\ &\quad (32.17\ \text{lb}_m\text{-ft/lb}_f\text{-s}^2)/[(62.4\ \text{lb}_m/\text{ft}^3)(2\ \text{ft})^5(126\ \text{rad/s})^3] \\ &= 2.8 \times 10^{-4} \end{aligned}$$

3. Calculate Schmidt number on the gas side, Sc_G:

$$\begin{aligned} \text{Sc}_G &= \mu_a/(\rho_a D_a) \\ &= (1.81 \times 10^{-4}\ \text{g/cm-s})/[(1.2 \times 10^{-3}\ \text{g/cm}^3)(0.088\ \text{cm}^2/\text{s})] \\ &= 1.71 \end{aligned}$$

4. Calculate Froude number, Fr:

$$\begin{aligned} \text{Fr} &= (d^*)w^2/g_c \\ &= (2\ \text{ft})(126\ \text{rad/s})^2/(32.17\ \text{lb}_m\text{-ft/lb}_f\text{-s}^2) \\ &= 990 \end{aligned}$$

Now, calculate k_g using the above calculations and information from II, III, and IV:

$$\begin{aligned} k_g\ (\text{m/s}) &= (1.35 \times 10^{-7})(3.1 \times 10^6)^{1.42}(2.8 \times 10^{-4})^{0.4}(1.71)^{0.5} * \\ &\quad (990)^{-0.21}(0.088\ \text{cm}^2/\text{s})(29\ \text{g/gmol})/(61\ \text{cm}) \\ &= 0.109\ \text{m/s} \end{aligned}$$

<u>Quiescent surface area of impoundment</u> — Equations 1 and 2 from Table 4.3-1

A. Calculate the individual liquid phase mass transfer coefficient, k_ℓ:

$$\begin{aligned} F/D &= 2(A/\pi)^{0.5}/D \\ &= 2(17{,}652\ \text{m}^2/\pi)^{0.5}/(1.97\ \text{m}) \\ &= 76.1 \\ U_{10} &= 4.47\ \text{m/s} \end{aligned}$$

For $U_{10} > 3.25$ m/s and F/D > 51.2 use the following:

$$\begin{aligned} k_\ell \text{ (m/s)} &= (2.61 \text{ x } 10^{-7})(U_{10})^2(D_w/D_{ether})^{2/3} \\ &= (2.61 \text{ x } 10^{-7})(4.47 \text{ m/s})^2[(9.8 \text{ x } 10^{-6} \text{ cm}^2/\text{s})/ \\ &\quad (8.5 \text{ x } 10^{-6} \text{ cm}^2/\text{s})]^{2/3} \\ &= 5.74 \text{ x } 10^{-6} \text{ m/s} \end{aligned}$$

B. Calculate the individual gas phase mass transfer coefficient, k_g:

$$k_g = (4.82 \text{ x } 10^{-3})(U_{10})^{0.78}(Sc_G)^{-0.67}(d_e)^{-0.11}$$

The Schmidt number on the gas side, Sc_G, and the effective diameter, d_e, are calculated separately:

1. Calculate the Schmidt number on the gas side, Sc_G:

$$Sc_G = \mu_a/(\rho_a D_a) = 1.71 \text{ (same as for turbulent impoundments)}$$

2. Calculate the effective diameter, d_e:

$$\begin{aligned} d_e \text{ (m)} &= 2(A/\pi)^{0.5} \\ &= 2(17{,}652 \text{ m}^2/\pi)^{0.5} \\ &= 149.9 \text{ m} \\ k_g\text{(m/s)} &= (4.82 \text{ x } 10^{-3})(4.47 \text{ m/s})^{0.78} \ (1.71)^{-0.67} \ (149.9 \text{ m})^{-0.11} \\ &= 6.24 \text{ x } 10^{-3} \text{ m/s} \end{aligned}$$

VI. Calculate The Overall Mass Transfer Coefficient — Because part of the impoundment is turbulent and part is quiescent, the overall mass transfer coefficient is determined as an area-weighted average of the turbulent and quiescent overall mass transfer coefficients. (Equation 7 from Table 4.3-1).

Overall mass transfer coefficient for the turbulent surface area of impoundment, K_T

$$\begin{aligned} K_T \text{ (m/s)} &= (k_\ell Keq k_g)/(Keq k_g + k_\ell) \\ Keq &= H/RT \\ &= (0.0055 \text{ atm-m}^3/\text{gmol})/[(8.21 \text{ x } 10^{-5} \text{ atm-m}^3/\text{ gmol-}^\circ\text{K})(298\,^\circ\text{K})] \\ &= 0.225 \\ K_T \text{ (m/s)} &= (5.35 \text{ x } 10^{-3} \text{ m/s})(0.225)(0.109)/[(0.109 \text{ m/s})(0.225) + \\ &\quad (5.35 \text{ x } 10^{-6} \text{ m/s})] \\ K_T &= 4.39 \text{ x } 10^{-3} \text{ m/s} \end{aligned}$$

Overall mass transfer coefficient for the quiescent surface area of impoundment, K_Q

$$\begin{aligned} K_Q \text{ (m/s)} &= (k_\ell Keq k_g)/(Keq k_g + k_\ell) \\ &= (5.74 \text{ x } 10^{-6} \text{ m/s})(0.225)(6.24 \text{ x } 10^{-3} \text{ m/s})/ \\ &\quad [(6.24 \text{ X } 10^{-3} \text{ m/s})(0.225) + (5.74 \text{ x } 10^{-6} \text{ m/s})] \\ &= 5.72 \text{ x } 10^{-6} \text{ m/s} \end{aligned}$$

Overall mass transfer coefficient, K, weighted by turbulent and quiescent surface areas, A_T and A_Q

$$\begin{aligned} K \text{ (m/s)} &= (K_T A_T + K_Q A_Q)/A \\ A_T &= 0.24(A) \text{ (Default value presented in III: } A_T = Va_v) \\ A_Q &= (1 - 0.24)A \\ K \text{ (m/s)} &= [(4.39 \text{ x } 10^{-3} \text{ m/s})(0.24 \text{ A}) + (5.72 \text{ x } 10^{-6} \text{ m/s})(1 - 0.24)A]/A \\ &= 1.06 \text{ x } 10^{-3} \text{ m/s} \end{aligned}$$

VII. Calculate VOC Emissions For An Aerated Biological Flowthrough Impoundment — Equation 16 from Table 4.3-1:

$$N\ (g/s) = K\ C_L\ A$$

where:

$$C_L\ (g/m^3) = [-b + (b^2 - 4ac)^{0.5}]/(2a)$$

and:

$$a = KA/Q + 1$$
$$b = K_s(KA/Q + 1) + Kmax\ b_i\ V/Q - Co$$
$$c = -K_sCo$$

Calculate a, b, c, and the concentration of benzene in the liquid phase, C_L, separately:

1. Calculate a:

$$\begin{aligned} a &= (KA/Q + 1) = [(1.06 \times 10^{-3}\ m/s)(17{,}652\ m^2)/(0.0623\ m^3/s)] + 1 \\ &= 301.3 \end{aligned}$$

2. Calculate b ($V = 34{,}774\ m^3$ from IV):

$$\begin{aligned} b &= K_s\ (KA/Q + 1) + Kmax\ b_i\ V/Q - Co \\ &= (13.6\ g/m^3)[(1.06 \times 10^{-3}\ m/s)(17{,}652\ m^2)/(0.0623\ m^3/s)] + \\ &\quad [(5.28 \times 10^{-6}\ g/g\text{-}s)(300\ g/m^3)(34{,}774\ m^3)/(0.0623\ m^3/s)] - 10.29\ g/m^3 \\ &= 4{,}084.6 + 884.1 - 10.29 \\ &= 4{,}958.46\ g/m^3 \end{aligned}$$

3. Calculate c:

$$\begin{aligned} c &= -K_sCo \\ &= -(13.6\ g/m^3)(10.29\ g/m^3) \\ &= -139.94 \end{aligned}$$

4. Calculate the concentration of benzene in the liquid phase, C_L, from a, b, and c above:

$$\begin{aligned} C_L\ (g/m^3) &= [-b + (b^2 - 4ac)^{0.5}]/(2a) \\ &= [(4{,}958.46\ g/m^3) + [(4{,}958.46\ g/m^3)^2 - \\ &\quad [4(301.3)(-139.94)]]^{0.5}]/(2(301.3)) \\ &= 0.0282\ g/m^3 \end{aligned}$$

Now calculate N with the above calculations and information from II and V:

$$\begin{aligned} N\ (g/s) &= K\ A\ C_L \\ &= (1.06 \times 10^{-3}\ m/s)(17{,}652\ m^2)(0.0282\ g/m^3) \\ &= 0.52\ g/s \end{aligned}$$

4.3.3 Controls

The types of control technology generally used in reducing VOC emissions from waste water include: steam stripping or air stripping, carbon adsorption (liquid phase), chemical oxidation, membrane separation, liquid-liquid extraction, and biotreatment (aerobic or anaerobic). For efficient control, all control elements should be placed as close as possible to the point of waste water generation, with all collection, treatment, and storage systems ahead of the control technology being covered to suppress emissions. Tightly covered, well-maintained collection systems can suppress emissions by 95 to 99 percent. However, if there is explosion potential, the components should be vented to a control device such as an incinerator or carbon adsorber.

The following are brief descriptions of the control technology listed above and of any secondary controls that may need to be considered for fugitive air emissions.

Steam stripping is the fractional distillation of waste water to remove volatile organic constituents, with the basic operating principle being the direct contact of steam with waste water. The steam provides the heat of vaporization for the more volatile organic constituents. Removal efficiencies vary with volatility and solubility of the organic impurities. For highly volatile compounds (HLC greater than 10^{-3} atm-m^3/gmol), average VOC removal ranges from 95 to 99 percent. For medium-volatility compounds (HLC between 10^{-5} and 10^{-3} atm-m^3/gmol), average removal ranges from 90 to 95 percent. For low-volatility compounds (HLC $< 10^{-5}$ atm-m^3/gmol), average removal ranges from less than 50 to 90 percent.

Air stripping involves the contact of waste water and air to strip out volatile organic constituents. By forcing large volumes of air through contaminated water, the surface area of water in contact with air is greatly increased, resulting in an increase in the transfer rate of the organic compounds into the vapor phase. Removal efficiencies vary with volatility and solubility of organic impurities. For highly volatile compounds, average removal ranges from 90 to 99 percent; for medium- to low-volatility compounds, removal ranges from less than 50 to 90 percent.

Steam stripping and air stripping controls most often are vented to a secondary control, such as a combustion device or gas phase carbon adsorber. Combustion devices may include incinerators, boilers, and flares. Vent gases of high fuel value can be used as an alternate fuel. Typically, vent gas is combined with other fuels such as natural gas and fuel oil. If the fuel value is very low, vent gases can be heated and combined with combustion air. It is important to note that organics such as chlorinated hydrocarbons can emit toxic pollutants when combusted.

Secondary control by gas phase carbon adsorption processes takes advantage of compound affinities for activated carbon. The types of gas phase carbon adsorption systems most commonly used to control VOC are fixed-bed carbon adsorbers and carbon canisters. Fixed-bed carbon adsorbers are used to control continuous organic gas streams with flow rates ranging from 30 to over 3000 m^3/min. Canisters are much simpler and smaller than fixed-bed systems and are usually installed to control gas flows of less than 3 m^3/min.[4] Removal efficiencies depend highly on the type of compound being removed. Pollutant-specific activated carbon is usually required. Average removal efficiency ranges from 90 to 99 percent.

Like gas phase carbon adsorption, liquid phase carbon adsorption takes advantage of compound affinities for activated carbon. Activated carbon is an excellent adsorbent, because of its large surface area and because it is usually in granular or powdered form for easy handling. Two types of liquid phase carbon adsorption are the fixed-bed and moving-bed systems. The fixed-bed system is used primarily for low-flow waste water streams with contact times around 15 minutes, and it is a batch operation (i. e., once the carbon is spent, the system is taken off line). Moving-bed carbon adsorption systems operate continuously with waste water typically being introduced from the bottom of the column and regenerated carbon from the top (countercurrent flow). Spent carbon is continuously removed from the bottom of the bed. Liquid phase carbon adsorption is usually used for low concentrations of nonvolatile components and for high concentrations of nondegradable compounds.[5] Removal efficiencies depend on whether the compound is adsorbed on activated carbon. Average removal efficiency ranges from 90 to 99 percent.

Chemical oxidation involves a chemical reaction between the organic compound and an oxidant such as ozone, hydrogen peroxide, permanganate, or chlorine dioxide. Ozone is usually added to the waste water through an ultraviolet-ozone reactor. Permanganate and chlorine dioxide are added directly into the waste water. It is important to note that adding chlorine dioxide can form chlorinated hydrocarbons in a side reaction. The applicability of this technique depends on the reactivity of the individual organic compound.

Two types of membrane separation processes are ultrafiltration and reverse osmosis. Ultrafiltration is primarily a physical sieving process driven by a pressure gradient across the membrane. This process separates organic compounds with molecular weights greater than 2000, depending on the size of the membrane pore. Reverse osmosis is the process by which a solvent is forced across a semipermeable membrane because of an osmotic pressure gradient. Selectivity is, therefore, based on osmotic diffusion properties of the compound and on the molecular diameter of the compound and membrane pores.[4]

Liquid-liquid extraction as a separation technique involves differences in solubility of compounds in various solvents. Contacting a solution containing the desired compound with a solvent in which the compound has a greater solubility may remove the compound from the solution. This technology is often used for product and process solvent recovery. Through distillation, the target compound is usually recovered, and the solvent reused.

Biotreatment is the aerobic or anaerobic chemical breakdown of organic chemicals by microorganisms. Removal of organics by biodegradation is highly dependent on the compound's biodegradability, its volatility, and its ability to be adsorbed onto solids. Removal efficiencies range from almost zero to 100 percent. In general, highly volatile compounds such as chlorinated hydrocarbons and aromatics will biodegrade very little because of their high-volatility, while alcohols and other compounds soluble in water, as well as low-volatility compounds, can be almost totally biodegraded in an acclimated system. In the acclimated biotreatment system, the microorganisms easily convert available organics into biological cells, or biomass. This often requires a mixed culture of organisms, where each organism utilizes the food source most suitable to its metabolism. The organisms will starve and the organics will not be biodegraded if a system is not acclimated, i. e., the organisms cannot metabolize the available food source.

4.3.4 Glossary Of Terms

Basin -	an earthen or concrete-lined depression used to hold liquid.
Completely mixed -	having the same characteristics and quality throughout or at all times.
Disposal -	the act of permanent storage. Flow of liquid into, but not out of a device.
Drain -	a device used for the collection of liquid. It may be open to the atmosphere or be equipped with a seal to prevent emissions of vapors.
Flowthrough -	having a continuous flow into and out of a device.
Plug flow -	having characteristics and quality not uniform throughout. These will change in the direction the fluid flows, but not perpendicular to the direction of flow (i. e., no axial movement)

Storage -	any device to accept and retain a fluid for the purpose of future discharge. Discontinuity of flow of liquid into and out of a device.
Treatment -	the act of improving fluid properties by physical means. The removal of undesirable impurities from a fluid.
VOC -	volatile organic compounds, referring to all organic compounds except the following, which have been shown not to be photochemically reactive: methane, ethane, trichlorotrifluoroethane, methylene chloride, 1,1,1,-trichloroethane, trichlorofluoromethane, dichlorodifluoromethane, chlorodifluoromethane, trifluoromethane, dichlorotetrafluoroethane, and chloropentafluoroethane.

Table 4.3-4. SIMS CHEMICAL PROPERTY DATA FILE (PART 1)

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m^3/mol)	Diffusivity Of Chemical In Water At 25°C (cm^2/s)	Diffusivity Of Chemical In Air At 25°C (cm^2/s)
ACETALDEHYDE	75-07-0	44.00	760	0.000095	0.0000141	0.124
ACETIC ACID	64-19-7	60.05	15.4	0.0627	0.000012	0.113
ACETIC ANHYDRIDE	108-24-7	102.09	5.29	0.00000591	0.00000933	0.235
ACETONE	67-64-1	58.00	266	0.000025	0.0000114	0.124
ACETONITRILE	75-05-8	41.03	90	0.0000058	0.0000166	0.128
ACROLEIN	107-02-8	56.10	244.2	0.0000566	0.0000122	0.105
ACRYLAMIDE	79-06-1	71.09	0.012	0.00000000052	0.0000106	0.097
ACRYLIC ACID	79-10-7	72.10	5.2	0.0000001	0.0000106	0.098
ACRYLONITRILE	107-13-1	53.10	114	0.000088	0.0000134	0.122
ADIPIC ACID	124-04-9	146.14	0.0000225	0.00000000005	0.00000684	0.0659
ALLYL ALCOHOL	107-18-6	58.10	23.3	0.000018	0.0000114	0.114
AMINOPHENOL(-O)	95-55-6	109.12	0.511	0.00000367	0.00000864	0.0774
AMINOPHENOL(-P)	123-30-8	109.12	0.893	0.0000197	0.00000239	0.0774
AMMONIA	7664-41-7	17.03	7470	0.000328	0.0000693	0.259
AMYL ACETATE(-N)	628-37-8	130.18	5.42	0.000464	0.0000012	0.064
ANILINE	62-53-3	93.10	1	0.0000026	0.0000083	0.07
BENZENE	71-43-2	78.10	95.2	0.0055	0.0000098	0.088
BENZO(A)ANTHRACENE	56-55-3	228.30	0.00000015	0.00000000138	0.000009	0.051
BENZO(A)PYRENE	50-32-8	252.30	0.00568	0.00000000138	0.000009	0.043

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m^3/mol)	Diffusivity Of Chemical In Water At 25°C (cm^2/s)	Diffusivity Of Chemical In Air At 25°C (cm^2/s)
CRESYLIC ACID	1319-77-3	108.00	0.3	0.0000017	0.0000083	0.074
CROTONALDEHYDE	4170-30-0	70.09	30	0.00000154	0.0000102	0.0903
CUMENE (ISOPROPYLBENZENE)	98-82-8	120.20	4.6	0.0146	0.0000071	0.065
CYCLOHEXANE	110-82-7	84.20	100	0.0137	0.0000091	0.0839
CYCLOHEXANOL	108-93-0	100.20	1.22	0.00000447	0.00000831	0.214
CYCLOHEXANONE	108-94-1	98.20	4.8	0.00000413	0.00000862	0.0784
DI-N-OCTYL PHTHALATE	117-84-0	390.62	0	0.137	0.0000041	0.0409
DIBUTYLPHTHALATE	84-74-2	278.30	0.00001	0.00000028	0.0000079	0.0438
DICHLORO(-2)BUTENE(1,4)	764-41-0	125.00	2.87	0.000259	0.00000812	0.0725
DICHLOROBENZENE(1,2) (-O)	95-50-1	147.00	1.5	0.00194	0.0000079	0.069
DICHLOROBENZENE(1,3) (-M)	541-73-1	147.00	2.28	0.00361	0.0000079	0.069
DICHLOROBENZENE(1,4) (-P)	106-46-7	147.00	1.2	0.0016	0.0000079	0.069
DICHLORODIFLUOROMETHANE	75-71-8	120.92	5000	0.401	0.00001	0.0001
DICHLOROETHANE(1,1)	75-34-3	99.00	234	0.00554	0.0000105	0.0914
DICHLOROETHANE(1,2)	107-06-2	99.00	80	0.0012	0.0000099	0.104
DICHLOROETHYLENE(1,2)	156-54-2	96.94	200	0.0319	0.000011	0.0935
DICHLOROPHENOL(2,4)	120-83-2	163.01	0.1	0.0000048	0.0000076	0.0709
DICHLOROPHENOXYACETIC ACID(2,4)	94-75-7	221.00	290	0.0621	0.00000649	0.0588
DICHLOROPROPANE(1,2)	78-87-5	112.99	40	0.0023	0.0000087	0.0782
DIETHYL (N,N) ANILIN	91-66-7	149.23	0.00283	0.0000000574	0.00000587	0.0513

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m^3/mol)	Diffusivity Of Chemical In Water At 25°C (cm^2/s)	Diffusivity Of Chemical In Air At 25°C (cm^2/s)
DIETHYL PHTHALATE	84-66-2	222.00	0.003589	0.0111	0.0000058	0.0542
DIMETHYL FORMAMIDE	68-12-2	73.09	4	0.0000192	0.0000103	0.0939
DIMETHYL HYDRAZINE(1,1)	57-14-7	60.10	157	0.000124	0.0000109	0.106
DIMETHYL PHTHALATE	131-11-3	194.20	0.000187	0.00000215	0.0000063	0.0568
DIMETHYLBENZ(A)ANTHRACENE	57-97-6	256.33	0	0.00000000027	0.00000498	0.0461
DIMETHYLPHENOL(2,4)	105-67-9	122.16	0.0573	0.000921	0.0000084	0.0712
DINITROBENZENE (-M)	99-65-0	168.10	0.05	0.000022	0.00000764	0.279
DINITROTOLUENE(2,4)	121-14-2	182.10	0.0051	0.00000407	0.00000706	0.203
DIOXANE(1,4)	123-91-1	88.20	37	0.0000231	0.0000102	0.229
DIOXIN	NOCAS2	322.00	0	0.0000812	0.0000056	0.104
DIPHENYLAMINE	122-39-4	169.20	0.00375	0.00000278	0.00000631	0.058
EPICHLOROHYDRIN	106-89-8	92.50	17	0.0000323	0.0000098	0.086
ETHANOL	64-17-5	46.10	50	0.0000303	0.000013	0.123
ETHANOLAMINE(MONO-)	141-43-5	61.09	0.4	0.000000322	0.0000114	0.107
ETHYL ACRYLATE	140-88-5	100.00	40	0.00035	0.0000086	0.077
ETHYL CHLORIDE	75-00-3	64.52	1200	0.014	0.0000115	0.271
ETHYL-(2)PROPYL-(3) ACROLEIN	645-62-5	92.50	17	0.0000323	0.0000098	0.086
ETHYLACETATE	141-78-6	88.10	100	0.000128	0.00000966	0.0732
ETHYLBENZENE	100-41-4	106.20	10	0.00644	0.0000078	0.075
ETHYLENEOXIDE	75-21-8	44.00	1250	0.000142	0.0000145	0.104

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m^3/mol)	Diffusivity Of Chemical In Water At 25°C (cm^2/s)	Diffusivity Of Chemical In Air At 25°C (cm^2/s)
ETHYLETHER	60-29-7	74.10	520	0.00068	0.0000093	0.074
FORMALDEHYDE	50-00-0	30.00	3500	0.0000576	0.0000198	0.178
FORMIC ACID	64-18-6	46.00	42	0.0000007	0.00000137	0.079
FREONS	NOCAS3	120.92	5000	0.401	0.00001	0.104
FURAN	110-00-9	68.08	596	0.00534	0.0000122	0.104
FURFURAL	96-01-1	96.09	2	0.0000811	0.0000104	0.0872
HEPTANE (ISO)	142-82-5	100.21	66	1.836	0.00000711	0.187
HEXACHLOROBENZENE	118-74-1	284.80	1	0.00068	0.00000591	0.0542
HEXACHLOROBUTADIENE	87-68-3	260.80	0.15	0.0256	0.0000062	0.0561
HEXACHLOROCYCLOPENTADIENE	77-47-4	272.80	0.081	0.016	0.00000616	0.0561
HEXACHLOROETHANE	67-72-1	237.00	0.65	0.00000249	0.0000068	0.00249
HEXANE(-N)	100-54-3	86.20	150	0.122	0.00000777	0.2
HEXANOL(-1)	111-27-3	102.18	0.812	0.0000182	0.00000753	0.059
HYDROCYANIC ACID	74-90-8	27.00	726	0.000000465	0.0000182	0.197
HYDROFLUORIC ACID	7664-39-3	20.00	900	0.000237	0.000033	0.388
HYDROGEN SULFIDE	7783-06-4	34.10	15200	0.023	0.0000161	0.176
ISOPHORONE	78-59-1	138.21	0.439	0.00000576	0.00000676	0.0623
METHANOL	67-56-1	32.00	114	0.0000027	0.0000164	0.15
METHYL ACETATE	79-20-9	74.10	235	0.000102	0.00001	0.104
METHYL CHLORIDE	74-87-3	50.50	3830	0.00814	0.0000065	0.126

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C ($atm \cdot m^3/mol$)	Diffusivity Of Chemical In Water At 25°C (cm^2/s)	Diffusivity Of Chemical In Air At 25°C (cm^2/s)
METHYL ETHYL KETONE	78-93-3	72.10	100	0.0000435	0.0000098	0.0808
METHYL ISOBUTYL KETONE	108-10-1	100.20	15.7	0.0000495	0.0000078	0.075
METHYL METHACRYLATE	80-62-6	100.10	39	0.000066	0.0000086	0.077
METHYL STYRENE (ALPHA)	98-83-9	118.00	0.076	0.00591	0.0000114	0.264
METHYLENE CHLORIDE	75-09-2	85.00	438	0.00319	0.0000117	0.101
MORPHOLINE	110-91-8	87.12	10	0.0000573	0.0000096	0.091
NAPHTHALENE	91-20-3	128.20	0.23	0.00118	0.0000075	0.059
NITROANILINE(-O)	88-74-4	138.14	0.003	0.0000005	0.000008	0.073
NITROBENZENE	98-95-3	123.10	0.3	0.0000131	0.0000086	0.076
PENTACHLOROBENZENE	608-93-5	250.34	0.0046	0.0073	0.0000063	0.057
PENTACHLOROETHANE	76-01-7	202.30	4.4	0.021	0.0000073	0.066
PENTACHLOROPHENOL	87-86-5	266.40	0.00099	0.0000028	0.0000061	0.056
PHENOL	108-95-2	94.10	0.34	0.000000454	0.0000091	0.082
PHOSGENE	75-44-5	98.92	1390	0.171	0.00000112	0.108
PHTHALIC ACID	100-21-0	166.14	121	0.0132	0.0000068	0.064
PHTHALIC ANHYDRIDE	85-44-9	148.10	0.0015	0.0000009	0.0000086	0.071
PICOLINE(-2)	108-99-6	93.12	10.4	0.000127	0.0000096	0.075
POLYCHLORINATED BIPHENYLS	1336-36-3	290.00	0.00185	0.0004	0.00001	0.104
PROPANOL (ISO)	71-23-8	60.09	42.8	0.00015	0.0000104	0.098
PROPIONALDEHYDE	123-38-6	58.08	300	0.00115	0.0000114	0.102

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m^3/mol)	Diffusivity Of Chemical In Water At 25°C (cm^2/s)	Diffusivity Of Chemical In Air At 25°C (cm^2/s)
PROPYLENE GLYCOL	57-55-6	76.11	0.3	0.0000015	0.0000102	0.093
PROPYLENE OXIDE	75-66-9	58.10	525	0.00134	0.00001	0.104
PYRIDINE	110-86-1	79.10	20	0.0000236	0.0000076	0.091
RESORCINOL	108-46-3	110.11	0.00026	0.0000000188	0.0000087	0.078
STYRENE	100-42-5	104.20	7.3	0.00261	0.000008	0.071
TETRACHLOROETHANE(1,1,1,2)	630-20-6	167.85	6.5	0.002	0.0000079	0.071
TETRACHLOROETHANE(1,1,2,2)	79-34-5	167.85	6.5	0.00038	0.0000079	0.071
TETRACHLOROETHYLENE	127-18-4	165.83	19	0.029	0.0000082	0.072
TETRAHYDROFURAN	109-99-9	72.12	72.1	0.000049	0.0000105	0.098
TOLUENE	109-88-3	92.40	30	0.00668	0.0000086	0.087
TOLUENE DIISOCYANATE(2,4)	584-84-9	174.16	0.08	0.0000083	0.0000062	0.061
TRICHLORO(1,1,2)TRIFLUOROETHANE	76-13-1	187.38	300	0.435	0.0000082	0.078
TRICHLOROBENZENE(1,2,4)	120-82-1	181.50	0.18	0.00142	0.0000077	0.0676
TRICHLOROBUTANE(1,2,3)	NOCAS5	161.46	4.39	4.66	0.0000072	0.066
TRICHLOROETHANE(1,1,1)	71-55-6	133.40	123	0.00492	0.0000088	0.078
TRICHLOROETHANE(1,1,2)	79-00-5	133.40	25	0.000742	0.0000088	0.078
TRICHLOROETHYLENE	79-01-6	131.40	75	0.0091	0.0000091	0.079
TRICHLOROFLUOROMETHANE	75-69-4	137.40	796	0.0583	0.0000097	0.087
TRICHLOROPHENOL(2,4,6)	88-06-2	197.46	0.0073	0.0000177	0.0000075	0.0661
TRICHLOROPROPANE(1,1,1)	NOCAS6	147.43	3.1	0.029	0.0000079	0.071

Table 4.3-4 (Part 1) (cont.).

Chemical Name	CAS Number	Molecular Weight	Vapor Pressure At 25°C (mm Hg)	Henry's Law Constant At 25°C (atm·m³/mol)	Diffusivity Of Chemical In Water At 25°C (cm²/s)	Diffusivity Of Chemical In Air At 25°C (cm²/s)
TRICHLOROPROPANE(1,2,3)	96-18-4	147.43	3	0.028	0.0000079	0.071
UREA	57-13-6	60.06	6.69	0.000264	0.0000137	0.122
VINYL ACETATE	108-05-4	86.09	115	0.00062	0.0000092	0.085
VINYL CHLORIDE	75-01-4	62.50	2660	0.086	0.0000123	0.106
VINYLIDENE CHLORIDE	75-35-4	97.00	591	0.015	0.0000104	0.09
XYLENE(-M)	1330-20-7	106.17	8	0.0052	0.0000078	0.07
XYLENE(-O)	95-47-6	106.17	7	0.00527	0.00001	0.087

Table 4.3-4. SIMS CHEMICAL PROPERTY DATA FILE (PART 2)

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
ACETALDEHYDE	8.005	1600.017	291.809	0.0000228944	419.0542	2.69153
ACETIC ACID	7.387	1533.313	222.309	0.0000038889	14.2857	0.48978
ACETIC ANHYDRIDE	7.149	1444.718	199.817	0.0000026944	1.9323	1
ACETONE	7.117	1210.595	229.664	0.0000003611	1.1304	0.57544
ACETONITRILE	7.119	1314.4	230	0.00000425	152.6014	0.45709
ACROLEIN	2.39	0	0	0.0000021667	22.9412	0.81283
ACRYLAMIDE	11.2932	3939.877	273.16	0.00000425	56.2388	6.32182
ACRYLIC ACID	5.652	648.629	154.683	0.0000026944	54.7819	2.04174
ACRYLONITRILE	7.038	1232.53	222.47	0.000005	24	0.12023
ADIPIC ACID	0	0	0	0.0000026944	66.9943	1.20226
ALLYL ALCOHOL	0	0	0	0.0000048872	3.9241	1.47911
AMINOPHENOL(-O)	0	0	0	0.00000425	68.1356	3.81533
AMINOPHENOL(-P)	-3.357	699.157	-331.343	0.00000425	68.1356	3.81533
AMMONIA	7.5547	1002.711	247.885	0.00000425	15.3	1
AMYL ACETATE(-N)	0	0	0	0.0000026944	16.1142	51.10801
ANILINE	7.32	1731.515	206.049	0.0000019722	.3381	7.94328
BENZENE	6.905	1211.033	220.79	0.0000052778	13.5714	141.25375
BENZO(A)ANTHRACENE	6.9824	2426.6	156.6	0.0000086389	1.7006	407380.2778
BENZO(A)PYRENE	9.2455	3724.363	273.16	0.0000086389	1.2303	954992.58602

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
BENZYL CHLORIDE	0	0	0	0.0000049306	17.5674	199.52623
BIS(2-CHLOROETHYL)ETHER	0	0	0	0.0000029889	20.0021	38.01894
BIS(2-CHLOROISOPROPYL)ETHER	0	0	0	0.0000029889	8.3382	380.1894
BIS(2-ETHYLHEXYL)PHTHALATE	0	0	0	0.0000002139	2.2	199526.2315
BROMOFORM	0	0	0	0.0000029889	10.653	199.52623
BROMOMETHANE	0	0	0	0.0000029889	30.4422	12.58925
BUTADIENE-(1,3)	6.849	930.546	238.854	0.0000042534	15.3	74.32347
BUTANOL (ISO)	7.4743	1314.19	186.55	0.0000021667	70.9091	5.62341
BUTANOL-(1)	7.4768	1362.39	178.77	0.0000021667	70.9091	5.62341
BUTYL BENZYL PHTHALATE	0	0	0	0.0000086389	14.1364	60255.95861
CARBON DISULFIDE	6.942	1169.11	241.59	0.0000042534	5.8175	1
CARBON TETRACHLORIDE	6.934	1242.43	230	0.0000004167	1	524.80746
CHLORO(-P)CRESOL(-M)	0	0	0	0.0000029889	5.2902	1258.92541
CHLOROACETALDEHYDE	0	0	0	0.0000029889	49.838	3.4405
CHLOROBENZENE	6.978	1431.05	217.55	0.0000001083	.039	316.22777
CHLOROFORM	6.493	929.44	196.03	0.0000008167	3.7215	91.20108
CHLORONAPHTHALENE-(2)	0	0	0	0.0000029889	2.167	13182.56739
CHLOROPRENE	6.161	783.45	179.7	0.0000029968	6.3412	1
CRESOL(-M)	7.508	1856.36	199.07	0.0000064472	1.3653	93.32543
CRESOL(-O)	6.911	1435.5	165.16	0.0000063278	1.34	95.49926

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
CRESOL(-P)	7.035	1511.08	161.85	0.0000064472	1.3653	87.09636
CRESYLIC ACID	0	0	0	0.0000041667	15	1
CROTONALDEHYDE	0	0	0	0.0000026944	27.6285	12.36833
CUMENE (ISOPROPYLBENZENE)	6.963	1460.793	207.78	0.0000086458	16.5426	1
CYCLOHEXANE	6.841	1201.53	222.65	0.0000042534	15.3	338.0687
CYCLOHEXANOL	6.255	912.87	109.13	0.0000026944	18.0816	37.74314
CYCLOHEXANONE	7.8492	2137.192	273.16	0.0000031917	41.8921	6.45654
DI-N-OCTYL PHTHALATE	0	0	0	0.000000083	0.02	141253.7
DIBUTYLPHTHALATE	6.639	1744.2	113.59	0.0000001111	0.4	158489.31925
DICHLORO(-2)BUTENE(1,4)	0	0	0	0.0000029889	9.8973	242.1542
DICHLOROBENZENE(1,2) (-O)	.176	0	0	0.0000006944	4.3103	2398.83292
DICHLOROBENZENE(1,3) (-M)	0	0	0	0.0000017778	2.7826	2398.83292
DICHLOROBENZENE(1,4) (-P)	.079	0	0	0.0000017778	2.7826	2454.70892
DICHLORODIFLUOROMETHANE	0	0	0	0.0000029889	12.0413	144.54398
DICHLOROETHANE(1,1)	0	0	0	0.0000029889	4.6783	61.6595
DICHLOROETHANE(1,2)	7.025	1272.3	222.9	0.0000005833	2.1429	61.6595
DICHLOROETHYLENE(1,2)	6.965	1141.9	231.9	0.0000029889	6.3294	1
DICHLOROPHENOL(2,4)	0	0	0	0.0000069444	7.5758	562.34133
DICHLOROPHENOXYACETIC ACID(2,4)	0	0	0	0.0000029889	14.8934	82.61445

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
DICHLOROPROPANE(1,2)	6.98	1380.1	22.8	0.0000047222	12.1429	1
DIETHYL (N,N) ANILIN	7.466	1993.57	218.5	0.00000425	27.0047	43.57596
DIETHYL PHTHALATE	0	0	0	0.000000753	1.28	1412.537
DIMETHYL FORMAMIDE	6.928	1400.87	196.43	0.00000425	15.3	1
DIMETHYL HYDRAZINE(1,1)	7.408	1305.91	225.53	0.00000425	15.3	1
DIMETHYL PHTHALATE	4.522	700.31	51.42	0.0000006111	0.7097	74.13102
DIMETHYLBENZ(A)ANTHRACENE	0	0	0	0.0000086389	0.3377	28680056.33087
DIMETHYLPHENOL(2,4)	0	0	0	0.0000029722	2.2766	263.0268
DINITROBENZENE (-M)	4.337	229.2	-137	0.00000425	29.9146	33.28818
DINITROTOLUENE(2,4)	5.798	1118	61.8	0.00000425	19.5233	102.3293
DIOXANE(1,4)	7.431	1554.68	240.34	0.0000026944	24.7001	16.60956
DIOXIN	12.88	6465.5	273	0.0000029968	6.3412	1
DIPHENYLAMINE	0	0	0	0.0000052778	8.4103	1659.58691
EPICHLOROHYDRIN	8.2294	2086.816	273.16	0.0000029968	6.3412	1.07152
ETHANOL	8.321	1718.21	237.52	0.0000024444	9.7778	0.47863
ETHANOLAMINE(MONO-)	7.456	1577.67	173.37	0.00000425	223.0321	0.16865
ETHYL ACRYLATE	7.9645	1897.011	273.16	0.0000026944	39.4119	4.85667
ETHYL CHLORIDE	6.986	1030.01	238.61	0.0000029889	22.8074	26.91535
ETHYL-(2)PROPYL-(3) ACROLEIN	0	0	0	0.00000425	15.3	1

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
ETHYLACETATE	7.101	1244.95	217.88	0.0000048833	17.58	1
ETHYLBENZENE	6.975	1424.255	213.21	0.0000018889	3.2381	1412.53754
ETHYLENEOXIDE	7.128	1054.54	237.76	0.0000011667	4.6154	0.50003
ETHYLETHER	6.92	1064.07	228.8	0.0000026944	17.1206	43.57596
FORMALDEHYDE	7.195	970.6	244.1	0.0000013889	20	87.09636
FORMIC ACID	7.581	1699.2	260.7	0.0000026944	161.3977	0.1191
FREONS	0	0	0	0.0000029968	6.3412	1
FURAN	6.975	1060.87	227.74	0.0000026944	14.1936	71.37186
FURFURAL	6.575	1198.7	162.8	0.0000026944	18.0602	37.86047
HEPTANE (ISO)	6.8994	1331.53	212.41	0.0000042534	15.3	1453.372
HEXACHLOROBENZENE	0	0	0	0.0000029889	0.6651	295120.92267
HEXACHLOROBUTADIENE	0.824	0	0	0.000003	6.3412	5495.408
HEXACHLOROCYCLOPENTADIENE	0	0	0	0.0000029968	0.3412	9772.372
HEXACHLOROETHANE	0	0	0	0.0000029889	3.3876	4068.32838
HEXANE(-N)	6.876	1171.17	224.41	0.0000042534	15.3	534.0845
HEXANOL(-1)	7.86	1761.26	196.66	0.0000026944	15.2068	59.52851
HYDROCYANIC ACID	7.528	1329.5	260.4	0.0000026944	1.9323	1
HYDROFLUORIC ACID	7.217	1268.37	273.87	0.0000026944	1.9323	1
HYDROGEN SULFIDE	7.614	885.319	250.25	0.0000029889	6.3294	1
ISOPHORONE	0	0	0	0.00000425	25.6067	50.11872

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
METHANOL	7.897	1474.08	229.13	0.000005	90	0.19953
METHYL ACETATE	7.065	1157.63	219.73	0.0000055194	159.2466	0.81283
METHYL CHLORIDE	7.093	948.58	249.34	0.0000029889	14.855	83.17638
METHYL ETHYL KETONE	6.9742	1209.6	216	0.0000005556	10	1.90546
METHYL ISOBUTYL KETONE	6.672	1168.4	191.9	0.0000002056	1.6383	23.98833
METHYL METHACRYLATE	8.409	2050.5	274.4	0.0000026944	109.2342	0.33221
METHYL STYRENE (ALPHA)	6.923	1486.88	202.4	0.000008639	11.12438	2907.589
METHYLENE CHLORIDE	7.409	1325.9	252.6	0.0000061111	54.5762	17.78279
MORPHOLINE	7.7181	1745.8	235	0.00000425	291.9847	0.08318
NAPHTHALENE	7.01	1733.71	201.86	0.0000117972	42.47	1
NITROANILINE(-O)	8.868	336.5	273.16	0.00000425	22.8535	67.6083
NITROBENZENE	7.115	1746.6	201.8	0.0000030556	4.7826	69.1831
PENTACHLOROBENZENE	0	0	0	0.0000029889	0.4307	925887.02902
PENTACHLOROETHANE	6.74	1378	197	0.0000029889	0.4307	925887.02902
PENTACHLOROPHENOL	0	0	0	0.0000361111	38.2353	102329.29923
PHENOL	7.133	1516.79	174.95	0.0000269444	7.4615	28.84032
PHOSGENE	6.842	941.25	230	0.00000425	70.8664	3.4405
PHTHALIC ACID	0	0	0	0.0000026944	34.983	6.64623
PHTHALIC ANHYDRIDE	8.022	2868.5	273.16	0.0000048872	3.9241	0.23988
PICOLINE(-2)	7.032	1415.73	211.63	0.00000425	44.8286	11.48154

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass-s)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
POLYCHLORINATED BIPHENYLS	0	0	0	0.000005278	20	1
PROPANOL (ISO)	8.117	1580.92	219.61	0.0000041667	200	0.69183
PROPIONALDEHYDE	16.2315	2659.02	-44.15	0.0000026944	39.2284	4.91668
PROPYLENE GLYCOL	8.2082	2085.9	203.5396	0.0000026944	109.3574	0.33141
PROPYLENE OXIDE	8.2768	1656.884	273.16	0.0000048872	3.9241	1
PYRIDINE	7.041	1373.8	214.98	0.0000097306	146.9139	4.46684
RESORCINOL	6.9243	1884.547	186.0596	0.0000026944	35.6809	6.30957
STYRENE	7.14	1574.51	224.09	0.0000086389	282.7273	1445.43977
TETRACHLOROETHANE(1,1,1,2)	6.898	1365.88	209.74	0.0000029889	6.3294	1
TETRACHLOROETHANE(1,1,2,2)	6.631	1228.1	179.9	0.0000017222	9.1176	363.07805
TETRACHLOROETHYLENE	6.98	1386.92	217.53	0.0000017222	9.1176	398.10717
TETRAHYDROFURAN	6.995	1202.29	226.25	0.0000026944	20.3702	27.58221
TOLUENE	6.954	1344.8	219.48	0.0000204111	30.6167	489.77882
TOLUENE DIISOCYANATE(2,4)	0	0	0	0.00000425	15.3	1
TRICHLORO(1,1,2)TRIFLUOROETHANE	6.88	1099.9	227.5	0.0000029889	3.3876	4068.32838
TRICHLOROBENZENE(1,2,4)	0	0	0	0.0000029889	2.4495	9549.92586
TRICHLOROBUTANE(1,2,3)	0	0	0	0.0000029968	6.3412	1450901.06626
TRICHLOROETHANE(1,1,1)	8.643	2136.6	302.8	0.0000009722	4.7297	309.02954
TRICHLOROETHANE(1,1,2)	6.951	1314.41	209.2	0.0000009722	4.7297	1

Table 4.3-4 (Part 2) (cont.).

Chemical Name	Antoine's Equation Vapor Pressure Coefficient A	Antoine's Equation Vapor Pressure Coefficient B	Antoine's Equation Vapor Pressure Coefficient C	Maximum Biodegradation Rate Constant (g/g Biomass)	Half Saturation Constant (g/m^3)	Octanol-Water Partition Coefficient At 25°C
TRICHLOROETHYLENE	6.518	1018.6	192.7	0.0000010833	4.4318	194.98446
TRICHLOROFLUOROMETHANE	6.884	1043.004	236.88	0.000003	6.3412	338.8441
TRICHLOROPHENOL(2,4,6)	0	0	0	0.00000425	58.8462	4897.78819
TRICHLOROPROPANE(1,1,1)	0	0	0	0.0000029889	10.7719	193.7827
TRICHLOROPROPANE(1,2,3)	6.903	788.2	243.23	0.0000029889	10.7719	193.7827
UREA	0	0	0	0.00000425	4.8169	4068.32838
VINYL ACETATE	7.21	1296.13	226.66	0.0000026944	31.8363	8.51722
VINYL CHLORIDE	3.425	0	0	0.000003	6.3412	1.14815
VINYLIDENE CHLORIDE	6.972	1099.4	237.2	0.0000029968	6.3412	1
XYLENE(-M)	7.009	1426.266	215.11	0.0000086389	14.0094	1584.89319
XYLENE(-O)	6.998	1474.679	213.69	0.0000113306	22.8569	891.25094

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4. *Industrial Waste Water Volatile Organic Compound Emissions — Background Information For BACT/LAER Determinations*, EPA-450/3-90-004, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1990.

5. Evan K. Nyer, *Ground Water Treatment Technology*, Van Nostrand Reinhold Company, New York, 1985.

4.4 Polyester Resin Plastic Products Fabrication

4.4.1 General Description[1-2]

A growing number of products are fabricated from liquid polyester resin reinforced with glass fibers and extended with various inorganic filler materials such as calcium carbonate, talc, mica, or small glass spheres. These composite materials are often referred to as fiberglass-reinforced plastic (FRP), or simply "fiberglass". The Society Of The Plastics industry designates these materials as "reinforced plastics/composites" (RP/C). Also, advanced reinforced plastics products are now formulated with fibers other than glass, such as carbon, aramid, and aramid/carbon hybrids. In some processes, resin products are fabricated without fibers. One major product using resins with fillers but no reinforcing fibers is the synthetic marble used in manufacturing bathroom countertops, sinks, and related items. Other applications of nonreinforced resin plastics include automobile body filler, bowling balls, and coatings.

Fiber-reinforced plastics products have a wide range of application in industry, transportation, home, and recreation. Industrial uses include storage tanks, skylights, electrical equipment, ducting, pipes, machine components, and corrosion resistant structural and process equipment. In transportation, automobile and aircraft applications are increasing rapidly. Home and recreational items include bathroom tubs and showers, boats (building and repair), surfboards and skis, helmets, swimming pools and hot tubs, and a variety of sporting goods.

The thermosetting polyester resins considered here are complex polymers resulting from the cross-linking reaction of a liquid unsaturated polyester with a vinyl type monomer, list often styrene. The unsaturated polyester is formed from the condensation reaction of an unsaturated dibasic acid or anhydride, a saturated dibasic acid or anhydride, and a polyfunctional alcohol. Table 4.4-1 lists the most common compounds used for each component of the polyester "backbone", as well as the principal cross-linking monomers. The chemical reactions that form both the unsaturated polyester and the cross-linked polyester resin are shown in Figure 4.4-1. The emission factors presented here apply to fabrication processes that use the finished liquid resins (as received by fabricators from chemical manufacturers), and not to the chemical processes used to produce these resins. (See Chapter 6, Organic Chemical Process Industry.)

In order to be used in the fabrication of products, the liquid resin must be mixed with a catalyst to initiate polymerization into a solid thermoset. Catalyst concentrations generally range from 1 to 2 percent by original weight of resin; within certain limits, the higher the catalyst concentration, the faster the cross-linking reaction proceeds. Common catalysts are organic peroxides, typically methyl ethyl ketone peroxide or benzoyl peroxide. Resins may contain inhibitors, to avoid self-curing during resin storage, and promoters, to allow polymerization to occur at lower temperatures.

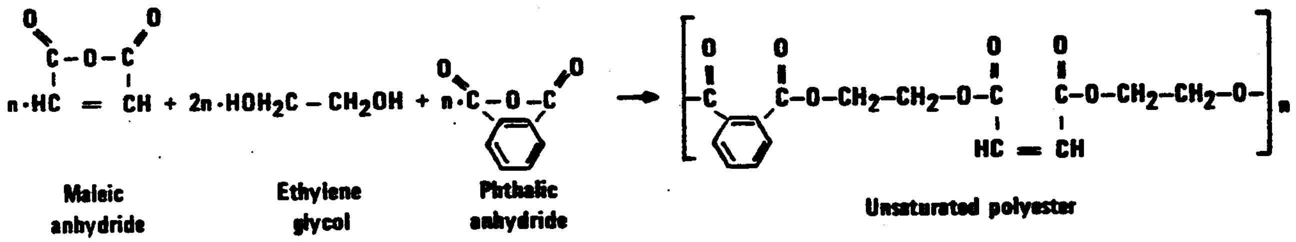
The polyester resin/fiberglass industry consists of many small facilities (such as boat repair and small contract firms) and relatively few large firms that consume the major fraction of the total resin. Resin usage at these operations ranges from less than 5,000 kilograms per year (11,000 pounds) to over 3 million kilograms (6.6 million pounds) per year.

Reinforced plastics products are fabricated using any of several processes, depending on their size, shape, and other desired physical characteristics. The principal processes include hand layup,

Table 4.4-1. TYPICAL COMPONENTS OF RESINS

To Form The Unsaturated Polyester		
Unsaturated Acids	Saturated Acids	Polyfunctional Alcohols
Maleic anhydride Fumaric acid	Phthalic anhydride Isophthalic acid Adipic acid	Propylene glycol Ethylene glycol Diethylene glycol Dipropylene glycol Neopentyl glycol Pentaerythritol
Cross-Linking Agents (Monomers)		
Styrene Methyl methacrylate Vinyl toluene Vinyl acetate Diallyl phthalate Acrylamide 2-Ethyl hexylacrylate		

REACTION 1



REACTION 2

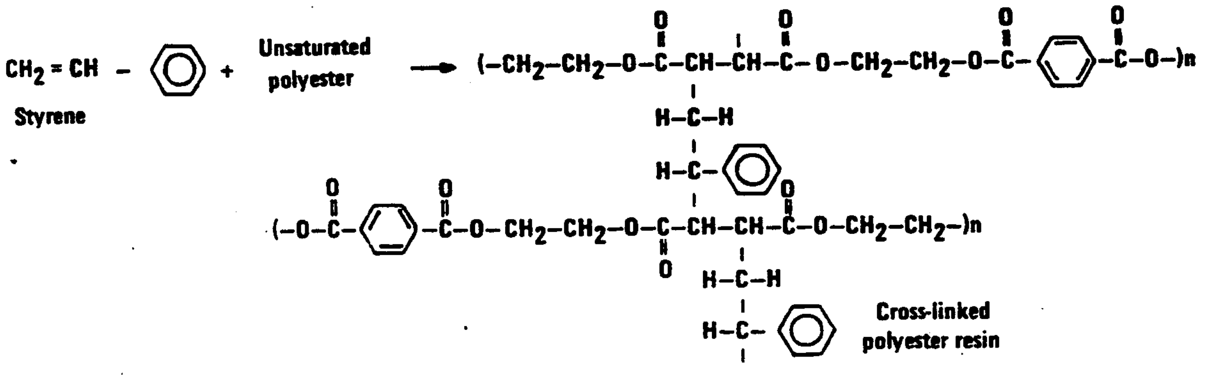


Figure 4.4-1. Typical reactions for unsaturated polyester and polyester resin formation.

spray layup (sprayup), continuous lamination, pultrusion, filament winding, and various closed molding operations.

Hand layup, using primarily manual techniques combined with open molds, is the simplest of the fabrication processes. Here, the reinforcement is manually fitted to a mold wetted with catalyzed resin mix, after which it is saturated with more resin. The reinforcement is in the form of either a chopped strand mat, a woven fabric, or often both. Layers of reinforcement and resin are added to build the desired laminate thickness. Squeegees, brushes, and rollers are used to smooth and compact each layer as it is applied. A release agent is usually first applied to the mold to facilitate removal of the composite. This is often a wax, which can be treated with a water soluble barrier coat such as polyvinyl alcohol to promote paint adhesion on parts that are to be painted. In many operations, the mold is first sprayed with gel coat, a clear or pigmented resin mix that forms the smooth outer surface of many products. Gel coat spray systems consist of separate sources of resin and catalyst, with an airless hand spray gun that mixes them together into an atomized resin/catalyst stream. Typical products are boat hulls and decks, swimming pools, bathtubs and showers, electrical consoles, and automobile components.

Spray layup, or "sprayup", is another open mold process, differing from hand layup in that it uses mechanical spraying and chopping equipment for depositing the resin and glass reinforcement. This process allows a greater production rate and more uniform parts than does hand layup, and often uses more complex molds. As in hand layup, gel coat is frequently applied to the mold before fabrication to produce the desired surface qualities. It is common practice to combine hand layup and sprayup operations.

For the reinforced layers, a device is attached to the sprayer system to chop glass fiber "roving" (uncut fiber) into predetermined lengths and project it to merge with the resin mix stream. The stream precoats the chop, and both are deposited simultaneously to the desired layer thickness on the mold surface (or on the gel coat that was applied to the mold). Layers are built up and rolled out on the mold as necessary to form the part. Products manufactured by sprayup are similar to those made by hand layup, except that more uniform and complex parts can generally be produced more efficiently with sprayup techniques. However, compared to hand layup, more resin generally is used to produce similar parts by spray layup because of the inevitable overspray of resin during application.

Continuous lamination of reinforced plastics materials involves impregnating various reinforcements with resins on an in-line conveyor. The resulting laminate is cured and trimmed as it passes through the various conveyor zones. In this process, the resin mix is metered onto a bottom carrier film, using a blade to control thickness. This film, which defines the panel's surface, is generally polyester, cellophane, or nylon and may have a smooth, embossed, or matte surface. Methyl methacrylate is sometimes used as the cross-linking agent, either alone or in combination with styrene, to increase strength and weather resistance. Chopped glass fibers free-fall into the resin mix and are allowed to saturate with resin, or "wet out". A second carrier film is applied on top of the panel before subsequent forming and curing. The cured panel is then stripped of its films, trimmed, and cut to the desired length. Principal products include translucent industrial skylights and greenhouse panels, wall and ceiling liners for food areas, garage doors, and cooling tower louvers. Figure 4.4-2 shows the basic elements of a continuous laminating production line.

Pultrusion, which can be thought of as extrusion by pulling, is used to produce continuous cross-sectional lineals similar to those made by extruding metals such as aluminum. Reinforcing fibers are pulled through a liquid resin mix bath and into a long machined steel die, where heat initiates an exothermic reaction to polymerize the thermosetting resin matrix. The composite profile

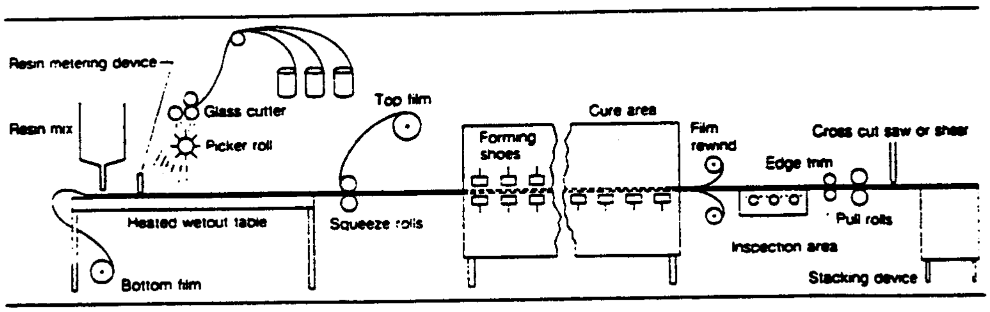


Figure 4.4-2. Typical continuous lamination production process.[2]

emerges from the die as a hot, constant cross-sectional that cools sufficiently to be fed into a clamping and pulling mechanism. The product can then be cut to desired lengths. Example products include electrical insulation materials, ladders, walkway gratings, structural supports, and rods and antennas.

Filament winding is the process of laying a band of resin impregnated fibers onto a rotating mandrel surface in a precise geometric pattern, and curing them to form the product. This is an efficient method of producing cylindrical parts with optimum strength characteristics suited to the specific design and application. Glass fiber is most often used for the filament, but aramid, graphite, and sometimes boron and various metal wires may be used. The filament can be wetted during fabrication, or previously impregnated filament ("prepreg") can be used. Figure 4.4-3 shows the filament winding process, and indicates the 3 most common winding patterns. The process illustration depicts circumferential winding, while the 2 smaller pictures show helical and polar winding. The various winding patterns can be used alone or in combination to achieve the desired strength and shape characteristics. Mandrels are made of a wide variety of materials and, in some applications, remain inside the finished product as a liner or core. Example products are storage tanks, fuselages, wind turbine and helicopter blades, and tubing and pipe.

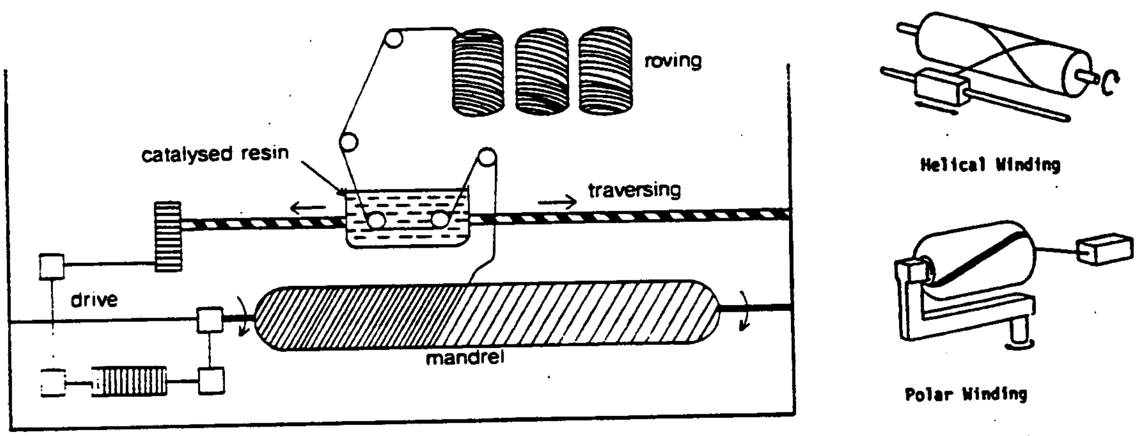


Figure 4.4-3. Typical filament winding process.[3]

Closed, such as compression or injection, molding operations involve the use of 2 matched dies to define the entire outer surface of the part. When closed and filled with a resin mix, the matched die mold is subjected to heat and pressure to cure the plastic. For the most durable production configuration, hardened metal dies are used (matched metal molding). Another closed molding process is vacuum or pressure bag molding. In bag molding, a hand layup or sprayup is covered with a plastic film, and vacuum or pressure is applied to rigidly define the part and improve surface quality. The range of closed molded parts includes tool and appliance housings, cookware, brackets and other small parts, and automobile body and electrical components.

Synthetic marble casting, a large segment of the resin products industry, involves production of bathroom sinks, vanity tops, bathtubs, and accessories using filled resins that have the look of natural marble. No reinforcing fibers are used in these products. Pigmented or clear gel coat can either be applied to the mold itself or sprayed onto the product after casting to simulate the look of natural polished marble. Marble casting can be an open mold process, or it may be considered a semiclosed process if cast parts are removed from a closed mold for subsequent gel coat spraying.

4.4.2 Emissions And Controls

Organic vapors consisting of volatile organic compounds (VOC) are emitted from fresh resin surfaces during the fabrication process, and from the use of solvents (usually acetone) for cleanup of hands, tools, molds, and spraying equipment. Cleaning solvent emissions can account for over 36 percent of the total plant VOC emissions.[4] There also may be some release of particulate emissions from automatic fiber chopping equipment, but these emissions have not been quantified.

Organic vapor emissions from polyester resin/fiberglass fabrication processes occur when the cross-linking agent (anomer) contained in the liquid resin evaporates into the air during resin application and curing. Styrene, methyl methacrylate, and vinyl toluene are 3 of the principal monomers used as cross-linking agents. Styrene is by far the most common. Other chemical components of resins are emitted only at trace levels because they not only have low vapor pressures, but also are substantially converted to polymers.[5-6]

Since emissions result from evaporation of monomer from the uncured resin, they depend upon the amount of resin surface exposed to the air and the time of exposure. Thus, the potential for emissions varies with the manner in which the resin is mixed, applied, handled, and cured. These factors vary among the different fabrication processes. For example, the spray layup process has the highest potential for VOC emissions because the atomization of resin into a spray creates an extremely large surface area from which volatile monomer can evaporate. By contrast, the emission potential in synthetic marble casting and closed molding operations is considerably lower because of the lower anomer content in the casting resins (30 to 38 percent, versus about 43 percent) and the enclosed nature of these molding operations. It has been found that styrene evaporation increases with increasing gel time, wind speed, and ambient temperature, and that increasing the hand rolling time on a hand layup or sprayup results in significantly higher styrene losses.[1] Thus, production changes that lessen the exposure of fresh resin surfaces to the air should be effective in reducing these evaporation losses.

In addition to production changes, resin formulation can be varied to affect the VOC emission potential. In general, a resin with lower monomer content should produce lower emissions. Evaluation tests with low-styrene emission laminating resins having a 36-percent styrene content found a 60- to 70-percent decrease in emission levels, compared to conventional resins (43 percent styrene), with no sacrifice in the physical properties of the laminate.[7] Vapor suppressing agents also are sometimes added to resins to reduce VOC emissions. Most vapor suppressants are paraffin waxes, stearates, or polymers of proprietary composition, constituting up to several weight percent of the mix. Limited laboratory and field data indicate that vapor suppressing resins reduce styrene losses by 30 to 70 percent.[7-8]

Emission factors for several fabrication processes using styrene content resins have been developed from the results of facility source tests (B Rating) and laboratory tests (C Rating), and through technology transfer estimations (D Rating).[1] Industry experts also provided additional information that was used to arrive at the final factors presented in Table 4.4-2.[6] Since the styrene content varies over a range of approximately 30 to 50 weight percent, these factors are based on the quantity of styrene monomer used in the process, rather than on the total amount of resin used. The factors for vapor-suppressed resins are typically 30 to 70 percent of those for regular resins. The factors are expressed as ranges because of the observed variability in source and laboratory test results and of the apparent sensitivity of emissions to process parameters.

Emissions should be calculated using actual resin monomer contents. When specific information about the percentage of styrene is unavailable, the representative average values in Table 4.4-3 should be used. The sample calculation illustrates the application of the emission factors.

Sample Calculation -

A fiberglass boat building facility consumes an average of 250 kg per day of styrene-containing resins using a combination of hand layup (75%) and spray layup (25%) techniques. The laminating resins for hand and spray layup contain 41.0 and 42.5 weight percent, respectively, of styrene. The resin used for hand layup contains a vapor-suppressing agent.

From Table 4.4-2 the weight percent of monomer emitted for hand layup using a vapor-suppressed resin is 2 - 7 (0.02 to 0.07 fraction of total styrene emitted); the factor for spray layup is 9 - 13 (0.09 to 0.13 fraction emitted). Assume the midpoints of these emission factor ranges (0.045 and 0.11, respectively).

Total VOC emissions are:

$$(250 \text{ kg/day}) [(0.75)(0.410)(0.045) + (0.25)(0.425)(0.11)] = 6.4 \text{ kg/day}.$$

Emissions from use of gel coat would be calculated in the same manner. If the monomer content of the resins were unknown, a representative value of 43 percent could be selected from Table 4.4-3 for this process combination. It should be noted that these emissions represent evaporation of styrene monomer only, and not of acetone or other solvents used for cleanup.

In addition to process changes and materials substitution, add-on control equipment can be used to reduce vapor emissions from styrene resins. However, control equipment is infrequently used at RP/C fabrication facilities, due to low exhaust VOC concentrations and the potential for contamination of adsorbent materials. Most plants use forced ventilation techniques to reduce worker exposure to styrene vapors, but vent the vapors directly to the atmosphere with no attempt at collection. At 1 continuous lamination facility where incineration was applied to vapors vented from the impregnation table, a 98.6 percent control efficiency was measured.[1] Carbon adsorption, absorption, and condensation have also been considered for recovering styrene and other organic vapors, but these techniques have not been applied to any significant extent in this industry.

Emissions from cleanup solvents can be controlled through good housekeeping and use practices, reclamation of spent solvent, and substitution with water-based solvent substitutes.

Table 4.4-2. EMISSION FACTORS FOR UNCONTROLLED POLYESTER RESIN PRODUCT FABRICATION PROCESSES[a]

(weight % of starting monomer emitted)

Process	Resin		EMISSION FACTOR RATING	Gel Coat		EMISSION FACTOR RATING
	NVS	VS[b]		NVS	VS[b]	
Hand layup	5 - 10	2 - 7	C	26 - 35	8 - 25	D
Spray layup	9 - 13	3 - 9	B	26 - 35	8 - 25	B
Continuous lamination	4 - 7	1 - 5	B	—[c]	—[c]	—
Pultrusion[d]	4 - 7	1 - 5	D	—[c]	—[c]	—
Filament winding[e]	5 - 10	2 - 7	D	—[c]	—[c]	—
Marble casting	1 - 3	1 - 2	B	—[f]	—[f]	—
Closed molding[g]	1 - 3	1 - 2	D	—[c]	—[c]	—

[a] Reference 9. Ranges represent the variability of processes and sensitivity of emissions to process parameters. Single value factors should be selected with caution. NVS = nonvapor-suppressed resin. VS = vapor-suppressed resin.

[b] Factors are 30 - 70% of those for nonvapor-suppressed resins.

[c] Gel coat is not normally used in this process.

[d] Resin factors for the continuous lamination process are assumed to apply.

[e] Resin factors for the hand layup process are assumed to apply.

[f] Factors unavailable. However, when cast parts are subsequently sprayed with gel coat, hand and spray layup gel coat factors are assumed to apply.

[g] Resin factors for marble casting, a semiclosed process, are assumed to apply.

Table 4.4-3. TYPICAL RESIN STYRENE PERCENTAGES

Resin Application	Resin Styrene Content[a] (wt. %)
Hand layup	43
Spray layup	43
Continuous lamination	40
Filament winding	40
Marble casting	32
Closed molding	35
Gel coat	35

[a] May vary by at least ±5 percentage points.

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4.5 Asphalt Paving Operations

4.5.1 General[1-3]

Asphalt surfaces and pavements are composed of compacted aggregate and an asphalt binder. Aggregate materials are produced from rock quarries as manufactured stone or are obtained from natural gravel or soil deposits. Metal ore refining processes produce artificial aggregates as a byproduct. In asphalt, the aggregate performs 3 functions: it transmits the load from the surface to the base course, takes the abrasive wear of traffic, and provides a nonskid surface. The asphalt binder holds the aggregate together, preventing displacement and loss of aggregate and providing a waterproof cover for the base.

Asphalt binders take the form of asphalt cement (the residue of the distillation of crude oils), and liquified asphalts. To be used for pavement, asphalt cement, which is semisolid, must be heated prior to mixing with aggregate. The resulting hot mix asphalt concrete is generally applied in thicknesses of from 5 to 15 centimeters (2 to 6 inches). Liquified asphalts are: (1) asphalt cutbacks (asphalt cement thinned or "cutback" with volatile petroleum distillates such as naptha, kerosene, etc.) and (2) asphalt emulsions (nonflammable liquids produced by combining asphalt and water with an emulsifying agent, such as soap). Liquified asphalts are used in tack and seal operations, in priming roadbeds for hot mix application, and for paving operations up to several inches thick.

Cutback asphalts fall into 3 broad categories: rapid cure (RC), medium cure (MC), and slow cure (SC) road oils. SC, MC, and RC cutbacks are prepared by blending asphalt cement with heavy residual oils, kerosene-type solvents, or naptha and gasoline solvents, respectively. Depending on the viscosity desired, the proportions of solvent added generally range from 25 to 45 percent by volume.

Emulsified asphalts are of 2 basic types: 1 type relies on water evaporation to cure, the other type (cationic emulsions) relies on ionic bonding of the emulsion and the aggregate surface. Emulsified asphalt can substitute for cutback in almost any application. Emulsified asphalts are gaining in popularity because of the energy and environmental problems associated with the use of cutback asphalts.

4.5.2 Emissions[1,2]

The primary pollutants of concern from asphalts and asphalt paving operations are volatile organic compounds (VOC). Of the 3 types of asphalts, the major source of VOC is cutback. Only minor amounts of VOCs are emitted from emulsified asphalts and asphalt cement.

VOC emissions from cutback asphalts result from the evaporation of the petroleum distillate solvent, or diluent, used to liquify the asphalt cement. Emissions occur at both the job site and the mixing plant. At the job site, VOCs are emitted from the equipment used to apply the asphaltic product and from the road surface. At the mixing plant, VOCs are released during mixing and stockpiling. The largest source of emissions, however, is the road surface itself.

For any given amount of cutback asphalt, total emissions are believed to be the same, regardless of stockpiling, mixing, and application times. The 2 major variables affecting both the quantity of VOCs emitted and the time over which emissions occur are the type and the quantity of petroleum distillate used as a diluent. As an approximation, long-term emissions from cutback asphalts can be estimated by assuming that 95 percent of the diluent evaporates from rapid cure (RC) cutback asphalts, 70 percent from MC cutbacks, and about 25 percent from SC asphalts, by weight percent. Some of the diluent appears to be retained permanently in the road surface after application. Limited test data suggest that from RC asphalt, 75 percent of the total diluent loss occurs on the first day after application, 90 percent occurs within the first month, and 95 percent in 3 to 4 months. Evaporation takes place more slowly from MC asphalts, with roughly 20 percent of the diluent being emitted during the first day, 50 percent during the first week, and 70 percent after 3 to 4 months. No measured data are available for SC asphalts, although the quantity emitted is believed to be considerably less than with either RC or MC asphalts, and the time during which emissions take place is expected to be considerably longer (Figure 4.5-1). An example calculation for determining VOC emissions from cutback asphalts is given below:

Example: Local records indicate that 10,000 kg of RC cutback asphalt (containing 45 percent diluent, by volume) was applied in a given area during the year. Calculate the mass of VOC emitted during the year from this application.

To determine VOC emissions, the volume of diluent present in the cutback asphalt must first be determined. Because the density of naptha (0.7 kg/L) differs from that of asphalt cement (1.1 kg/L), the following equations should be solved to determine the volume of diluent (x) and the volume of asphalt cement (y) in the cutback asphalt:

$$10{,}000 \text{ kg cutback asphalt} = (x \text{ liter, diluent}) \cdot \left[\frac{0.7 \text{ kg}}{\text{liter}}\right] + (y \text{ liter, asphalt cement}) \cdot \left[\frac{1.1 \text{ kg}}{\text{liter}}\right]$$

and

$$x \text{ liter, diluent} = 0.45\,(x \text{ liter, diluent} + y \text{ liter, asphalt cement})$$

From these equations, the volume of diluent present in the cutback asphalt is determined to be about 4900 liters, or about 3400 kg. Assuming that 95 percent of this is evaporative VOC, emissions are then: 3400 kg x 0.95 = 3200 kg (i. e., 32%, by weight, of the cutback asphalt eventually evaporates).

These equations can be used for medium cure and slow cure asphalts by assuming typical diluent densities of 0.8 and 0.9 kg/liter, respectively. Of course, if actual density values are known from local records, they should be used in the above equations rather than typical values. Also, if different diluent contents are used, they should also be reflected in the above calculations. If actual diluent contents are not known, a typical value of 35 percent may be assumed for inventory purposes.

In lieu of solving the equations in the above example, Table 4.5-1 may be used to estimate long-term emissions from cutback asphalts. Table 4.5-1 directly yields long-term emissions as a function of the volume of diluent added to the cutback and of the density of the diluents and asphalt cement used in the cutback asphalt. If short-term emissions are to be estimated, Figure 4.5-1 should be used in conjunction with Table 4.5-1.

No control devices are employed to reduce evaporative emissions from cutback asphalts. Asphalt emulsions are typically used in place of cutback asphalts to eliminate VOC emissions.

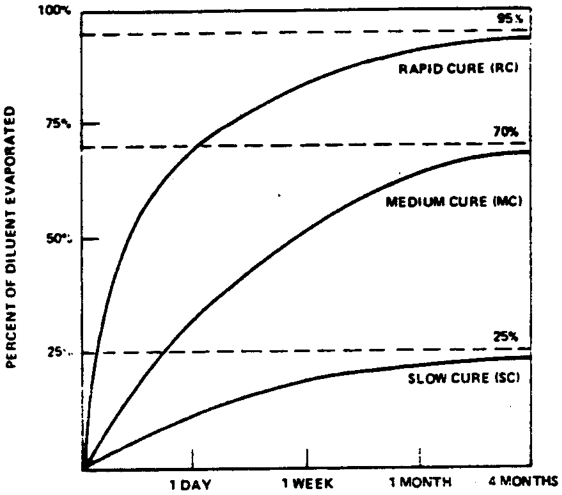

Figure 4.5-1. Percent of diluent evaporated from cutback asphalt over time.

Table 4.5-1. EVAPORATIVE VOC EMISSIONS FROM CUTBACK ASPHALTS AS A FUNCTION OF DILUENT CONTENT AND CUTBACK ASPHALT TYPE[a]

EMISSION FACTOR RATING: C

Type Of Cutback[b]	Percent, By Volume, Of Diluent In Cutback[c]		
	25%	35%	45%
Rapid cure	17	24	32
Medium cure	14	20	26
Slow cure	5	8	10

[a] These numbers represent the percent, by weight, of cutback asphalt evaporated. Factors are based on References 1-2.

[b] Typical densities assumed for diluents used in RC, MC, and SC cutbacks are 0.7, 0.8, and 0.9 kg/liter, respectively.

[c] Diluent contents typically range between 25 - 45%, by volume. Emissions may be linearly interpolated for any given type of cutback between these values.

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4.6 Solvent Degreasing

4.6.1 General[1,2]

Solvent degreasing (or solvent cleaning) is the physical process of using organic solvents to remove grease, fats, oils, wax or soil from various metal, glass, or plastic items. The types of equipment used in this method are categorized as cold cleaners, open top vapor degreasers, or conveyorized degreasers. Nonaqueous solvents such as petroleum distillates, chlorinated hydrocarbons, ketones, and alcohols are used. Solvent selection is based on the solubility of the substance to be removed and on the toxicity, flammability, flash point, evaporation rate, boiling point, cost, and several other properties of the solvent.

The metalworking industries are the major users of solvent degreasing, i. e., automotive, electronics, plumbing, aircraft, refrigeration, and business machine industries. Solvent cleaning is also used in industries such as printing, chemicals, plastics, rubber, textiles, glass, paper, and electric power. Most repair stations for transportation vehicles and electric tools use solvent cleaning at least part of the time. Many industries use water-based alkaline wash systems for degreasing, and since these systems emit no solvent vapors to the atmosphere, they are not included in this discussion.

4.6.1.1 Cold Cleaners -

The 2 basic types of cold cleaners are maintenance and manufacturing. Cold cleaners are batch loaded, nonboiling solvent degreasers, usually providing the simplest and least expensive method of metal cleaning. Maintenance cold cleaners are smaller, more numerous, and generally use petroleum solvents as mineral spirits (petroleum distillates and Stoddard solvents). Manufacturing cold cleaners use a wide variety of solvents, which perform more specialized and higher quality cleaning with about twice the average emission rate of maintenance cold cleaners. Some cold cleaners can serve both purposes.

Cold cleaner operations include spraying, brushing, flushing, and immersion. In a typical maintenance cleaner (Figure 4.6-1), dirty parts are cleaned manually by spraying and then soaking in the tank. After cleaning, the parts are either suspended over the tank to drain or are placed on an external rack that routes the drained solvent back into the cleaner. The cover is intended to be closed whenever parts are not being handled in the cleaner. Typical manufacturing cold cleaners vary widely in design, but there are 2 basic tank designs: the simple spray sink and the dip tank. Of these, the dip tank provides more thorough cleaning through immersion, and often is made to improve cleaning efficiency by agitation. Small cold cleaning operations may be numerous in urban areas. However, because of the small quantity of emissions from each operation, the large number of individual sources within an urban area, and the application of small cold cleaning to industrial uses not directly associated with degreasing, it is difficult to identify individual small cold cleaning operations. For these reasons, factors are provided in Table 4.6-1 to estimate emissions from small cold cleaning operations over large urban geographical areas. Factors in Table 4.6-1 are for nonmethane VOC and include 25 percent 1,1,1 trichloroethane, methylene chloride, and trichlorotrifluoroethane.

4.6.1.2 Open-Top Vapor Systems -

Open-top vapor degreasers are batch loaded boiling degreasers that clean with condensation of hot solvent vapor on colder metal parts. Vapor degreasing uses halogenated solvents (usually

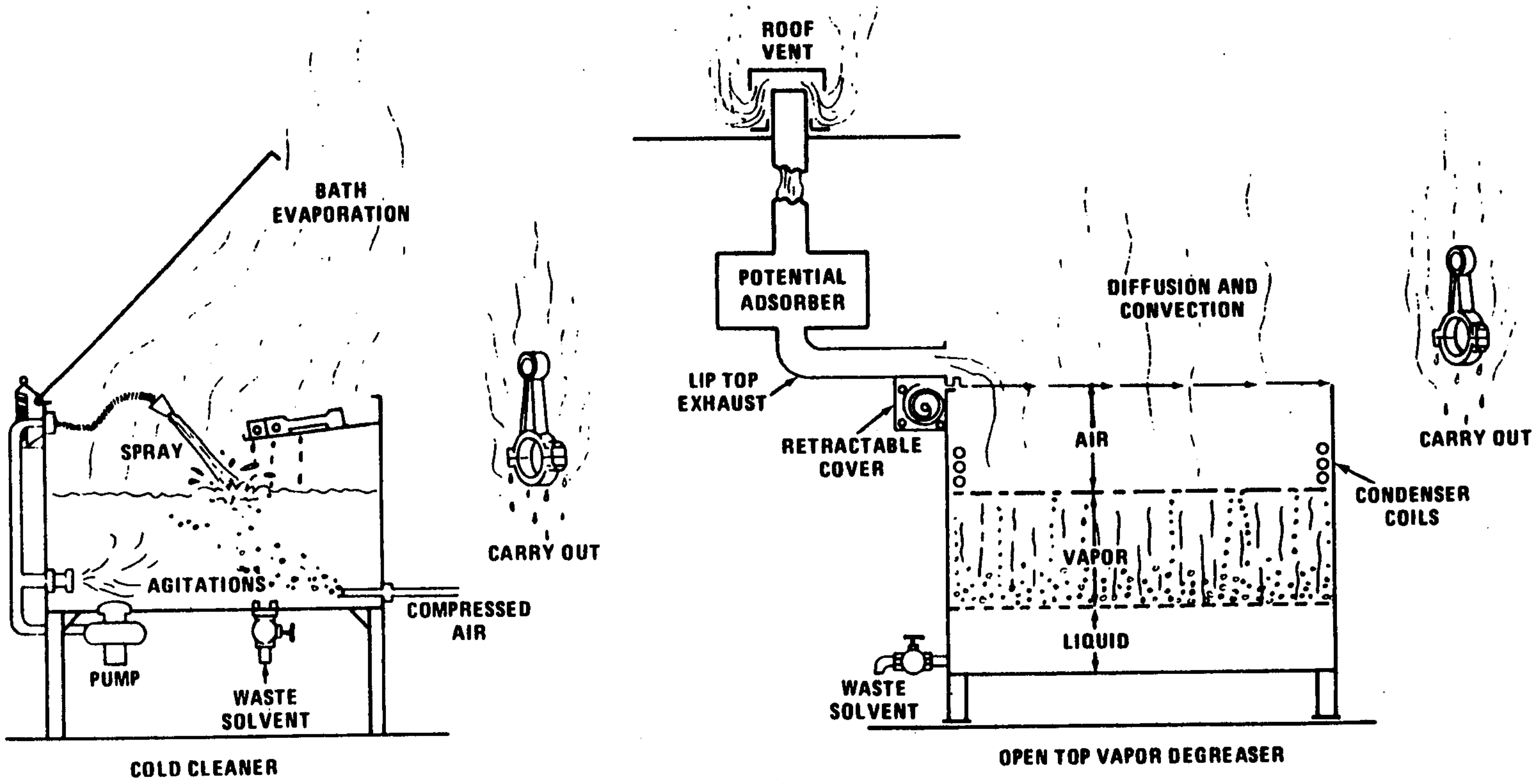

Figure 4.6-1. Degreaser emissions points.

Table 4.6-1 (Metric And English Units). NONMETHANE VOC EMISSIONS FROM SMALL COLD CLEANING DEGREASING OPERATIONS[a]

EMISSION FACTOR RATING: C

Operating Period	Per Capita Emission Factor
Annual	1.8 kg 4.0 lb
Daily[b]	5.8 g 0.013 lb

[a] Reference 3.
[b] Assumes a 6-day operating week (313 days/yr).

perchloroethylene, trichloroethylene, or 1,1,1-trichloroethane), because they are not flammable and their vapors are much heavier than air.

A typical vapor degreaser (Figure 4.6-1) is a sump containing a heater that boils the solvent to generate vapors. The height of these pure vapors is controlled by condenser coils and/or a water jacket encircling the device. Solvent and moisture condensed on the coils are directed to a water separator, where the heavier solvent is drawn off the bottom and is returned to the vapor degreaser. A "freeboard" extends above the top of the vapor zone to minimize vapor escape. Parts to be cleaned are immersed in the vapor zone, and condensation continues until they are heated to the vapor temperature. Residual liquid solvent on the parts rapidly evaporates as they are slowly removed from the vapor zone. Lip mounted exhaust systems carry solvent vapors away from operating personnel. Cleaning action is often increased by spraying the parts with solvent below the vapor level or by immersing them in the liquid solvent bath. Nearly all vapor degreasers are equipped with a water separator which allows the solvent to flow back into the degreaser.

Emission rates are usually estimated from solvent consumption data for the particular degreasing operation under consideration. Solvents are often purchased specifically for use in degreasing and are not used in any other plant operations. In these cases, purchase records provide the necessary information, and an emission factor of 1000 kg of volatile organic emissions per Mg (2000 lb/ton) of solvent purchased can be applied, based on the assumption that all solvent purchased is eventually emitted. When information on solvent consumption is not available, emission rates can be estimated if the number and type of degreasing units are known. The factors in Table 4.6-2 are based on the number of degreasers and emissions produced nationwide and may be considerably in error when applied to a particular unit.

The expected effectiveness of various control devices and procedures is listed in Table 4.6-3. As a first approximation, this efficiency can be applied without regard for the specific solvent being used. However, efficiencies are generally higher for more volatile solvents. These solvents also result in higher emission rates than those computed from the "average" factors listed in Table 4.6-2.

4.6.1.3 Conveyorized Degreasers -

Conveyorized degreasers may operate with either cold or vaporized solvent, but they merit separate consideration because they are continuously loaded and are almost always hooded or enclosed. About 85 percent are vapor types, and 15 percent are nonboiling.

Table 4.6-2 (Metric And English Units). SOLVENT LOSS EMISSION FACTORS FOR DEGREASING OPERATIONS

EMISSION FACTOR RATING: C

Type Of Degreasing	Activity Measure	Uncontrolled Organic Emission Factor[a]	
All[b]	Solvent consumed	1,000 kg/Mg	2,000 lb/ton
Cold cleaner			
Entire unit[c]	Units in operation	0.30 Mg/yr/unit	0.33 tons/yr/unit
Waste solvent loss		0.165 Mg/yr/unit	0.18 tons/yr/unit
Solvent carryout		0.075 Mg/yr/unit	0.08 tons/yr/unit
Bath and spray evaporation		0.06 Mg/yr/unit	0.07 tons/yr/unit
Entire unit	Surface area and duty cycle[d]	0.4 $kg/hr/m^2$	0.08 $lb/hr/ft^2$
Open top vapor			
Entire unit	Units in operation	9.5 Mg/yr/unit	10.5 ton/yr/unit
Entire unit	Surface area and duty cycle[e]	0.7 $kg/hr/m^2$	0.15 $lb/hr/ft^2$
Conveyorized, vapor			
Entire unit	Units in operation	24 Mg/yr/unit	26 tons/yr/unit
Conveyorized, nonboiling			
Entire unit	Units in operation	47 Mg/yr/unit	52 tons/yr/unit

[a] 100% Nonmethane VOC.

[b] Solvent consumption data will provide much more accurate emission estimates than any of the other factors presented.

[c] Emissions generally would be higher for manufacturing units and lower for maintenance units.

[d] Reference 4, Appendix C-6. For trichloroethane degreaser.

[e] For trichloroethane degreaser. Does not include waste solvent losses.

4.6.2 Emissions And Controls[1-3]

Emissions from cold cleaners occur through: (1) waste solvent evaporation, (2) solvent carryout (evaporation from wet parts), (3) solvent bath evaporation, (4) spray evaporation, and (5) agitation (Figure 4.6-1). Waste solvent loss, cold cleaning's greatest emission source, can be reduced through distillation and transport of waste solvent to special incineration plants. Draining cleaned parts for at least 15 seconds reduces carryout emissions. Bath evaporation can be controlled by using a cover regularly, by allowing an adequate freeboard height, and by avoiding excessive drafts in the workshop. If the solvent used is insoluble in and heavier than water, a layer of water 5 to 10 centimeters (2 to 4 inches) thick covering the solvent can also reduce bath evaporation. This is known as a "water cover". Spraying at low pressure also helps to reduce solvent loss from this part of the process. Agitation emissions can be controlled by using a cover, by agitating no longer than necessary, and by avoiding the use of agitation with low volatility solvents. Emissions of low volatility solvents increase significantly with agitation. However, contrary to what one might expect, agitation causes only a small increase in emissions of high volatility solvents. Solvent type is the variable that most affects cold cleaner emission rates, particularly the volatility at operating temperatures.

Table 4.6-3. PROJECTED EMISSION REDUCTION FACTORS FOR SOLVENT DEGREASING[a]

System	Cold Cleaner		Vapor Degreaser		Conveyorized Degreaser	
	A	B	A	B	A	B
Control devices						
Cover or enclosed design	X	X	X	X	X	X
Drainage facility	X	X	X			X
Water cover, refrigerated chiller, carbon adsorption or high freeboard[b]		X		X		X
Solid, fluid spray stream[c]		X		X		
Safety switches and thermostats				X		X
Emission reduction from control devices (%)	13-38	NA[d]	20-40	30-60		40-60
Operating procedures						
Proper use of equipment	X	X	X	X	X	X
Waste solvent reclamation	X	X	X	X	X	X
Reduced exhaust ventilation			X	X	X	X
Reduced conveyor or entry speed			X	X	X	X
Emission reduction from operating procedures (%)	15-45	NA[d]	15-35	20-40	20-30	20-30
Total emission reduction (%)	28-83[e]	55-69[f]	30-60	45-75	20-30	50-70

[a] Reference 2. Ranges of emission reduction present poor to excellent compliance. X indicates devices or procedures that will produce the given reductions. Letters A and B indicate different control device circumstances. See Appendix B of Reference 2.

[b] Only one of these major control devices would be used in any degreasing system. Cold cleaner system B could employ any of them. Vapor degreaser system B could employ any except water cover. Conveyorized degreaser system B could employ any except water cover and high freeboard.

[c] If agitation by spraying is used, the spray should not be a shower type.

[d] Breakout between control equipment and operating procedures is not available.

[e] A manual or mechanically assisted cover would contribute 6 - 18% reduction; draining parts 15 seconds within the degreaser, 7 - 20%; and storing waste solvent in containers, an additional 15 - 45%.

[f] Percentages represent average compliance.

As with cold cleaning, open top vapor degreasing emissions relate heavily to proper operating methods. Most emissions are due to (6) diffusion and convection, which can be reduced by using an automated cover, by using a manual cover regularly, by spraying below the vapor level, by optimizing work loads, or by using a refrigerated freeboard chiller (for which a carbon adsorption unit would be substituted on larger units). Safety switches and thermostats that prevent emissions during malfunctions and abnormal operation also reduce diffusion and convection of the vaporized solvent. Additional sources of emissions are solvent carryout, exhaust systems, and waste solvent evaporation. Carryout is directly affected by the size and shape of the workload, by racking of parts, and by cleaning and drying time. Exhaust emissions can be nearly eliminated by a carbon adsorber that collects the solvent vapors for reuse. Waste solvent evaporation is not so much a problem with vapor degreasers as it is with cold cleaners, because the halogenated solvents used are often distilled and recycled by solvent recovery systems.

Because of their large workload capacity and the fact that they are usually enclosed, conveyorized degreasers emit less solvent per part cleaned than do either of the other 2 types of degreaser. More so than operating practices, design and adjustment are major factors affecting emissions, the main source of which is carryout of vapor and liquid solvents.

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4.7 Waste Solvent Reclamation

4.7.1 Process Description[1-4]

Waste solvents are organic dissolving agents that are contaminated with suspended and dissolved solids, organics, water, other solvents, and/or any substance not added to the solvent during its manufacture. Reclamation is the process of restoring a waste solvent to a condition that permits its reuse, either for its original purpose or for other industrial needs. All waste solvent is not reclaimed, because the cost of reclamation may exceed the value of the recovered solvent.

Industries that produce waste solvents include solvent refining, polymerization processes, vegetable oil extraction, metallurgical operations, pharmaceutical manufacture, surface coating, and cleaning operations (dry cleaning and solvent degreasing). The amount of solvent recovered from the waste varies from about 40 to 99 percent, depending on the extent and characterization of the contamination and on the recovery process employed.

Design parameters and economic factors determine whether solvent reclamation is accomplished as a main process by a private contractor, as an integral part of a main process (such as solvent refining), or as an added process (as in the surface coating and cleaning industries). Most contract solvent reprocessing operations recover halogenated hydrocarbons (e. g., methylene chloride, trichlorotrifluoroethane, and trichloroethylene) from degreasing, and/or aliphatic, aromatic, and naphthenic solvents such as those used in the paint and coatings industry. They may also reclaim small quantities of numerous specialty solvents such as phenols, nitriles, and oils.

The general reclamation scheme for solvent reuse is illustrated in Figure 4.7-1. Industrial operations may not incorporate all of these steps. For instance, initial treatment is necessary only when liquid waste solvents contain dissolved contaminants.

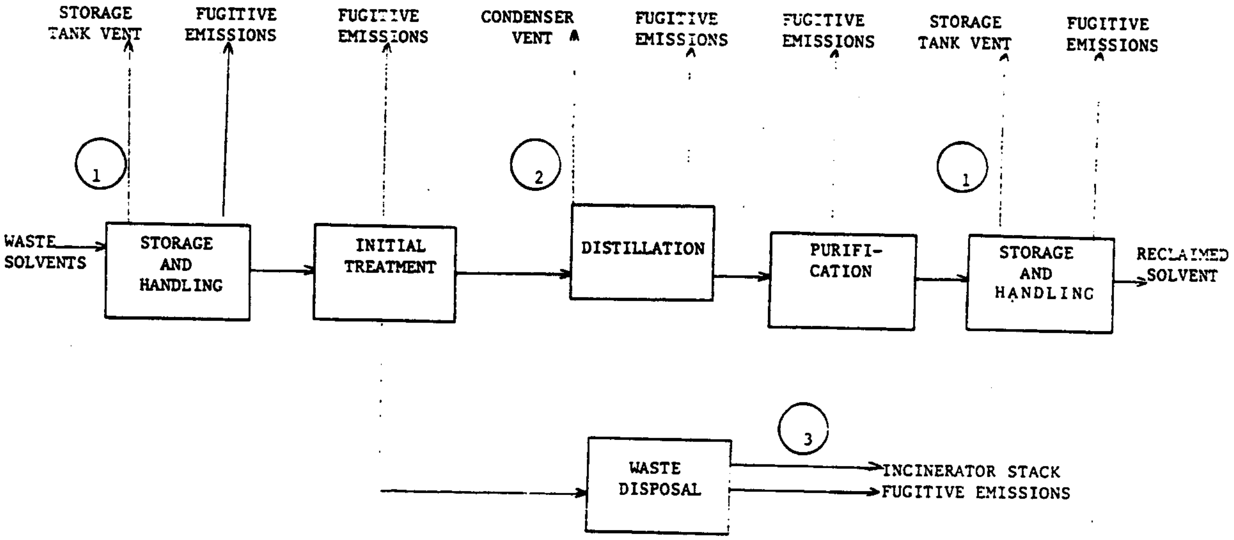

Figure 4.7-1. General waste solvent reclamation scheme and emission points.[1]

4.7.1.1 Solvent Storage And Handling -

Solvents are stored before and after reclamation in containers ranging in size from 0.2-m^3 (55-gallon) drums to tanks with capacities of 75 m^3 (20,000 gallons) or more. Storage tanks are of fixed or floating roof design. Venting systems prevent solvent vapors from creating excessive pressure or vacuum inside fixed roof tanks.

Handling includes loading waste solvent into process equipment and filling drums and tanks prior to transport and storage. The filling is most often done through submerged or bottom loading.

4.7.1.2 Initial Treatment -

Waste solvents are initially treated by vapor recovery or mechanical separation. Vapor recovery entails removal of solvent vapors from a gas stream in preparation for further reclaiming operations. In mechanical separation, undissolved solid contaminants are removed from liquid solvents.

Vapor recovery or collection methods employed include condensation, adsorption, and absorption. Technical feasibility of the method chosen depends on the solvent's miscibility, vapor composition and concentration, boiling point, reactivity, and solubility, as well as several other factors.

Condensation of solvent vapors is accomplished by water-cooled condensers and refrigeration units. For adequate recovery, a solvent vapor concentration well above 20 milligrams per cubic meter (mg/m^3) (0.009 grains per cubic foot [gr/ft^3]) is required. To avoid explosive mixtures of a flammable solvent and air in the process gas stream, air is replaced with an inert gas, such as nitrogen. Solvent vapors that escape condensation are recycled through the main process stream or recovered by adsorption or absorption.

Activated carbon adsorption is the most common method of capturing solvent emissions. Adsorption systems are capable of recovering solvent vapors in concentrations below 4 mg/m^3 (0.002 gr/ft^3) of air. Solvents with boiling points of 200°C (290°F) or more do not desorb effectively with the low-pressure steam commonly used to regenerate the carbon beds. Figure 4.7-2 shows a flow diagram of a typical fixed-bed activated carbon solvent recovery system. The mixture of steam and solvent vapor passes to a water-cooled condenser. Water-immiscible solvents are simply decanted to separate the solvent, but water-miscible solvents must be distilled, and solvent mixtures must be both decanted and distilled. Fluidized bed operations are also in use.

Absorption of solvent vapors is accomplished by passing the waste gas stream through a liquid in scrubbing towers or spray chambers. Recovery by condensation and adsorption results in a mixture of water and liquid solvent, while absorption recovery results in an oil and solvent mixture. Further reclaiming procedures are required if solvent vapors are collected by any of these 3 methods.

Initial treatment of liquid waste solvents is accomplished by mechanical separation methods. This includes both removing water by decanting and removing undissolved solids by filtering, draining, settling, and/or centrifuging. A combination of initial treatment methods may be necessary to prepare waste solvents for further processing.

4.7.1.3 Distillation -

After initial treatment, waste solvents are distilled to remove dissolved impurities and to separate solvent mixtures. Separation of dissolved impurities is accomplished by simple batch, simple continuous, or steam distillation. Mixed solvents are separated by multiple simple distillation methods, such as batch or continuous rectification. These processes are shown in Figure 4.7-3.

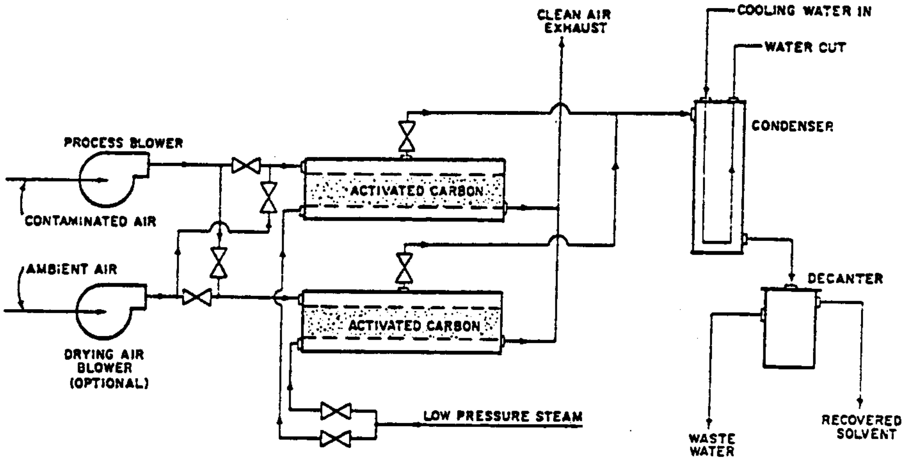

Figure 4.7-2. Typical fixed-bed activated carbon solvent recovery system.[6]

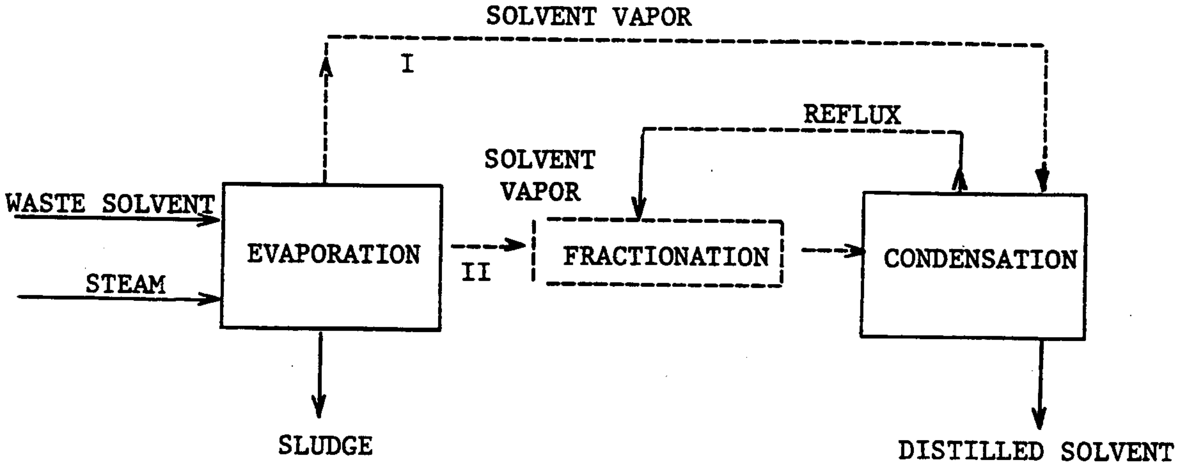

Figure 4.7-3. Distillation process for solvent reclaiming.[1]

In simple distillation, waste solvent is charged to an evaporator. Vapors are then continuously removed and condensed, and the resulting sludge or still bottoms are drawn off. In steam distillation, solvents are vaporized by direct contact with steam which is injected into the evaporator. Simple batch, continuous, and steam distillations follow Path I in Figure 4.7-3.

The separation of mixed solvents requires multiple simple distillation or rectification. Batch and continuous rectification are represented by Path II in Figure 4.7-3. In batch rectification, solvent vapors pass through a fractionating column, where they contact condensed solvent (reflux) entering at the top of the column. Solvent not returned as reflux is drawn off as overhead product. In continuous rectification, the waste solvent feed enters continuously at an intermediate point in the column. The more volatile solvents are drawn off at the top, while those with higher boiling points collect at the bottom.

Design criteria for evaporating vessels depend on waste solvent composition. Scraped surface stills or agitated thin film evaporators are the most suitable for heat sensitive or viscous materials. Condensation is accomplished by barometric or shell and tube condensers. Azeotropic solvent mixtures are separated by the addition of a third solvent component, while solvents with higher boiling points, e. g., in the range of high-flash naphthas (155°C, 310°F), are most effectively distilled under vacuum. Purity requirements for the reclaimed solvent determine the number of distillations, reflux ratios, and processing time needed.

4.7.1.4 Purification -

After distillation, water is removed from solvent by decanting or salting. Decanting is accomplished with immiscible solvent and water which, when condensed, form separate liquid layers, 1 or the other of which can be drawn off mechanically. Additional cooling of the solvent/water mix before decanting increases the separation of the 2 components by reducing their solubility. In salting, solvent is passed through a calcium chloride bed, and water is removed by absorption.

During purification, reclaimed solvents are stabilized, if necessary. Buffers are added to virgin solvents to ensure that pH level is kept constant during use. To renew it, special additives are used during purification. The composition of these additives is considered proprietary.

4.7.1.5 Waste Disposal -

Waste materials separated from solvents during initial treatment and distillation are disposed of by incineration, landfilling, or deep well injection. The composition of such waste varies, depending on the original use of the solvent. But up to 50 percent is unreclaimed solvent, which keeps the waste product viscous yet liquid, thus facilitating pumping and handling procedures. The remainder consists of components such as oils, greases, waxes, detergents, pigments, metal fines, dissolved metals, organics, vegetable fibers, and resins.

About 80 percent of the waste from solvent reclaiming by private contractors is disposed of in liquid waste incinerators. About 14 percent is deposited in sanitary landfills, usually in 55-gallon drums. Deep well injection is the pumping of wastes between impermeable geologic strata. Viscous wastes may have to be diluted for pumping into the desired stratum level.

4.7.2 Emissions And Controls[1,3-5]

Volatile organic and particulate emissions result from waste solvent reclamation. Emission points include storage tank vents [1], condenser vents [2], incinerator stacks [3], and fugitive losses (numbers refer to Figure 4.7-1 and Figure 4.7-3). Emission factors for these sources are given in Table 4.7-1.

Solvent storage results in volatile organic compound (VOC) emissions from solvent evaporation (Figure 4.7-1, emission point 1). The condensation of solvent vapors during distillation (Figure 4.7-3) also involves VOC emissions, and if steam ejectors are used, emission of steam and noncondensables as well (Figure 4.7-1 and Figure 4.7-3, point 2). Incinerator stack emissions consist

Table 4.7-1 (Metric And English Units). EMISSION FACTORS FOR SOLVENT RECLAIMING[a]

EMISSION FACTOR RATING: D

Source	Criteria Pollutant	Emission Factor Average	
		kg/Mg	lb/ton
Storage tank vent[b]	Volatile organics	0.01 (0.002 - 0.04)	0.02 (0.004 - 0.09)
Condenser vent	Volatile organics	1.65 (0.26 - 4.17)	3.30 (0.52 - 8.34)
Incinerator stack[c]	Volatile organics	0.01	0.02
Incinerator stack	Particulates	0.72 (0.55 - 1.0)	1.44 (1.1 - 2.0)
Fugitive emissions			
Spillage[c]	Volatile organics	0.10	0.20
Loading	Volatile organics	0.36 (0.00012 - 0.71)	0.72 (0.00024 - 1.42)
Leaks	Volatile organics	ND	ND
Open sources	Volatile organics	ND	ND

[a] Reference 1. Data obtained from state air pollution control agencies and presurvey sampling. All emission factors are for uncontrolled process equipment, except those for the incinerator stack. (Reference 1 does not, however, specify what the control is on this stack.) Average factors are derived from the range of data points available. Factors for these sources are given in terms of kilograms per megagram and pounds per ton of reclaimed solvent. Ranges in parentheses. ND = no data.

[b] Storage tank is of fixed roof design.

[c] Only 1 value available.

of solid contaminants that are oxidized and released as particulates, unburned organics, and combustion stack gases (Figure 4.7-1, point 3).

VOC emissions from equipment leaks, open solvent sources (sludge drawoff and storage from distillation and initial treatment operations), solvent loading, and solvent spills are classified as fugitive. The former 2 sources are continuously released, and the latter 2, intermittently.

Solvent reclamation is viewed by industry as a form of control in itself. Carbon adsorption systems can remove up to 95 percent of the solvent vapors from an air stream. It is estimated that less than 50 percent of reclamation plants run by private contractors use any control technology.

Volatile organic emissions from the storage of solvents can be reduced by as much as 98 percent by converting from fixed to floating roof tanks, although the exact percent reduction also depends on solvent evaporation rate, ambient temperature, loading rate, and tank capacity. Tanks may also be refrigerated or equipped with conservation vents which prevent air inflow and vapor escape until some preset vacuum or pressure develops.

Solvent vapors vented during distillation are controlled by scrubbers and condensers. Direct flame and catalytic afterburners can also be used to control noncondensables and solvent vapors not condensed during distillation. The time required for complete combustion depends on the flammability of the solvent. Carbon or oil adsorption may be employed also, as in the case of vent gases from the manufacture of vegetable oils.

Wet scrubbers are used to remove particulates from sludge incinerator exhaust gases, although they do not effectively control submicron particles.

Submerged rather than splash filling of storage tanks and tank cars can reduce solvent emissions from this source by more than 50 percent. Proper plant maintenance and loading procedures reduce emissions from leaks and spills. Open solvent sources can be covered to reduce these fugitive emissions.

References For Section 4.7

1. D. R. Tierney and T. W. Hughes, *Source Assessment: Reclaiming Of Waste Solvents — State Of The Art*, EPA-600/2-78/004f, U. S. Environmental Protection Agency, Cincinnati, OH, April 1978.

2. J. E. Levin and F. Scofield, "An Assessment Of The Solvent Reclaiming Industry", Proceedings of the 170th Meeting of the American Chemical Society, Chicago, IL, *35*(2):416-418, August 25-29, 1975.

3. H. M. Rowson, "Design Considerations In Solvent Recovery", Proceedings of the Metropolitan Engineers' Council On Air Resources (MECAR) Symposium On New Developments In Air Pollutant Control, New York, NY, October 23, 1961, pp. 110-128.

4. J. C. Cooper and F. T. Cuniff, "Control Of Solvent Emissions", Proceedings of the Metropolitan Engineers' Council On Air Resources (MECAR) Symposium On New Developments In Air Pollution Control, New York, NY, October 23, 1961, pp. 30-41.

5. W. R. Meyer, "Solvent Broke", Proceedings of TAPPI Testing Paper Synthetics Conference, Boston, MA, October 7-9, 1974, pp. 109-115.

6. Nathan R. Shaw, "Vapor Adsorption Technology For Recovery Of Chlorinated Hydrocarbons And Other Solvents", Presented at the 80th Annual Meeting of the Air Pollution Control Association, Boston, MA, June 15-20, 1975.

4.8 Tank And Drum Cleaning

4.8.1 General

Rail tank cars, tank trucks, and drums are used to transport about 700 different commodities. Rail tank cars and most tank trucks and drums are in dedicated service (carrying one commodity only) and, unless contaminated, are cleaned only prior to repair or testing. Nondedicated tank trucks (about 20,000, or 22 percent of the total in service) and drums (approximately 5.6 million, or 12.5 percent of the total) are cleaned after every trip.

4.8.1.1 Rail Tank Cars -

Most rail tank cars are privately owned. Some cars, like those owned by the railroads, are operated for hire. The commodities hauled are 35 percent petroleum products, 20 percent organic chemicals, 25 percent inorganic chemicals, 15 percent compressed gases, and 5 percent food products. Petroleum products considered in this study are glycols, vinyls, acetones, benzenes, creosote, etc. Not included in these figures are gasoline, diesel oil, fuel oils, jet fuels, and motor oils, the greatest portion of these being transported in dedicated service.

Much tank car cleaning is conducted at shipping and receiving terminals, where the wastes go to the manufacturers' treatment systems. However, 30 to 40 percent is done at service stations operated by tank car owners/lessors. These installations clean waste of a wide variety of commodities, many of which require special cleaning methods.

A typical tank car cleaning facility cleans 4 to 10 cars per day. Car capacity varies from 40 to 130 cubic meters (m^3) (10,000 to 34,000 gallons [gal]). Cleaning agents include steam, water, detergents, and solvents, which are applied using steam hoses, pressure wands, or rotating spray heads placed through the opening in the top of the car. Scraping of hardened or crystallized products is often necessary. Cars carrying gases and volatile materials, and those needing to be pressure tested, must be filled or flushed with water. The average amount of residual material cleaned from each car is estimated to be 250 kilograms (kg) (550 pounds [lb]). Vapors from car cleaning not flared or dissolved in water are dissipated to the atmosphere.

4.8.1.2 Tank Trucks -

Two-thirds of the tank trucks in service in the United States are operated for hire. Of these, 80 percent are used to haul bulk liquids. Most companies operate fleets of 5 trucks or less, and whenever possible, these trucks are assigned to dedicated service. Commodities hauled and cleaned are 15 percent petroleum products (except as noted in Part 4.8.1.1), 35 percent organic chemicals, 5 percent food products, and 10 percent other products.

Interior washing is carried out at many tank truck dispatch terminals. Cleaning agents include water, steam, detergents, bases, acids, and solvents, which are applied with hand-held pressure wands or by Turco or Butterworth rotating spray nozzles. Detergent, acidic, or basic solutions are usually used until spent and then sent to treatment facilities. Solvents are recycled in a closed system, with sludges either incinerated or landfilled. The average amount of material cleaned from each trailer is 100 kg (220 lb). Vapors from volatile material are flared at a few terminals, but most commonly are dissipated to the atmosphere. Approximately 0.23 m^3 (60 gal) of liquid are used per tank truck steam cleaning and 20.9 m^3 (5500 gal) for full flushing.

4.8.1.3 Drums -

Both 0.2- and 0.11-m^3 (30- and 55-gal) drums are used to ship a vast variety of commodities, with organic chemicals (including solvents) accounting for 50 percent. The remaining 50 percent includes inorganic chemicals, asphaltic materials, elastomeric materials, printing inks, paints, food additives, fuel oils, and other products.

Drums made entirely of 18-gauge steel have an average life, with total cleaning, of 8 trips. Those with 20-gauge bodies and 18-gauge heads have an average life of 3 trips. Not all drums are cleaned, especially those of thinner construction.

Tighthead drums that have carried materials that are easy to clean are steamed or washed with base. Steam cleaning is done by inserting a nozzle into the drum, with vapors going to the atmosphere. Base washing is done by tumbling the drum with a charge of hot caustic solution and some pieces of chain.

Drums used to carry materials that are difficult to clean are burned out, either in a furnace or in the open. Those with tightheads have the tops cut out and are reconditioned as open head drums. Drum burning furnaces may be batch or continuous. Several gas burners bathe the drum in flame, burning away the contents, lining, and outside paint in a nominal 4-minute period and at a temperature of at least 480°C (900°F) but not more than 540°C (1000°F) to prevent warping of the drum. Emissions are vented to an afterburner or secondary combustion chamber, where the gases are raised to at least 760°C (1400°F) for a minimum of 0.5 seconds. The average amount of material removed from each drum is 2 kg (4.4 lb).

4.8.2 Emissions And Controls

4.8.2.1 Rail Tank Cars And Tank Trucks -

Atmospheric emissions from tank car and truck cleaning are predominantly volatile organic chemical vapors. To achieve a practical but representative picture of these emissions, the organic chemicals hauled by the carriers must be known by classes of high, medium, and low viscosities and of high, medium, and low vapor pressures. High-viscosity materials do not drain readily, affecting the quantity of material remaining in the tank, and high-vapor-pressure materials volatilize more readily during cleaning and tend to lead to greater emissions.

Practical and economically feasible controls of atmospheric emissions from tank car and truck cleaning do not exist, except for containers transporting commodities that produce combustible gases and water soluble vapors (such as ammonia and chlorine). Gases displaced as tanks are filled are sent to a flare and burned. Water soluble vapors are absorbed in water and are sent to the waste water system. Any other emissions are vented to the atmosphere.

Tables 4.8-1 and 4.8-2 give emission factors for representative organic chemicals hauled by tank cars and trucks.

4.8.2.2 Drums -

There is no control for emissions from steaming of drums. Solution or caustic washing yields negligible air emissions, because the drum is closed during the wash cycle. Atmospheric emissions from steaming or washing drums are predominantly organic chemical vapors.

Air emissions from drum burning furnaces are controlled by proper operation of the afterburner or secondary combustion chamber, where gases are raised to at least 760°C (1400°F) for a minimum of 0.5 seconds. This normally ensures complete combustion of organic materials and

Table 4.8-1 (Metric And English Units). EMISSION FACTORS FOR RAIL TANK CAR CLEANING[a]

EMISSION FACTOR RATING: D

Compound	Chemical Class		Total Emissions[a]	
	Vapor Pressure	Viscosity	g/car	lb/car
Ethylene glycol[b]	low	high	0.3	0.0007
Chlorobenzene[b]	medium	medium	15.7	0.0346
o-Dichlorobenzene[b]	low	medium	75.4	0.1662
Creosote[c]	low	high	2350	5.1808

[a] Reference 1. Emission factors are in terms of average weight of pollutant released per car cleaned.
[b] Two-hour test duration.
[c] Eight-hour test duration.

Table 4.8-2 (Metric And English Units). EMISSION FACTORS FOR TANK TRUCK CLEANING[a]

EMISSION FACTOR RATING: D

Compound	Chemical Class		Total Emissions[a]	
	Vapor Pressure	Viscosity	g/truck	lb/truck
Acetone	high	low	311	0.686
Perchloroethylene	high	low	215	0.474
Methyl methacrylate	medium	medium	32.4	0.071
Phenol	low	low	5.5	0.012
Propylene glycol	low	high	1.07	0.002

[a] Reference 1. One-hour test duration.

prevents the formation, and subsequent release, of large quantities of NO_x, CO, and particulates. In open burning, however, there is no feasible way of controlling the release of incomplete combustion products to the atmosphere. The conversion of open cleaning operations to closed-cycle cleaning, and the elimination of open-air drum burning seem to be the only control alternatives immediately available.

Table 4.8-3 gives emission factors for representative criteria pollutants emitted from drum burning and cleaning.

Table 4.8-3 (Metric And English Units). EMISSION FACTORS FOR DRUM BURNING[a]

EMISSION FACTOR RATING: E

Pollutant	Total Emissions			
	Controlled		Uncontrolled	
	g/drum	lb/drum	g/drum	lb/drum
Particulate	12[b]	0.02646	16	0.035
NO_x	0.018	0.00004	0.89	0.002
VOC	Neg	Neg	Neg	Neg

[a] Reference 1. Emission factors are in terms of weight of pollutant released per drum burned, except for VOC, which are per drum washed. Neg = negligible.

[b] Reference 1, Table 17, and Appendix A.

Reference For Section 4.8

1. T. R. Blackwood, *et al.*, *Source Assessment: Rail Tank Car, Tank Truck, And Drum Cleaning, State Of The Art*, EPA-600/2-78-004g, U. S. Environmental Protection Agency, Cincinnati, OH, April 1978.

4.9 Graphic Arts

4.9.1 General Graphic Printing

4.9.2 Publication Gravure Printing

4.9.1 General Graphic Printing

4.9.1.1 Process Description

The term "graphic arts" as used here means 4 basic processes of the printing industry: web offset lithography, web letterpress, rotogravure, and flexography. Screen printing and manual and sheet-fed techniques are not included in this discussion.

Printing may be performed on coated or uncoated paper and on other surfaces, as in metal decorating and some fabric coating (see Section 4.2, Surface Coating). The material to receive the printing is called the substrate. The distinction between printing and paper coating, which may employ rotogravure or lithographic methods, is that printing invariably involves the application of ink by a printing press. However, printing and paper coating have these elements in common: application of a relatively high-solvent-content material to the surface of a moving web or film, rapid solvent evaporation by movement of heated air across the wet surface, and solvent-laden air exhausted from the system.

Printing inks vary widely in composition, but all consist of 3 major components: pigments, which produce the desired colors and are composed of finely divided organic and inorganic materials; binders, the solid components that lock the pigments to the substrate and are composed of organic resins and polymers or, in some inks, oils and rosins; and solvents, which dissolve or disperse the pigments and binders and are usually composed of organic compounds. The binder and solvent make up the "vehicle" part of the ink. The solvent evaporates from the ink into the atmosphere during the drying process.

4.9.1.1.1 Web Offset Lithography -

Lithography, the process used to produce about 75 percent of books and pamphlets and an increasing number of newspapers, is characterized by a planographic image carrier (i. e., the image and nonimage areas are on the same plane). The image area is ink wettable and water repellant, and the nonimage area is chemically repellant to ink. The solution used to dampen the plate may contain 15 to 30 percent isopropanol, if the Dalgren dampening system is used.[8] When the image is applied to a rubber-covered "blanket" cylinder and then transferred onto the substrate, the process is known as "offset" lithography. When a web (i. e., a continuous roll) of paper is employed with the offset process, this is known as web offset printing. Figure 4.9.1-1 illustrates a web offset lithography publication printing line. A web newspaper printing line contains no dryer, because the ink contains very little solvent, and somewhat porous paper is generally used.

Web offset employs "heatset" (i. e., heat drying offset) inks that dry very quickly. For publication work the inks contain about 40 percent solvent, and for newspaper work 5 percent solvent is used. In both cases, the solvents are usually petroleum-derived hydrocarbons. In a publication web offset process, the web is printed on both sides simultaneously and passed through a tunnel or floater dryer at about 200 - 290°C (400 - 500°F) . The dryer may be hot air or direct flame. Approximately 40 percent of the incoming solvent remains in the ink film, and more may be thermally degraded in a direct flame dryer. The web passes over chill rolls before folding and cutting. In newspaper work no dryer is used, and most of the solvent is believed to remain in the ink film on the paper.[11]

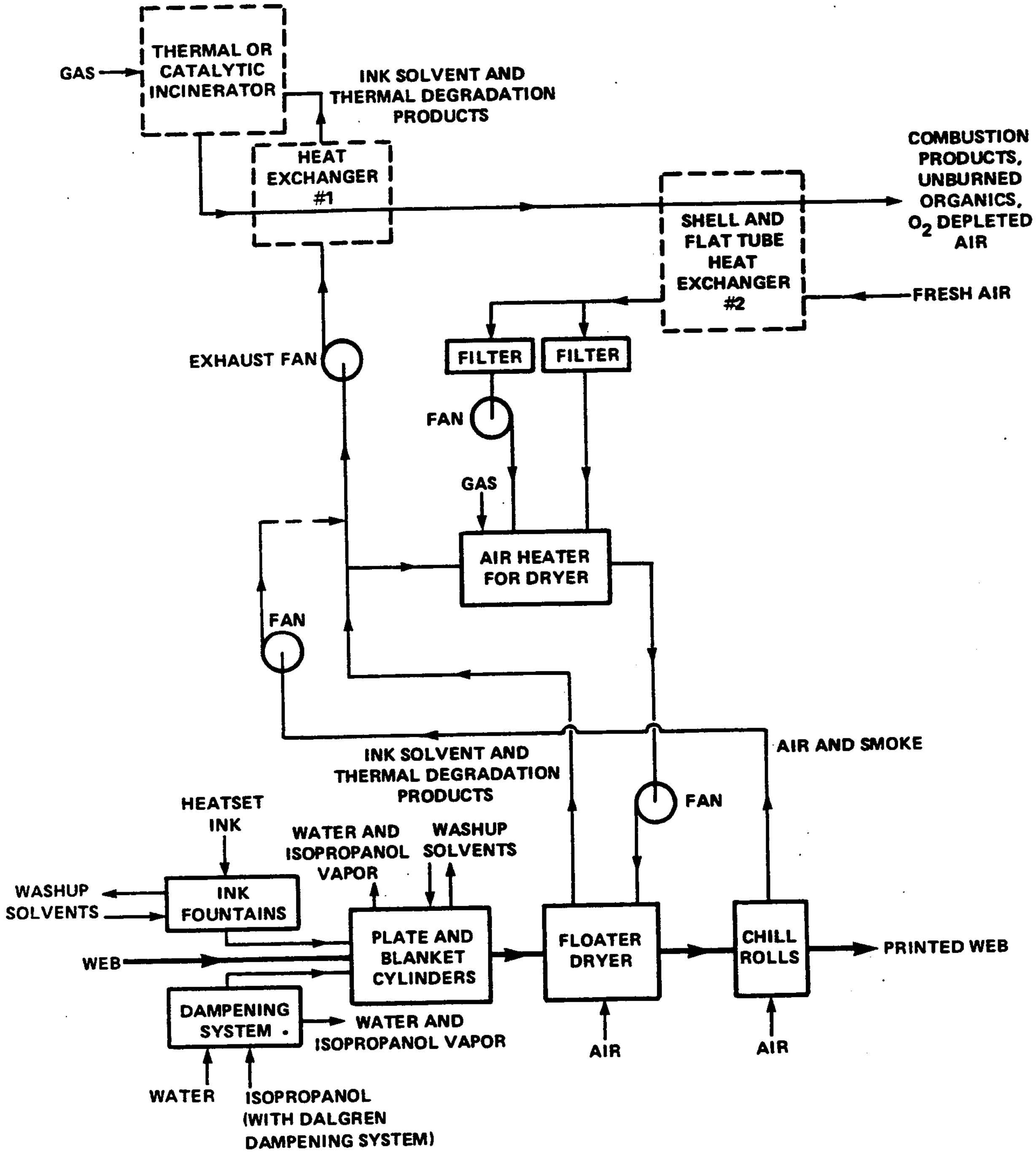

Figure 4.9.1-1. Web offset lithography publication printing line emission points.[11]

4.9.1.1.2 Web Letterpress -

Letterpress is the oldest form of moveable type printing, and it still dominates in periodical and newspaper publishing, although numerous major newspapers are converting to web offset. In letterpress printing, the image area is raised, and the ink is transferred to the paper directly from the image surface. The image carrier may be made of metal or plastic. Only web presses using solventborne inks are discussed here. Letterpress newspaper and sheet-fed printing use oxidative drying inks, not a source of volatile organic emissions. Figure 4.9.1-2 shows 1 unit of a web publication letterpress line.

Publication letterpress printing uses a paper web that is printed on 1 side at a time and dried after each color is applied. The inks employed are heatset, usually of about 40 volume percent solvent. The solvent in high-speed operations is generally a selected petroleum fraction akin to kerosene and fuel oil, with a boiling point of 200 - 370°C (400 - 700°F).[13]

4.9.1.1.3 Rotogravure -

In gravure printing, the image area is engraved, or "intaglio" relative to the surface of the image carrier, which is a copper-plated steel cylinder that is usually also chrome plated to enhance wear resistance. The gravure cylinder rotates in an ink trough or fountain. The ink is picked up in the engraved area, and ink is scraped off the nonimage area with a steel "doctor blade". The image is transferred directly to the web when it is pressed against the cylinder by a rubber covered impression roll, and the product is then dried. Rotary gravure (web fed) systems are known as "rotogravure" presses.

Rotogravure can produce illustrations with excellent color control, and it may be used on coated or uncoated paper, film, foil, and almost every other type of substrate. Its use is concentrated in publications and advertising such as newspaper supplements, magazines, and mail order catalogues; folding cartons and other flexible packaging materials; and specialty products such as wall and floor coverings, decorated household paper products, and vinyl upholstery. Figure 4.9.1-3 illustrates 1 unit of a publication rotogravure press. Multiple units are required for printing multiple colors.

The inks used in rotogravure publication printing contain from 55 to 95 volume percent low boiling solvent (average is 75 volume percent), and they must have low viscosities. Typical gravure solvents include alcohols, aliphatic naphthas, aromatic hydrocarbons, esters, glycol ethers, ketones, and nitroparaffins. Water-base inks are in regular production use in some packaging and specialty applications, such as sugar bags.

Rotogravure is similar to letterpress printing in that the web is printed on one side at a time and must be dried after application of each color. Thus, for 4-color, 2-sided publication printing, 8 presses are employed, each including a pass over a steam drum or through a hot air dryer at temperatures from ambient up to 120°C (250°F) where nearly all of the solvent is removed.[3] For further information, see Section 4.9.2.

4.9.1.1.4 Flexography -

In flexographic printing, as in letterpress, the image area is above the surface of the plate. The distinction is that flexography uses a rubber image carrier and alcohol-base inks. The process is usually web fed and is employed for medium or long multicolor runs on a variety of substrates, including heavy paper, fiberboard, and metal and plastic foil. The major categories of the flexography market are flexible packaging and laminates, multiwall bags, milk cartons, gift wrap, folding cartons, corrugated paperboard (which is sheet fed), paper cups and plates, labels, tapes, and envelopes. Almost all milk cartons and multiwall bags and half of all flexible packaging are printed by this process.

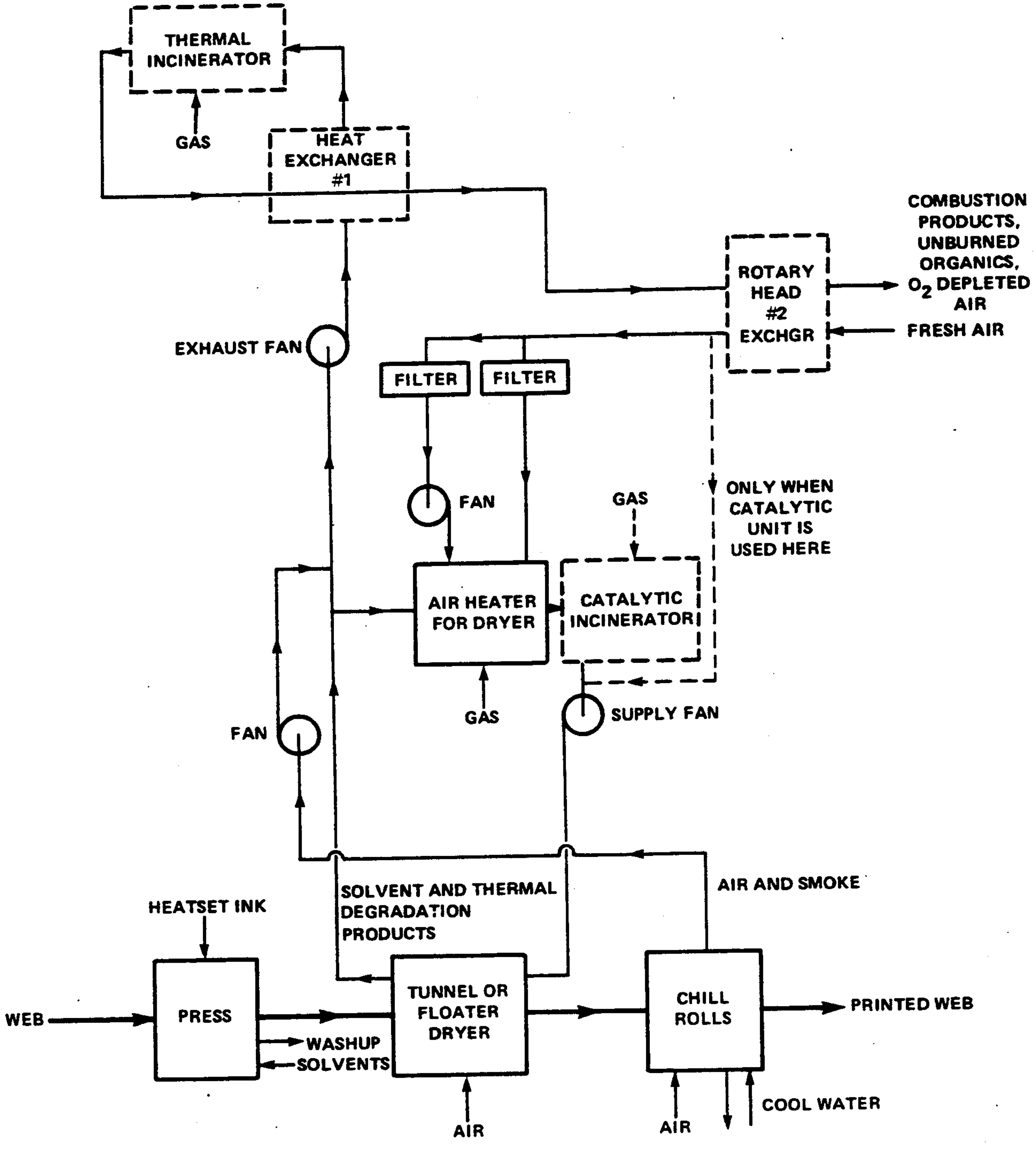

Figure 4.9.1-2. Web letterpress publication printing line emission points.[11]

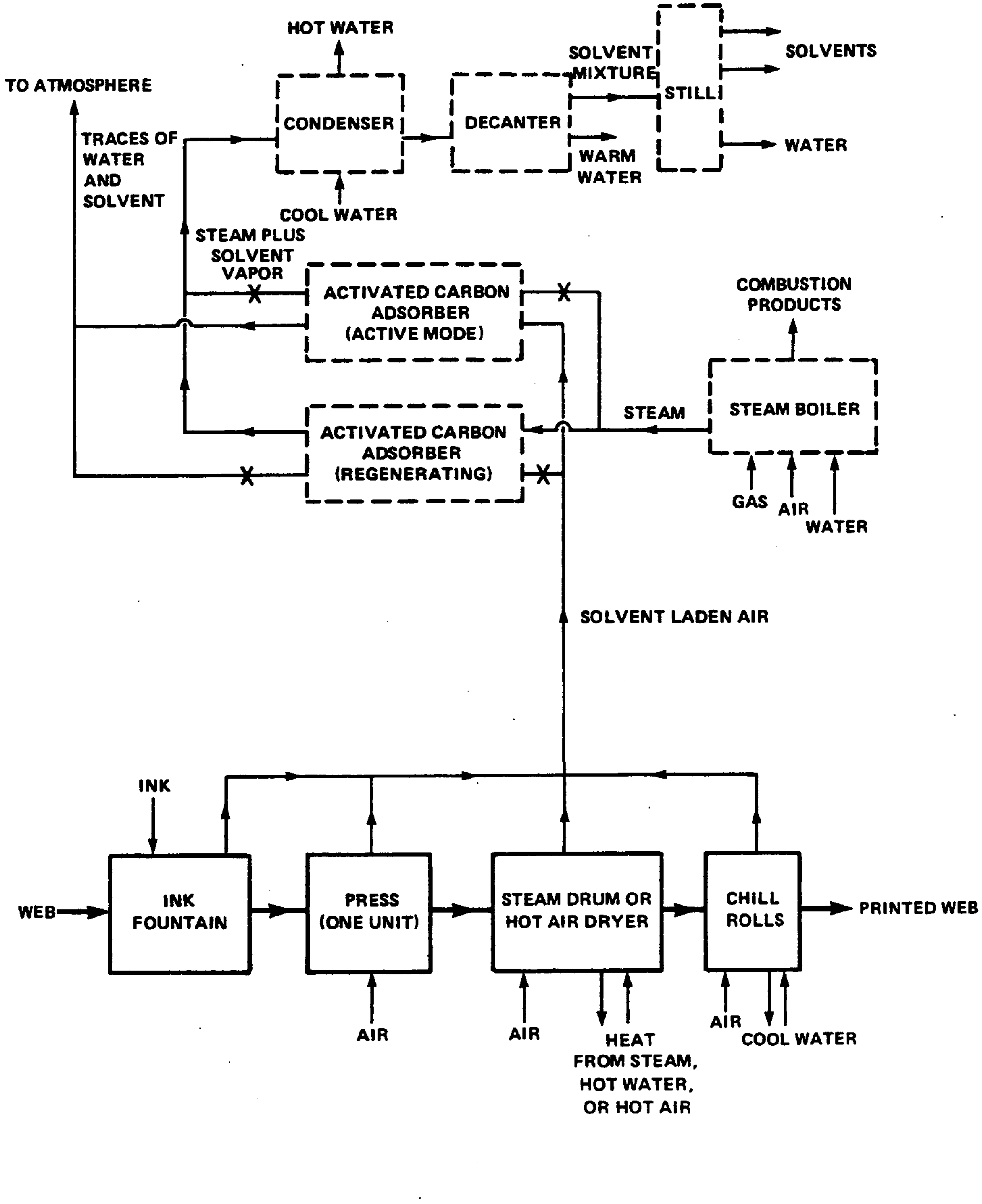

Figure 4.9.1-3. Rotogravure and flexography printing line emission points (chill rolls not used in rotogravure publication printing).[11]

Steam set inks, employed in the "water flexo" or "steam set flexo" process, are low-viscosity inks of a paste consistency that are gelled by water or steam. Steam-set inks are used for paper bag printing, and they produce no significant emissions. Water-base inks, usually pigmented suspensions in water, are also available for some flexographic operations, such as the printing of multiwall bags.

Solvent-base inks are used primarily in publication printing, as shown in Figure 4.9.1-3. As with rotogravure, flexography publication printing uses very fluid inks of about 75 volume percent organic solvent. The solvent, which must be rubber compatible, may be alcohol, or alcohol mixed with an aliphatic hydrocarbon or ester. Typical solvents also include glycols, ketones, and ethers. The inks dry by solvent absorption into the web and by evaporation, usually in high velocity steam drum or hot air dryers, at temperatures below 120°C (250°F).[3,13] As in letterpress publishing, the web is printed on only 1 side at a time. The web passes over chill rolls after drying.

4.9.1.2 Emissions And Controls

Significant emissions from printing operations consist primarily of volatile organic solvents. Such emissions vary with printing process, ink formulation and coverage, press size and speed, and operating time. The type of paper (coated or uncoated) has little effect on the quantity of emissions, although low levels of organic emissions are derived from the paper stock during drying.[13] High-volume web-fed presses such as those discussed above are the principal sources of solvent vapors. Total annual emissions from the industry in 1977 were estimated to be 380,000 megagrams (Mg) (418,000 tons). Of this total, lithography emits 28 percent, letterpress 18 percent, gravure 41 percent, and flexography 13 percent.[3]

Most of the solvent contained in the ink and used for dampening and cleanup eventually finds its way into the atmosphere, but some solvent remains with the printed product leaving the plant and is released to the atmosphere later. Overall solvent emissions can be computed from Equation 1 using a material balance concept, except in cases where a direct flame dryer is used and some of the solvent is thermally degraded.

The density of naphtha base solvent at 21°C (70°F) is 0.742 kilogams per liter (kg/L) (6.2 pounds per gallon [lb/gal]).

$$E_{total} = T \qquad (1)$$

where:

E_{total} = total solvent emissions including those from the printed product, kg (lb)
T = total solvent use including solvent contained in ink as used, kg (lb)

The solvent emissions from the dryer and other printline components can be computed from Equation 2. The remaining solvent leaves the plant with the printed product and/or is degraded in the dryer.

$$E = \frac{ISd}{100}\,\frac{(100-P)}{100} \qquad (2)$$

where:

E = solvent emissions from printline, kg (lb)
I = ink use, liters (gallons)
S and P = factors from Table 4.9.1-1.
d = solvent density, kg/L (lb/gal)

Table 4.9.1-1. TYPICAL PARAMETERS FOR COMPUTING SOLVENT EMISSIONS FROM PRINTING LINES[a,b]

Process	Solvent Content Of Ink (Volume %) [S]	Solvent Remaining In Product Plus That Destroyed In Dryer (%) [P][c]	EMISSION FACTOR RATING
Web Offset Lithography			
Publication	40	40 (hot air dryer) 60 (direct flame dryer)	B
Newspaper	5	100	B
Web Letterpress			
Publication	40	40	B
Newspaper	0	NA	NA
Rotogravure	75	2 - 7	C
Flexography	75	2 - 7	C

[a] References 1,14. NA = not applicable.

[b] Values for S and P are typical. Specific values for S and P should be obtained from a source to estimate its emissions.

[c] For certain packaging products, amount of solvent retained is regulated by the Food and Drug Administration (FDA).

4.9.1.2.1 Per Capita Emission Factors -

Although major sources contribute most of the emissions for graphic arts operations, considerable emissions also originate from minor graphic arts applications, including inhouse printing services in general industries. Small sources within the graphic arts industry are numerous and difficult to identify, since many applications are associated with nonprinting industries. Table 4.9.1-2 presents per capita factors for estimating emissions from small graphic arts operations. The factors are entirely nonmethane VOC and should be used for emission estimates over broad geographical areas.

Table 4.9.1-2 (Metric And English Units). PER CAPITA NONMETHANE VOC EMISSION FACTORS FOR SMALL GRAPHIC ARTS APPLICATIONS

EMISSION FACTOR RATING: D

Units	Emission Factor[a]
kg/year/capita	0.4
lb/year/capita	0.8
g/day/capita	1[b]
lb/day/capita	0.003[b]

[a] Reference 15. All nonmethane VOC.

[b] Assumes a 6-day operating week (313 days/yr).

4.9.1.2.2 Web Offset Lithography -

Emission points on web offset lithography publication printing lines include: (1) the ink fountains, (2) the dampening system, (3) the plate and blanket cylinders, (4) the dryer, (5) the chill rolls, and (6) the product (see Figure 4.9.1-1).

Alcohol is emitted from Points 2 and 3. Washup solvents are a small source of emissions from Points 1 and 3. Drying (Point 4) is the major source, because 40 to 60 percent of the ink solvent is removed from the web during this process.

The quantity of web offset emissions may be estimated from Equation 1, or from Equation 2 and the appropriate data from Table 4.9.1-1.

4.9.1.2.3 Web Letterpress -

Emission points on web letterpress publication printing lines are: (1) the press (includes the image carrier and inking mechanism), (2) the dryer, (3) the chill rolls, and (4) the product (see Figure 4.9.1-2).

Web letterpress publication printing produces significant emissions, primarily from the ink solvent, about 60 percent of which is lost in the drying process. Washup solvents are a small source of emissions. The quantity of emissions can be computed as described for web offset.

Letterpress publication printing uses a variety of papers and inks that lead to emission control problems, but losses can be reduced by a thermal or catalytic incinerator, either of which may be coupled with a heat exchanger.

4.9.1.2.4 Rotogravure -

Emissions from rotogravure printing occur at: (1) the ink fountain, (2) the press, (3) the dryer, and (4) the chill rolls (see Figure 4.9.1-3). The dryer is the major emission point, because most of the VOC in the low boiling ink is removed during drying. The quantity of emissions can be computed from Equation 1, or from Equation 2 and the appropriate parameters from Table 4.9.1-1.

Vapor capture systems are necessary to minimize fugitive solvent vapor loss around the ink fountain and at the chill rolls. Fume incinerators and carbon adsorbers are the only devices that have a high efficiency in controlling vapors from rotogravure operations.

Solvent recovery by carbon adsorption systems has been quite successful at a number of large publication rotogravure plants. These presses use a single water-immiscible solvent (toluene) or a simple mixture that can be recovered in approximately the proportions used in the ink. All new publication gravure plants are being designed to include solvent recovery.

Some smaller rotogravure operations, such as those that print and coat packaging materials, use complex solvent mixtures in which many of the solvents are water soluble. Thermal incineration with heat recovery is usually the most feasible control for such operations. With adequate primary and secondary heat recovery, the amount of fuel required to operate both the incinerator and the dryer system can be reduced to less than that normally required to operate the dryer alone.

In addition to thermal and catalytic incinerators, pebble bed incinerators are also available. Pebble bed incinerators combine the functions of a heat exchanger and a combustion device, and can achieve a heat recovery efficiency of 85 percent.

VOC emissions can also be reduced by using low-solvent inks. Waterborne inks, in which the volatile portion contains up to 20 volume percent water soluble organic compounds, are used extensively in rotogravure printing of multiwall bags, corrugated paperboard, and other packaging products, although water absorption into the paper limits the amount of waterborne ink that can be printed on thin stock before the web is seriously weakened.

4.9.1.2.5 Flexography -

Emission points on flexographic printing lines are: (1) the ink fountain, (2) the press, (3) the dryer, and (4) the chill rolls (see Figure 4.9.1-3). The dryer is the major emission point, and emissions can be estimated from Equation 1, or from Equation 2 and the appropriate parameters from Table 4.9.1-1.

Vapor capture systems are necessary to minimize fugitive solvent vapor loss around the ink fountain and at the chill rolls. Fume incinerators are the only devices proven highly efficient in controlling vapors from flexographic operations. VOC emissions can also be reduced by using waterborne inks, which are used extensively in flexographic printing of packaging products.

Table 4.9-3 shows estimated control efficiencies for printing operations.

Table 4.9-3. ESTIMATED CONTROL TECHNOLOGY EFFICIENCIES FOR PRINTING LINES

Method	Application	Reduction in Organic Emissions (%)
Carbon adsorption	Publication rotogravure operations	75[a]
Incineration[b]	Web offset lithography	95[c]
	Web letterpress	95[d]
	Packaging rotogravure printing operations	65[a]
	Flexography printing operations	60[a]
Waterborne inks[e]	Some packaging rotogravure printing operations[f]	65 - 75[a]
	Some flexography packaging printing operations	60[a]

[a] Reference 3. Overall emission reduction efficiency (capture efficiency multiplied by control device efficiency).

[b] Direct flame (thermal) catalytic and pebble bed. Three or more pebble beds in a system have a heat recovery efficiency of 85%.

[c] Reference 12. Efficiency of volatile organic removal — does not consider capture efficiency.

[d] Reference 13. Efficiency of volatile organic removal — does not consider capture efficiency.

[e] Solvent portion consists of 75 volume % water and 25 volume % organic solvent.

[f] With less demanding quality requirements.

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4.9.2 Publication Gravure Printing

4.9.2.1 Process Description[1-2]

Publication gravure printing is the printing by the rotogravure process of a variety of paper products such as magazines, catalogs, newspaper supplements and preprinted inserts, and advertisements. Publication printing is the largest sector involved in gravure printing, representing over 37 percent of the total gravure product sales value in a 1976 study.

The rotogravure press is designed to operate as a continuous printing facility, and normal operation may be either continuous or nearly so. Normal press operation experiences numerous shutdowns caused by web breaks or mechanical problems. Each rotogravure press generally consists of 8 to 16 individual printing units, with an 8-unit press the most common. In publication printing, only 4 colors of ink are used: yellow, red, blue, and black. Each unit prints 1 ink color on 1 side of the web, and colors other than these 4 are produced by printing 1 color over another to yield the desired product.

In the rotogravure printing process, a web or substrate from a continuous roll is passed over the image surface of a revolving gravure cylinder. For publication printing, only paper webs are used. The printing images are formed by many tiny recesses or cells etched or engraved into the surface of the gravure cylinder. The cylinder is about one-fourth submerged in a fountain of low-viscosity mixed ink. Raw ink is solvent-diluted at the press and is sometimes mixed with related coatings, usually referred to as extenders or varnishes. The ink, as applied, is a mixture of pigments, binders, varnish, and solvent. The mixed ink is picked up by the cells on the revolving cylinder surface and is continuously applied to the paper web. After impression is made, the web travels through an enclosed heated air dryer to evaporate the volatile solvent. The web is then guided along a series of rollers to the next printing unit. Figure 4.9.2-1 illustrates this printing process by an end (or side) view of a single printing unit.

At present, only solventborne inks are used on a large scale for publication printing. Waterborne inks are still in research and development stages, but some are now being used in a few limited cases. Pigments, binders, and varnishes are the nonvolatile solid components of the mixed ink. For publication printing, only aliphatic and aromatic organic liquids are used as solvents. Presently, 2 basic types of solvents, toluene and a toluene-xylene-naphtha mixture, are used. The naphtha base solvent is the more common. Benzene is present in both solvent types as an impurity, in concentrations up to about 0.3 volume percent. Raw inks, as purchased, have 40 to 60 volume percent solvent, and the related coatings typically contain about 60 to 80 volume percent solvent. The applied mixed ink consists of 75 to 80 volume percent solvent, required to achieve the proper fluidity for rotogravure printing.

4.9.2.2 Emissions And Controls[1,3-4]

Volatile organic compound (VOC) vapors are the only significant air pollutant emissions from publication rotogravure printing. Emissions from the printing presses depend on the total amount of solvent used. The sources of these VOC emissions are the solvent components in the raw inks, related coatings used at the printing presses, and solvent added for dilution and press cleaning. These solvent organics are photochemically reactive. VOC emissions from both controlled and uncontrolled publication rotogravure facilities in 1977 were about 57,000 megagrams (Mg) (63,000 tons),

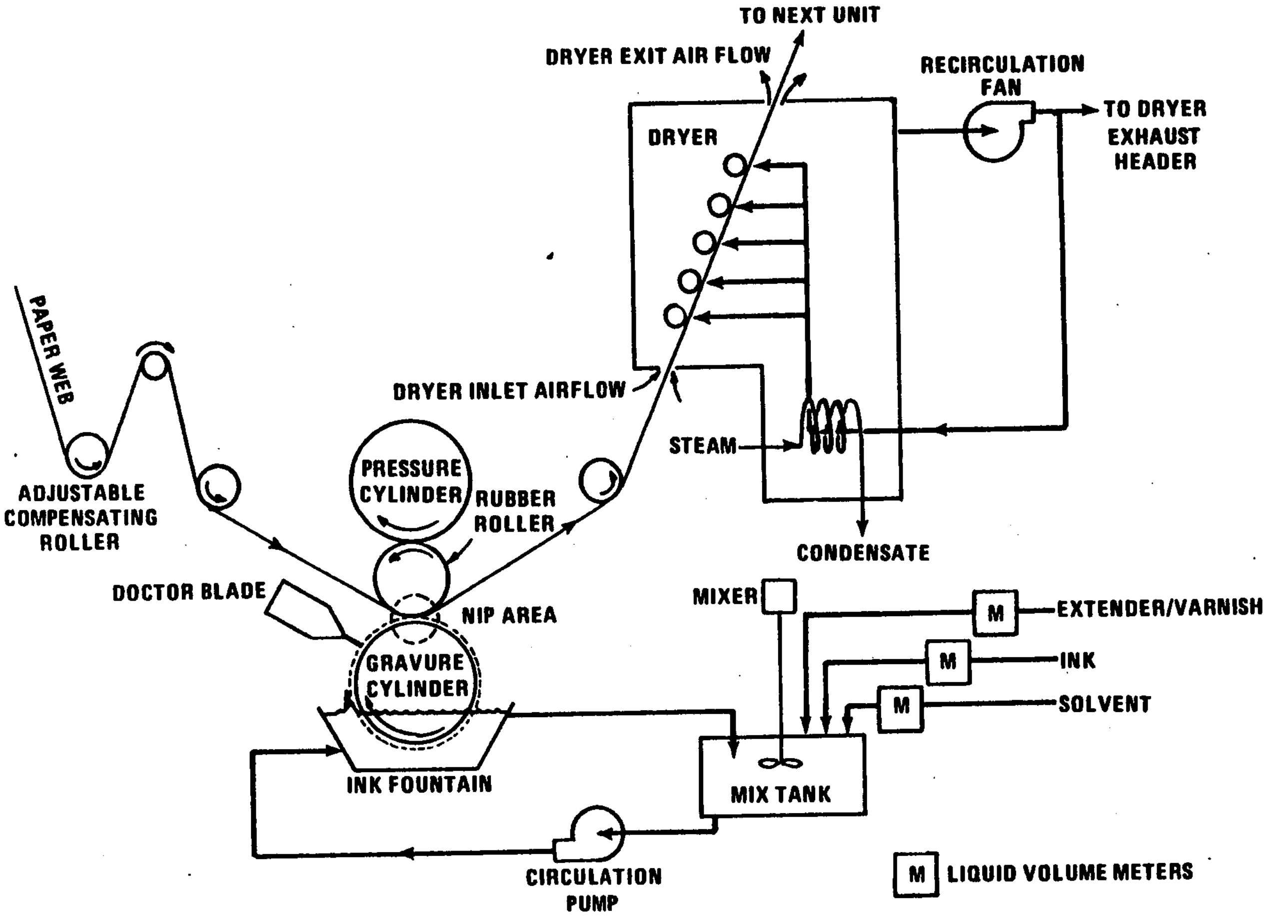

Figure 4.9.2-1. Diagram of a rotogravure printing unit.

15 percent of the total from the graphic arts industry. Emissions from ink and solvent storage and transfer facilities are not considered here.

Table 4.9.2-1 presents emission factors for publication printing on rotogravure presses with and without control equipment. The potential amount of VOC emissions from the press is equal to the total amount of solvent consumed in the printing process (see Footnote f). For uncontrolled presses, emissions occur from the dryer exhaust vents, printing fugitive vapors, and evaporation of solvent retained in the printed product. About 75 to 90 percent of the VOC emissions occur from the dryer exhausts, depending on press operating speed, press shutdown frequency, ink and solvent composition, product printed, and dryer designs and efficiencies. The amount of solvent retained by the various rotogravure printed products is 3 to 4 percent of the total solvent in the ink used. The retained solvent eventually evaporates after the printed product leaves the press.

There are numerous points around the printing press from which fugitive emissions occur. Most of the fugitive vapors result from solvent evaporation in the ink fountain, exposed parts of the gravure cylinder, the paper path at the dryer inlet, and from the paper web after exiting the dryers between printing units. The quantity of fugitive vapors depends on the solvent volatility, the temperature of the ink and solvent in the ink fountain, the amount of exposed area around the press, dryer designs and efficiencies, and the frequency of press shutdowns.

The complete air pollution control system for a modern publication rotogravure printing facility consists of 2 sections: the solvent vapor capture system and the emission control device. The capture system collects VOC vapors emitted from the presses and directs them to a control device where they are either recovered or destroyed. Low-VOC waterborne ink systems to replace a significant amount of solventborne inks have not been developed as an emission reduction alternative.

4.9.2.2.1 Capture Systems -

Presently, only the concentrated dryer exhausts are captured at most facilities. The dryer exhausts contain the majority of the VOC vapors emitted. The capture efficiency of dryers is limited by their operating temperatures and other factors that affect the release of the solvent vapors from the print and web to the dryer air. Excessively high temperatures impair product quality. The capture efficiency of older design dryer exhaust systems is about 84 percent, and modern dryer systems can achieve 85 to 89 percent capture. For a typical press, this type capture system consists of ductwork from each printing unit's dryer exhaust joined in a large header. One or more large fans are employed to pull the solvent-laden air from the dryers and to direct it to the control device.

A few facilities have increased capture efficiency by gathering fugitive solvent vapors along with the dryer exhausts. Fugitive vapors can be captured by a hood above the press, by a partial enclosure around the press, by a system of multiple spot pickup vents, by multiple floor sweep vents, by total pressroom ventilation capture, or by various combinations of these. The design of any fugitive vapor capture system needs to be versatile enough to allow safe and adequate access to the press in press shutdowns. The efficiencies of these combined dryer exhaust and fugitive capture systems can be as high as 93 to 97 percent at times, but the demonstrated achievable long term average when printing several types of products is only about 90 percent.

4.9.2.2.2 Control Devices -

Various control devices and techniques may be employed to control captured VOC vapors from rotogravure presses. All such controls are of 2 categories: solvent recovery and solvent destruction.

Table 4.9.2-1 (Metric And English Units). EMISSION FACTORS FOR PUBLICATION ROTOGRAVURE PRINTING PRESSES

EMISSION FACTOR RATING: C

	VOC Emissions[a]								
	Uncontrolled			75% Control			85% Control		
	Total Solvent	Raw Ink		Total Solvent	Raw Ink		Total Solvent	Raw Ink	
Emission Points	kg/kg (lb/lb)	$\frac{\text{kg}}{\text{L}}$	$\frac{\text{lb}}{\text{gal}}$	kg/kg (lb/lb)	$\frac{\text{kg}}{\text{L}}$	$\frac{\text{lb}}{\text{gal}}$	kg/kg (lb/lb)	$\frac{\text{kg}}{\text{L}}$	$\frac{\text{lb}}{\text{gal}}$
Dryer exhausts[b]	0.84	1.24	10.42	—	—	—	—	—	—
Fugitives[c]	0.13	0.19	1.61	0.13	0.19	1.61	0.07	0.10	0.87
Printed product[d]	0.03	0.05	0.37	0.03	0.05	0.37	0.03	0.05	0.37
Control device[e]	—	—	—	0.09	0.13	1.12	0.05	0.07	0.62
Total emissions[f]	1.0	1.48	12.40	0.25	0.37	3.10	0.15	0.22	1.86

[a] All nonmethane. Mass of VOC emitted per mass of total solvent used are more accurate factors. Solvent assumed to consist entirely of VOC. Total solvent used includes all solvent in raw ink and related coatings, all dilution solvent added and all cleaning solvent used. Mass of VOC emitted per volume of raw ink (and coatings) used are general factors, based on typical dilution solvent volume addition. Actual factors based on ink use can vary significantly, as follows:

- Typical total solvent volume/raw ink (and coatings) volume ratio - 2.0 (liter/liter) (L/L) (gal/gal); range, 1.6 - 2.4. See References 1,5-8.

- Solvent density (D_s) varies with composition and temperature. At 21°C (70°F), the density of the most common mixed solvent used is 0.742 kg/L (6.2 lb/gal); density of toluene solvent used is 0.863 kg/L (7.2 lb/gal). See Reference 1.

- Mass of VOC emitted/raw ink (and coating) volume ratio determined from the mass emission factor ratio, the solvent/ink volume ratio, and the solvent density.

$$\text{kg/L} = \text{kg/kg} \times \text{L/L} \times D_s$$
$$(\text{lb/gal} = \text{lb/lb} \times \text{gal/gal} \times D_s)$$

[b] Reference 3 and test data for presses with dryer exhaust control only (Reference 1). Dryer exhaust emissions depend on press operating speed, press shutdown frequency, ink and solvent composition, product printed, and dryer design and efficiencies. Emissions can range from 75 - 90% of total press emissions.

[c] Determined by difference between total emissions and other point emissions.

[d] Reference 1. Solvent temporarily retained in product after leaving press depends on dryer efficiency, type of paper, and type of ink used. Emissions have been reported to range from 1 - 7% of total press emissions.

[e] Based on capture and control device efficiencies (see Footnote f). Emissions are residual content in captured solvent-laden air vented after treatment.

[f] References 1,3. Uncontrolled presses eventually emit 100% of total solvent used. Controlled press emissions are based on overall reduction efficiency equal to capture efficiency x control device efficiency. For 75% control, the capture efficiency is 84% with a 90% efficient control device. For 85% control, the capture efficiency is 90% with a 95% control device.

Solvent recovery is the only present technique to control VOC emissions from publication presses. Fixed-bed carbon adsorption by multiple vessels operating in parallel configuration, regenerated by steaming, represents the most used control device. A new adsorption technique using a fluidized bed of carbon might be employed in the future. The recovered solvent can be directly recycled to the presses.

There are 3 types of solvent destruction devices used to control VOC emissions: (1) conventional thermal oxidation, (2) catalytic oxidation, and (3) regenerative thermal combustion. These control devices are employed for other rotogravure printing. At present, none are being used on publication rotogravure presses.

The efficiency of both solvent destruction and solvent recovery control devices can be as high as 99 percent. However, the achievable long-term average efficiency for publication printing is about 95 percent. Older carbon adsorber systems were designed to perform at about 90 percent efficiency. Control device emission factors presented in Table 4.9.2-1 represent the residual vapor content of the captured solvent-laden air vented after treatment.

4.9.2.2.3 Overall Control -

The overall emission reduction efficiency for VOC control systems is equal to the capture efficiency times the control device efficiency. Emission factors for 2 control levels are presented in Table 4.9.2-1. The 75 percent control level represents 84 percent capture with a 90 percent efficient control device. (This is the EPA control techniques guideline recommendation for State regulations on old existing presses.) The 85 percent control level represents 90 percent capture with a 95 percent efficient control device. This corresponds to application of best demonstrated control technology for new publication presses.

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4.10 Commercial/Consumer Solvent Use

4.10.1 General[1-2]

Commercial and consumer use of various products containing volatile organic compounds (VOC) contributes to formation of tropospheric ozone. The organics in these products may be released through immediate evaporation of an aerosol spray, evaporation after application, and direct release in the gaseous phase. Organics may act either as a carrier for the active product ingredients or as active ingredients themselves. Commercial and consumer products that release VOCs include aerosols, household products, toiletries, rubbing compounds, windshield washing fluids, polishes and waxes, nonindustrial adhesives, space deodorants, moth control applications, and laundry detergents and treatments.

4.10.2 Emissions

Major volatile organic constituents of these products which are released to the atmosphere include special naphthas, alcohols, and various chloro- and fluorocarbons. Although methane is not included in these products, 31 percent of the VOCs released in the use of these products is considered nonreactive under EPA policy.[3,4]

National emissions and per capita emission factors for commercial and consumer solvent use are presented in Table 4.10-1. Per capita emission factors can be applied to area source inventories by multiplying the factors by inventory area population. Note that adjustment to exclude the nonreactive emission fraction cited above should be applied to total emissions or to the composite factor. Care is advised in making adjustments, in that substitution of compounds within the commercial/consumer products market may alter the nonreactive fraction of compounds.

Table 4.10-1 (Metric And English Units). EVAPORATIVE EMISSIONS FROM COMMERCIAL/CONSUMER SOLVENT USE

EMISSION FACTOR RATING: C

	Nonmethane VOC[a]					
	National Emissions		Per Capita Emission Factors			
Use	10^3 Mg/yr	10^3 tons/yr	kg/yr	lb/yr	g/day[b]	10^{-3} lb/day
Aerosol products	342	376	1.6	3.5	4.4	9.6
Household products	183	201	0.86	1.9	2.4	5.2
Toiletries	132	145	0.64	1.4	1.8	3.8
Rubbing compounds	62	68	0.29	0.64	0.80	1.8
Windshield washing	61	67	0.29	0.63	0.77	1.7
Polishes and waxes	48	53	0.22	0.49	0.59	1.3

Table 4.10-1 (cont.).

Nonmethane VOC[a]						
	National Emissions		Per Capita Emission Factors			
Use	10^3 Mg/yr	10^3 tons/yr	kg/yr	lb/yr	g/day[b]	10^{-3} lb/day
Nonindustrial adhesives	29	32	0.13	0.29	0.36	0.79
Space deodorant	18	20	0.09	0.19	0.24	0.52
Moth control	16	18	0.07	0.15	0.19	0.41
Laundry detergent	4	4	0.02	0.04	0.05	0.10
Total[c]	895	984	4.2	9.2	11.6	25.2

[a] References 1-2.

[b] Calculated by dividing kg/yr (lb/yr) by 365 and converting to appropriate units.

[c] Totals may not be additive because of rounding.

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4.11 Textile Fabric Printing

4.11.1 Process Description[1-2]

Textile fabric printing is part of the textile finishing industry. In fabric printing, a decorative pattern or design is applied to constructed fabric by roller, flat screen, or rotary screen methods. Pollutants of interest in fabric printing are volatile organic compounds (VOC) from mineral spirit solvents in print pastes or inks. Tables 4.11-1, 4.11-2, and 4.11-3 show typical printing run characteristics and VOC emission sources, respectively, for roller, flat screen, and rotary screen printing methods.

In the roller printing process, print paste is applied to an engraved roller, and the fabric is guided between it and a central cylinder. The pressure of the roller and central cylinder forces the print paste into the fabric. Because of the high quality it can achieve, roller printing is the most appealing method for printing designer and fashion apparel fabrics.

In flat screen printing, a screen on which print paste has been applied is lowered onto a section of fabric. A squeegee then moves across the screen, forcing the print paste through the screen and into the fabric. Flat screen machines are used mostly in printing terry towels.

In rotary screen printing, tubular screens rotate at the same velocity as the fabric. Print paste distributed inside the tubular screen is forced into the fabric as it is pressed between the screen and a printing blanket (a continuous rubber belt). Rotary screen printing machines are used mostly but not exclusively for bottom weight apparel fabrics or fabric not for apparel use. Host knit fabric is printed by the rotary screen method, because it does not stress (pull or stretch) the fabric during the process.

Major print paste components include clear and color concentrates, a solvent, and in pigment printing, a low crock or binder resin. Print paste color concentrates contain either pigments or dyes. Pigments are insoluble particles physically bound to fabrics. Dyes are in solutions applied to impart color by becoming chemically or physically incorporated into individual fibers. Organic solvents are used almost exclusively with pigments. Very little organic solvent is used in nonpigment print pastes. Clear concentrates extend color concentrates to create light and dark shades. Clear and color concentrates do contain some VOC but contribute less than 1 percent of total VOC emissions from textile printing operations. Defoamers and resins are included in print paste to increase color fastness. A small amount of thickening agent is also added to each print paste to control print paste viscosity. Print defoamers, resins, and thickening agents do not contain VOC.

The majority of emissions from print paste are from the solvent, which may be aqueous, organic (mineral spirits), or both. The organic solvent concentration in print pastes may vary from 0 to 60 weight percent, with no consistent ratio of organic solvent to water. Mineral spirits used in print pastes vary widely in physical and chemical properties (see Table 4.11-4).

Although some mineral spirits evaporate in the early stages of the printing process, the majority of emissions to the atmosphere is from the printed fabric drying process, which drives off volatile compounds (see Tables 4.11-2 and 4.11-3 for typical VOC emission splits). For some specific print paste/fabric combinations, color fixing occurs in a curing process, which may be entirely separate or merely a separate segment of the drying process.

Table 4.11-1 (Metric And English Units). TYPICAL TEXTILE FABRIC PRINTING RUN CHARACTERISTICS[a]

Characteristic	Roller		Rotary Screen		Flat Screen	
	Range	Average	Range	Average	Range	Average
Wet pickup rate, kg (lb)[b] print paste consumed/kg (lb) of fabric[c]	0.51 - 0.58	0.56	0.10 - 1.89	0.58	0.22 - 0.83	0.35
Fabric weight, kg/m^2 (lb/yd^2)[d]	0.116 - 0.116 (0.213 - 0.213)	0.116 (0.213)	0.116 - 0.116 (0.213 - 0.213)	0.116 (0.213)	0.314 - 0.314 (0.579 - 0.579)	0.314 (0.579)
Mineral spirits added to print paste, weight %	0 - 60	26	0 - 50	3	23 - 23	23
Print paste used per fabric area, kg/m^2 (lb/yd^2)[e]	0.059 - 0.067 (0.109 - 0.124)	0.065 (0.119)	0.012 - 0.219 (0.021 - 0.403)	0.067 (0.124)	0.069 - 0.261 (0.127 - 0.481)	0.110 (0.203)
Mineral spirits used per fabric area, kg/m^2 (lb/yd^2)[f]	0 - 0.040 (0 - 0.074)	0.017 (0.031)	0 - 0.109 (0 - 0.201)	0.0002 (0.0004)	0.016 - 0.060 (0.030 - 0.111)	0.025 (0.046)
Print paste used in run, kg (lb)[g]	673 - 764 (1,490 - 1,695)	741 (1,627)	137 - 2,497 (287 - 5,509)	764 (1,695)	787 - 2,975 (1,736 - 6,575)	1,254 (2,775)

[a] Length of run = 10,000 m (10,936 yd); fabric width = 1.14 m (1.25 yd); total fabric area = 11,400 m^2 (13,634 yd^2); line speed = 40 m/min (44 yd/min); distance, printer to oven = 5 m (5.5 yd).

[b] Wet pickup rate is a method of yield calculation in which mass of print paste consumed is divided by mass of fabric used.

[c] Reference 3.

[d] Only average fabric weight is presented.

[e] Fabric weight multiplied by wet pickup rate.

[f] Fabric weight multiplied by wet pickup multiplied by percent mineral spirits in formulation.

[g] Print paste used per fabric area multiplied by area of fabric printed.

Table 4.11-2 (Metric Units). SOURCES OF MINERAL SPIRIT EMISSIONS FROM A TYPICAL TEXTILE FABRIC PRINTING RUN[a]

Source	Percent Of Total Emissions	Roller		Rotary Screen		Flat Screen	
		Range (kg)	Average (kg)	Range (kg)	Average (kg)	Range (kg)	Average (kg)
Mineral spirits used in run[b]	100.0	0 - 458	193	0 - 1,249	23	181 - 684	288
Wasted mineral spirits (potential water emissions)[c]	6.2	0 - 28	12	0 - 77	1	11 - 42	18
Overprinted mineral spirit fugitives[d]	3.5	0 - 16	7	0 - 44	1	6 - 24	10
Tray and barrel fugitives[e]	0.3	0 - 1	1	0 - 4	0	1 - 2	1
Flashoff fugitives[e]	1.5	0 - 7	3	0 - 19	0	3 - 10	4
Dryer emissions[e]	88.5	0 - 405	170	0 - 1,105	21	160 - 606	255

[a] Length of run = 10,000 m; fabric width = 1.14 m; total fabric area = 11,400 m^2; line speed = 40 m/min; distance, printer to oven = 5 m.

[b] Print paste used in run multiplied by mineral spirits added to print paste, weight percent.

[c] Estimate provided by industry contacts.

[d] Estimated on the basis of 2.5 cm of overprint on each side of fabric.

[e] Emission splits calculated from percentages provided by evaporation computations.

Table 4.11-3 (English Units). SOURCES OF MINERAL SPIRIT EMISSIONS FROM A TYPICAL TEXTILE FABRIC PRINTING RUN[a]

Source	Percent Of Total Emissions	Roller		Rotary Screen		Flat Screen	
		Range (lb)	Average (lb)	Range (lb)	Average (lb)	Range (lb)	Average (lb)
Mineral spirits used in run[b]	100.0	0 - 1,005	425	0 - 2,754	51	399 - 1,508	635
Wasted mineral spirits (potential water emissions)[c]	6.2	0 - 62	26	0 - 170	2	24 - 93	40
Overprinted mineral spirit fugitives[d]	3.5	0 - 35	15	0 - 97	2	13 - 53	22
Tray and barrel fugitives[e]	0.3	0 - 2	2	0 - 9	0	1 - 4	2
Flashoff fugitives[e]	1.5	0 - 15	6	0 - 41	1	6 - 22	9
Dryer emissions[e]	88.5	0 - 889	375	0 - 2,436	46	353 - 1,337	562

[a] Length of run = 10,936 yd; fabric width = 1.25 yd; total fabric area = 13,634 yd^2; line speed = 44 yd/min; distance, printer to oven = 5.5 yd.

[b] Print paste used in run multiplied by mineral spirits added to print paste, weight percent.

[c] Estimate provided by industry contacts.

[d] Estimated on the basis of 1 in. of overprint on each side of fabric.

[e] Emission splits calculated from percentages provided by evaporation computations.

Table 4.11-4 (Metric And English Units). TYPICAL INSPECTION VALUES FOR MINERAL SPIRITS[a]

Parameter	Range
Specific gravity at 15°C (60°F)	0.778 - 0.805
Viscosity at 25°C (77°F)	0.83 - 0.95 cP
Flash point (closed cup)	41 - 45°C (105 - 113°F)
Aniline point	43 - 62°C (110 - 144°F)
Kauri-Butanol number	32 - 45
Distillation range	
Initial boiling points	157 - 166°C (315 - 330°F)
50 percent value	168 - 178°C (334 - 348°F)
Final boiling points	199 - 201°C (390 - 394°F)
Composition (%)	
Total saturates	81.5 - 92.3
Total aromatics	7.7 - 18.5
C_8 and higher	7.5 - 18.5

[a] References 2,4.

Two types of dryers are used for printed fabric, steam coil or natural gas fired dryers, through which the fabric is conveyed on belts, racks, etc., and steam cans, with which the fabric makes direct contact. Most screen printed fabrics and practically all printed knit fabrics and terry towels are dried with the first type of dryer, not to stress the fabric. Roller printed fabrics and apparel fabrics requiring soft handling are dried on steam cans, which have lower installation and operating costs and which dry the fabric more quickly than other dryers.

Figure 4.11-1 is a schematic diagram of the rotary screen printing process, with emission points indicated. The flat screen printing process is virtually identical. The symbols for fugitive VOC emissions to the atmosphere indicate mineral spirits evaporating from print paste during application to fabric before drying. The largest VOC emission source is the drying and curing oven stack, which vents evaporated solvents (mineral spirits and water) to the atmosphere. The symbol for fugitive VOC emissions to the waste water indicates print paste mineral spirits washed with water from the printing blanket (continuous belt) and discharged in waste water.

Figure 4.11-2 is a schematic diagram of a roller printing process in which all emissions are fugitive. Fugitive VOC emissions from the "back grey" (fabric backing material that absorbs excess print paste) in the illustrated process are emissions to the atmosphere because the back grey is dried before being washed. In processes where the back grey is washed before drying, most of the fugitive VOC emissions from the back grey will be discharged into the waste water. In some roller printing processes, steam cans for drying printed fabric are enclosed, and drying process emissions are vented directly to the atmosphere.

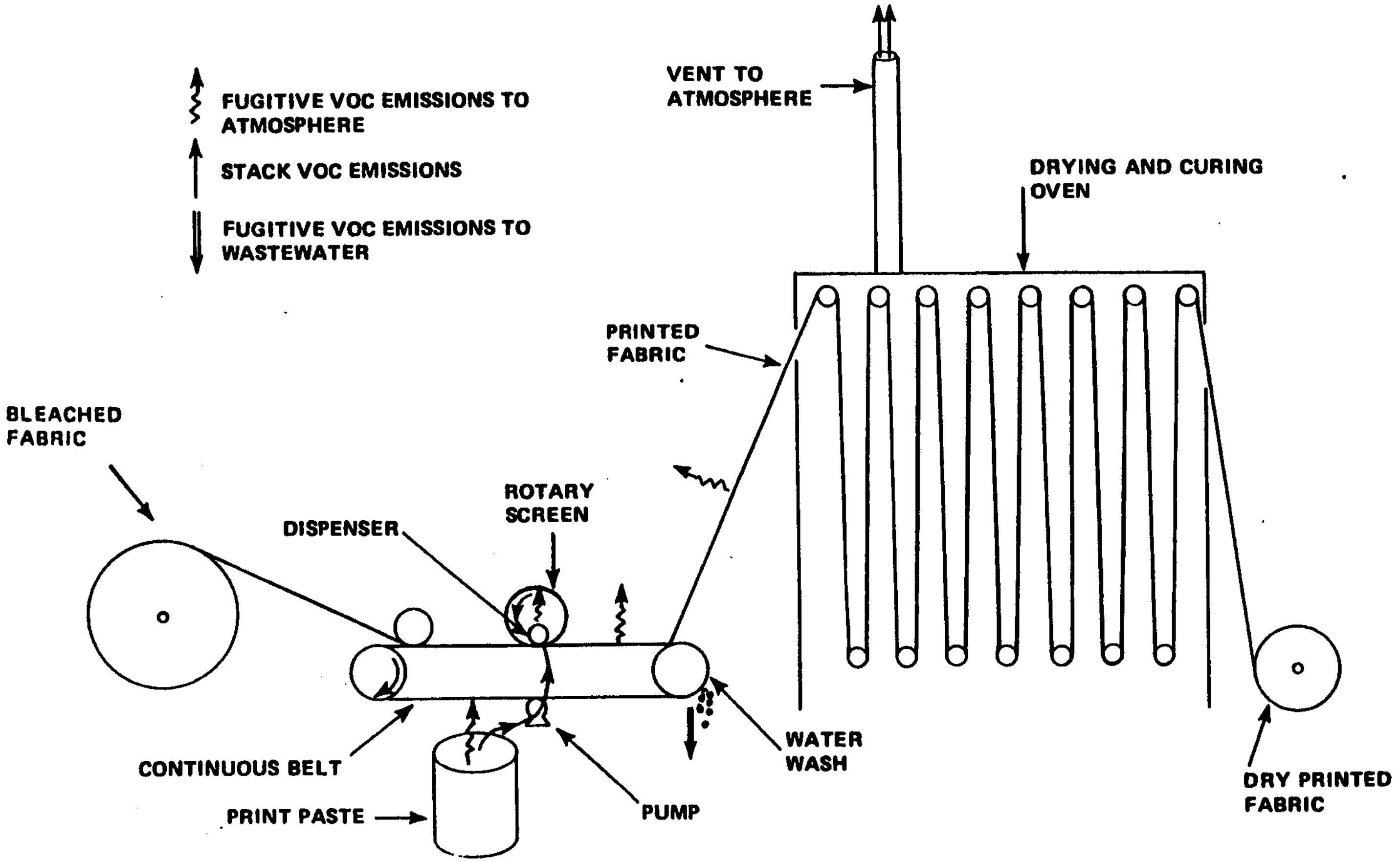

Figure 4.11-1. Schematic diagram of the rotary screen printing process, with fabric drying in a vented oven.

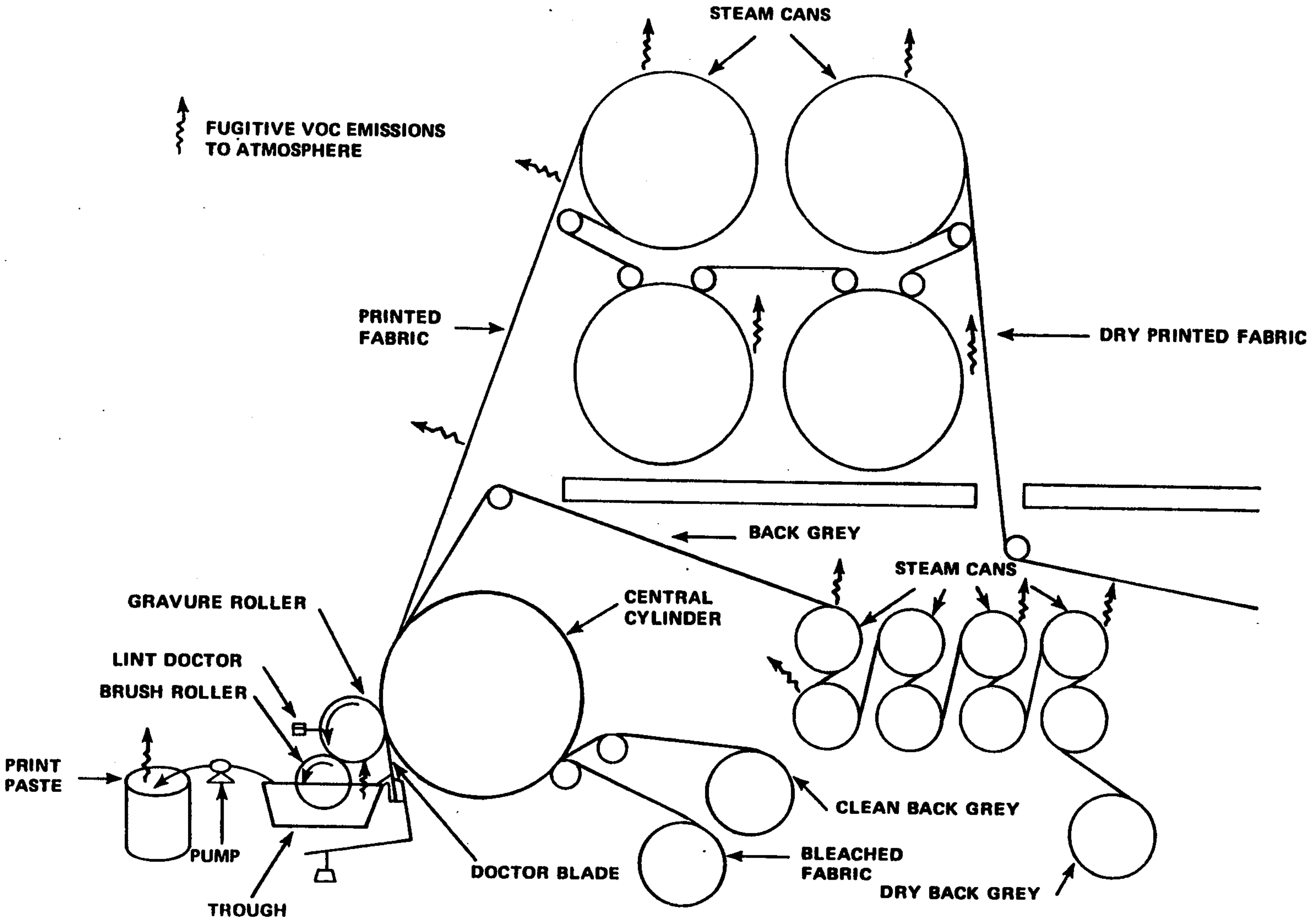

Figure 4.11-2. Schematic diagram of the roller printing process, with fabric drying on steam cans.

4.11.2 Emissions And Controls[1,3-12]

Presently there is no add-on emission control technology for organic solvent used in the textile fabric printing industry. Thermal incineration of oven exhaust has been evaluated in the Draft Background Information Document for New Source Performance Standard development[1] and has been found unaffordable for some fabric printers. The feasibility of using other types of add-on emission control equipment has not been fully evaluated. Significant organic solvent emissions reduction has been accomplished by reducing or eliminating the consumption of mineral spirit solvents. The use of aqueous or low organic solvent print pastes has increased during the past decade, because of the high price of organic solvents and higher energy costs associated with the use of higher solvent volumes. The only fabric printing applications presently requiring the use of large quantities of organic solvents are pigment printing of fashion or designer apparel fabric, and terry towels.

Table 4.11-5 presents average emission factors and ranges for each type of printing process and an average annual emission factor per print line, based on estimates submitted by individual fabric printers. No emission tests were done. VOC emission rates involve 3 parameters: organic solvent content of print pastes, consumption of print paste (a function of pattern coverage and fabric weight), and rate of fabric processing. With the quantity of fabric printed held constant, the lowest emission rate represents minimum organic solvent content print paste and minimum print paste consumption, and the maximum emission rate represents maximum organic solvent content print paste and maximum print paste consumption. The average emission rates shown for roller and rotary screen printing are based on the results of a VOC usage survey conducted by the American Textile Manufacturers Institute, Inc. (ATMI), in 1979. The average flat screen printing emission factor is based on information from 2 terry towel printers.

Although the average emission factors for roller and rotary screen printing are representative of the use of medium organic solvent content print pastes at average rates of print paste consumption, very little printing is actually done with medium organic solvent content pastes. The distribution of

Table 4.11-5 (Metric And English Units). TEXTILE FABRIC PRINTING ORGANIC EMISSION FACTORS[a]

EMISSION FACTOR RATING: C

VOC	Roller		Rotary Screen		Flat Screen[b]	
	Range	Average	Range	Average	Range	Average
kg/Mg fabric or lb/1000 lb fabric	0 - 348[c]	142[d]	0 - 945[c]	23[d]	51 - 191[c]	79[e]
Mg (ton)/yr/print line[c]		130[c] (139)		29[c] (31)		29[e] (31)

[a] Transfer printing, carpet printing, and printing of vinyl-coated cloth are specifically excluded from this compilation.

[b] Flat screen factors apply to terry towel printing. Rotary screen factors should be applied to flat screen printing of other types of fabric (e. g., sheeting, bottom weight apparel, etc.).

[c] Reference 13.

[d] Reference 5.

[e] Reference 6.

print paste use is bimodal, with the arithmetic average falling between the modes. Most fabric is printed with aqueous or low organic solvent print pastes. However, in applications where the use of organic solvents is beneficial, high organic solvent content print pastes are used to derive the full benefit of using organic solvents. The most accurate emissions data can be generated by obtaining organic solvent use data for a particular facility. The emission factors presented here should only be used to estimate actual process emissions.

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5. PETROLEUM INDUSTRY

The petroleum industry involves the refining of crude petroleum and the processing of natural gas into a multitude of products, as well as the distribution and marketing of petroleum-derived products. The primary pollutant emitted is volatile organic compounds arising from leakage, venting, and evaporation of the raw materials and finished products. Significant amounts of sulfur oxides, hydrogen sulfide, particulate matter, and a number of toxic species can also be generated from operations specific to this industry. In addition, a wide variety of fuel combustion devices emits all of the criteria pollutants and a number of toxic species.

5.1 Petroleum Refining[1]

5.1.1 General Description

The petroleum refining industry converts crude oil into more than 2500 refined products, including liquefied petroleum gas, gasoline, kerosene, aviation fuel, diesel fuel, fuel oils, lubricating oils, and feedstocks for the petrochemical industry. Petroleum refinery activities start with receipt of crude for storage at the refinery, include all petroleum handling and refining operations, and they terminate with storage preparatory to shipping the refined products from the refinery.

The petroleum refining industry employs a wide variety of processes. A refinery's processing flow scheme is largely determined by the composition of the crude oil feedstock and the chosen slate of petroleum products. The example refinery flow scheme presented in Figure 5.1-1 shows the general processing arrangement used by refineries in the United States for major refinery processes. The arrangement of these processes will vary among refineries, and few, if any, employ all of these processes. Petroleum refining processes having direct emission sources are presented on the figure in bold-line boxes.

Listed below are 5 categories of general refinery processes and associated operations:

1. Separation processes
    a. Atmospheric distillation
    b. Vacuum distillation
    c. Light ends recovery (gas processing)
2. Petroleum conversion processes
    a. Cracking (thermal and catalytic)
    b. Reforming
    c. Alkylation
    d. Polymerization
    e. Isomerization
    f. Coking
    g. Visbreaking
3. Petroleum treating processes
    a. Hydrodesulfurization
    b. Hydrotreating
    c. Chemical sweetening
    d. Acid gas removal
    e. Deasphalting
4. Feedstock and product handling
    a. Storage
    b. Blending
    c. Loading
    d. Unloading
5. Auxiliary facilities
    a. Boilers
    b. Waste water treatment
    c. Hydrogen production
    d. Sulfur recovery plant

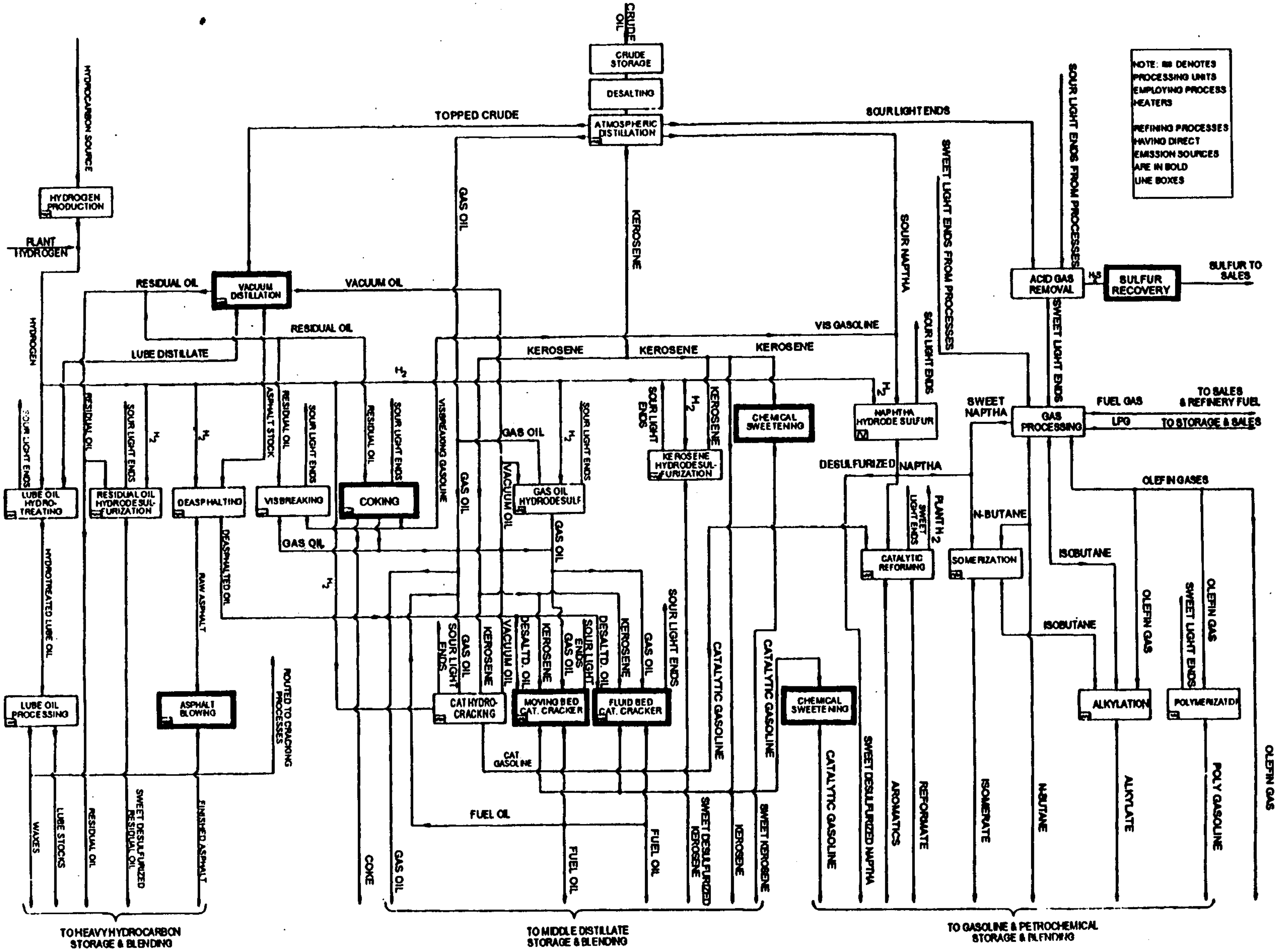

Figure 5.1-1. Schematic of an example integrated petroleum refinery.

e. Cooling towers
f. Blowdown system
g. Compressor engines

These refinery processes are defined below, and their emission characteristics and applicable emission control technology are discussed.

5.1.1.1 Separation Processes -

The first phase in petroleum refining operations is the separation of crude oil into its major constituents using 3 petroleum separation processes: atmospheric distillation, vacuum distillation, and light ends recovery (gas processing). Crude oil consists of a mixture of hydrocarbon compounds including paraffinic, naphthenic, and aromatic hydrocarbons with small amounts of impurities including sulfur, nitrogen, oxygen, and metals. Refinery separation processes separate these crude oil constituents into common boiling-point fractions.

5.1.1.2 Conversion Processes -

To meet the demands for high-octane gasoline, jet fuel, and diesel fuel, components such as residual oils, fuel oils, and light ends are converted to gasolines and other light fractions. Cracking, coking, and visbreaking processes are used to break large petroleum molecules into smaller ones. Polymerization and alkylation processes are used to combine small petroleum molecules into larger ones. Isomerization and reforming processes are applied to rearrange the structure of petroleum molecules to produce higher-value molecules of a similar molecular size.

5.1.1.3 Treating Processes -

Petroleum treating processes stabilize and upgrade petroleum products by separating them from less desirable products and by removing objectionable elements. Undesirable elements such as sulfur, nitrogen, and oxygen are removed by hydrodesulfurization, hydrotreating, chemical sweetening, and acid gas removal. Treating processes, employed primarily for the separation of petroleum products, include such processes as deasphalting. Desalting is used to remove salt, minerals, grit, and water from crude oil feedstocks before refining. Asphalt blowing is used for polymerizing and stabilizing asphalt to improve its weathering characteristics.

5.1.1.4 Feedstock And Product Handling -

The refinery feedstock and product handling operations consist of unloading, storage, blending, and loading activities.

5.1.1.5 Auxiliary Facilities -

A wide assortment of processes and equipment not directly involved in the refining of crude oil is used in functions vital to the operation of the refinery. Examples are boilers, waste water treatment facilities, hydrogen plants, cooling towers, and sulfur recovery units. Products from auxiliary facilities (clean water, steam, and process heat) are required by most process units throughout the refinery.

5.1.2 Process Emission Sources And Control Technology

This section presents descriptions of those refining processes that are significant air pollutant contributors. Process flow schemes, emission characteristics, and emission control technology are discussed for each process. Table 5.1-1 lists the emission factors for direct-process emissions in

Table 5.1-1 (Metric And English Units). EMISSION FACTORS FOR PETROLEUM REFINERIES[a]

Process	Particulate	Sulfur Oxides (as SO_2)	Carbon Monoxide	Total Hydrocarbons[b]	Nitrogen Oxides (as NO_2)	Aldehydes	Ammonia	EMISSION FACTOR RATING
Boilers and process heaters								
Fuel oil	See Section 1.3 - "Fuel Oil Combustion"							
Natural gas	See Section 1.4 - "Natural Gas Combustion"							
Fluid catalytic cracking units (FCC)[c]								
Uncontrolled								
kg/10^3 L fresh feed	0.695 (0.267 to 0.976)	1.413 (0.286 to 1.505)	39.2	0.630	0.204 (0.107 to 0.416)	0.054	0.155	B
lb/10^3 bbl fresh feed	242 (93 to 340)	493 (100 to 525)	13,700	220	71.0 (37.1 to 145.0)	19	54	B
Electrostatic precipitator and CO boiler								
kg/10^3 L fresh feed	0.128[d] (0.020 to 0.428)	1.413 (0.286 to 1.505)	Neg	Neg	0.204[e] (0.107 to 0.416)	Neg	Neg	B
lb/10^3 bbl fresh feed	45[d] (7 to 150)	493 (100 to 525)	Neg	Neg	71.0[e] (37.1 to 145.0)	Neg	Neg	B
Moving-bed catalytic cracking units[f]								
kg/10^3 L fresh feed	0.049	0.171	10.8	0.250	0.014	0.034	0.017	B
lb/10^3 bbl fresh feed	17	60	3,800	87	5	12	6	B
Fluid coking units[g]								
Uncontrolled								
kg/10^3 L fresh feed	1.50	ND	ND	ND	ND	ND	ND	C
lb/10^3 bbl fresh feed	523	ND	ND	ND	ND	ND	ND	C
Electrostatic precipitator and CO boiler								
kg/10^3 L fresh feed	0.0196	ND	Neg	Neg	ND	Neg	Neg	C
lb/10^3 bbl fresh feed	6.85	ND	Neg	Neg	ND	Neg	Neg	C

Table 5.1-1 (cont.).

Process	Particulate	Sulfur Oxides (as SO_2)	Carbon Monoxide	Total Hydro-carbons[b]	Nitrogen Oxides (as NO_2)	Aldehydes	Ammonia	EMISSION FACTOR RATING
Delayed coking units	ND	ND	ND	ND	ND	ND	ND	NA
Compressor engines[h]								
Reciprocating engines								
kg/10^3 m^3 gas burned	Neg	2s[j]	7.02	21.8	55.4	1.61	3.2	B
lb/10^3 ft^3 gas burned	Neg	2s	0.43	1.4	3.4	0.1	0.2	B
Gas turbines								
kg/10^3 m^3 gas burned	Neg	2s	1.94	0.28	4.7	ND	ND	B
lb/10^3 ft^3 gas burned	Neg	2s	0.12	0.02	0.3	ND	ND	B
Blowdown systems[k]								
Uncontrolled								
kg/10^3 L refinery feed	Neg	Neg	Neg	1,662	Neg	Neg	Neg	C
lb/10^3 bbl refinery feed	Neg	Neg	Neg	580	Neg	Neg	Neg	C
Vapor recovery system and flaring								
kg/10^3 L refinery feed	Neg	0.077	0.012	0.002	0.054	Neg	Neg	C
lb/10^3 bbl refinery feed	Neg	26.9	4.3	0.8	18.9	Neg	Neg	C
Vacuum distillation column condensers[m]								
Uncontrolled								
kg/10^3 L vacuum feed	Neg	Neg	Neg	0.14 (0 to 0.37)	Neg	Neg	Neg	C
lb/10^3 bbl vacuum feed	Neg	Neg	Neg	50 (0 to 130)	Neg	Neg	Neg	C
Controlled (vented to heater or incinerator)	Neg	Neg	Neg	Neg	Neg	Neg	Neg	C

Table 5.1-1 (cont.).

Process	Particulate	Sulfur Oxides (as SO_2)	Carbon Monoxide	Total Hydro-carbons[b]	Nitrogen Oxides (as NO_2)	Aldehydes	Ammonia	EMISSION FACTOR RATING
Claus plant and tail gas treatment	See Section 8.13 - "Sulfur Recovery"							

[a] Numbers in parentheses indicate range of values observed. Neg = negligible. ND = no data.

[b] Overall, less than 1 weight % of total hydrocarbon emissions is methane.

[c] References 2-8.

[d] Under the New Source Performance Standards, controlled FCC regenerators must have particulate emissions lower than 0.054 kg/10^3 L (19 lb/10^3 bbl) fresh feed.

[e] May be higher, from the combustion of ammonia.

[g] Reference 2.

[g] Reference 5.

[h] References 9-10.

[j] Based on 100% combustion of sulfur to SO_2. s = refinery gas sulfur content (in kg/1000 m^3 or lb/1000 ft^3, depending on desired units for emission factor).

[k] References 2,11.

[m] References 2,12-13. If refinery feed rate is known, rather than vacuum feed rate, assume vacuum feed is 36% of refinery feed. Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column.

petroleum refineries. Factors are expressed in units of kilograms per 1000 liters ($kg/10^3$ L) or kilograms per 1000 cubic meters ($kg/10^3\ m^3$) and pounds per 1000 barrels ($lb/10^3$ bbl) or pounds per 1000 cubic feet ($lb/10^3\ ft^3$). The following process emission sources are discussed here:

1. Vacuum distillation
2. Catalytic cracking
3. Thermal cracking processes
4. Utility boilers
5. Heaters
6. Compressor engines
7. Blowdown systems
8. Sulfur recovery

5.1.2.1 Vacuum Distillation -

Topped crude withdrawn from the bottom of the atmospheric distillation column is composed of high boiling-point hydrocarbons. When distilled at atmospheric pressures, the crude oil decomposes and polymerizes and will foul equipment. To separate topped crude into components, it must be distilled in a vacuum column at a very low pressure and in a steam atmosphere.

In the vacuum distillation unit, topped crude is heated with a process heater to temperatures ranging from 370 to 425°C (700 to 800°F). The heated topped crude is flashed into a multitray vacuum distillation column operating at absolute pressures ranging from 350 to 1400 kilograms per square meter (kg/m^2) (0.5 to 2 pounds per square inch absolute [psia]). In the vacuum column, the topped crude is separated into common boiling-point fractions by vaporization and condensation. Stripping steam is normally injected into the bottom of the vacuum distillation column to assist the separation by lowering the effective partial pressures of the components. Standard petroleum fractions withdrawn from the vacuum distillation column include lube distillates, vacuum oil, asphalt stocks, and residual oils. The vacuum in the vacuum distillation column is usually maintained by the use of steam ejectors but may be maintained by the use of vacuum pumps.

The major sources of atmospheric emissions from the vacuum distillation column are associated with the steam ejectors or vacuum pumps. A major portion of the vapors withdrawn from the column by the ejectors or pumps is recovered in condensers. Historically, the noncondensable portion of the vapors has been vented to the atmosphere from the condensers. There are approximately 0.14 kg of noncondensable hydrocarbons per m^3 (50 $lb/10^3$ bbl) of topped crude processed in the vacuum distillation column.[2,12-13] A second source of atmospheric emissions from vacuum distillation columns is combustion products from the process heater. Process heater requirements for the vacuum distillation column are approximately 245 megajoules per cubic meter (MJ/m^3) (37,000 British thermal units per barrel [Btu/bbl]) of topped crude processed in the vacuum column. Process heater emissions and their control are discussed below. Fugitive hydrocarbon emissions from leaking seals and fittings are also associated with the vacuum distillation unit, but these are minimized by the low operating pressures and low vapor pressures in the unit. Fugitive emission sources are also discussed later.

Control technology applicable to the noncondensable emissions vented from the vacuum ejectors or pumps includes venting into blowdown systems or fuel gas systems, and incineration in furnaces or waste heat boilers.[2,12-13] These control techniques are generally greater than 99 percent efficient in the control of hydrocarbon emissions, but they also contribute to the emission of combustion products.

5.1.2.2 Catalytic Cracking -

Catalytic cracking, using heat, pressure, and catalysts, converts heavy oils into lighter products with product distributions favoring the more valuable gasoline and distillate blending components. Feedstocks are usually gas oils from atmospheric distillation, vacuum distillation, coking, and deasphalting processes. These feedstocks typically have a boiling range of 340 to 540°C (650 to 1000°F). All of the catalytic cracking processes in use today can be classified as either fluidized-bed or moving-bed units.

5.1.2.2.1 Fluidized-bed Catalytic Cracking (FCC) -

The FCC process uses a catalyst in the form of very fine particles that act as a fluid when aerated with a vapor. Fresh feed is preheated in a process heater and introduced into the bottom of a vertical transfer line or riser with hot regenerated catalyst. The hot catalyst vaporizes the feed, bringing both to the desired reaction temperature, 470 to 525°C (880 to 980°F) The high activity of modern catalysts causes most of the cracking reactions to take place in the riser as the catalyst and oil mixture flows upward into the reactor. The hydrocarbon vapors are separated from the catalyst particles by cyclones in the reactor. The reaction products are sent to a fractionator for separation.

The spent catalyst falls to the bottom of the reactor and is steam stripped as it exits the reactor bottom to remove absorbed hydrocarbons. The spent catalyst is then conveyed to a regenerator. In the regenerator, coke deposited on the catalyst as a result of the cracking reactions is burned off in a controlled combustion process with preheated air. Regenerator temperature is usually 590 to 675°C (1100 to 1250°F). The catalyst is then recycled to be mixed with fresh hydrocarbon feed.

5.1.2.2.2 Moving-bed Catalytic Cracking-

In the moving-bed system, typified by the Thermafor Catalytic Cracking (TCC) units, catalyst beads (~0.5 centimeters [cm] [0.2 inches (in.)]) flow into the top of the reactor, where they contact a mixed-phase hydrocarbon feed. Cracking reactions take place as the catalyst and hydrocarbons move concurrently downward through the reactor to a zone where the catalyst is separated from the vapors. The gaseous reaction products flow out of the reactor to the fractionation section of the unit. The catalyst is steam stripped to remove any adsorbed hydrocarbons. It then falls into the regenerator, where coke is burned from the catalyst with air. The regenerated catalyst is separated from the flue gases and recycled to be mixed with fresh hydrocarbon feed. The operating temperatures of the reactor and regenerator in the TCC process are comparable to those in the FCC process.

Air emissions from catalytic cracking processes are (1) combustion products from process heaters and (2) flue gas from catalyst regeneration. Emissions from process heaters are discussed below. Emissions from the catalyst regenerator include hydrocarbons, oxides of sulfur, ammonia, aldehydes, oxides of nitrogen, cyanides, carbon monoxide (CO), and particulates (Table 5.1-1). The particulate emissions from FCC units are much greater than those from TCC units because of the higher catalyst circulation rates used.[2-3,5]

FCC particulate emissions are controlled by cyclones and/or electrostatic precipitators. Particulate control efficiencies are as high as 80 to 85 percent.[3,5] Carbon monoxide waste heat boilers reduce the CO and hydrocarbon emissions from FCC units to negligible levels.[3] TCC catalyst regeneration produces similar pollutants to FCC units, but in much smaller quantities (Table 5.1-1). The particulate emissions from a TCC unit are normally controlled by high-efficiency cyclones. Carbon monoxide and hydrocarbon emissions from a TCC unit are incinerated to negligible levels by passing the flue gases through a process heater firebox or smoke plume burner. In some installations, sulfur oxides are removed by passing the regenerator flue gases through a water or caustic scrubber.[2-3,5]

5.1.2.3 Thermal Cracking -

Thermal cracking processes include visbreaking and coking, which break heavy oil molecules by exposing them to high temperatures.

5.1.2.3.1 Visbreaking -

Topped crude or vacuum residuals are heated and thermally cracked (455 to 480°C, 3.5 to 17.6 kg/cm^2 [850 to 900°F, 50 to 250 pounds per square inch gauge (psig)]) in the visbreaker furnace to reduce the viscosity, or pour point, of the charge. The cracked products are quenched with gas oil and flashed into a fractionator. The vapor overhead from the fractionator is separated into light distillate products. A heavy distillate recovered from the fractionator liquid can be used as either a fuel oil blending component or catalytic cracking feed.

5.1.2.3.2 Coking -

Coking is a thermal cracking process used to convert low value residual fuel oil to higher-value gas oil and petroleum coke. Vacuum residuals and thermal tars are cracked in the coking process at high temperature and low pressure. Products are petroleum coke, gas oils, and lighter petroleum stocks. Delayed coking is the most widely used process today, but fluid coking is expected to become an important process in the future.

In the delayed coking process, heated charge stock is fed into the bottom of a fractionator, where light ends are stripped from the feed. The stripped feed is then combined with recycle products from the coke drum and rapidly heated in the coking heater to a temperature of 480 to 590°C (900 to 1100°F). Steam injection is used to control the residence time in the heater. The vapor-liquid feed leaves the heater, passing to a coke drum where, with controlled residence time, pressure (1.8 to 2.1 kg/cm^2 [25 to 30 psig]), and temperature (400°C [750°F]), it is cracked to form coke and vapors. Vapors from the drum return to the fractionator, where the thermal cracking products are recovered.

In the fluid coking process, typified by Flexicoking, residual oil feeds are injected into the reactor, where they are thermally cracked, yielding coke and a wide range of vapor products. Vapors leave the reactor and are quenched in a scrubber, where entrained coke fines are removed. The vapors are then fractionated. Coke from the reactor enters a heater and is devolatilized. The volatiles from the heater are treated for fines and sulfur removal to yield a particulate-free, low-sulfur fuel gas. The devolatilized coke is circulated from the heater to a gasifier where 95 percent of the reactor coke is gasified at high temperature with steam and air or oxygen. The gaseous products and coke from the gasifier are returned to the heater to supply heat for the devolatilization. These gases exit the heater with the heater volatiles through the same fines and sulfur removal processes.

From available literature, it is unclear what emissions are released and where they are released. Air emissions from thermal cracking processes include coke dust from decoking operations, combustion gases from the visbreaking and coking process heaters, and fugitive emissions. Emissions from the process heaters are discussed below. Fugitive emissions from miscellaneous leaks are significant because of the high temperatures involved, and are dependent upon equipment type and configuration, operating conditions, and general maintenance practices. Fugitive emissions are also discussed below. Particulate emissions from delayed coking operations are potentially very significant. These emissions are associated with removing the coke from the coke drum and subsequent handling and storage operations. Hydrocarbon emissions are also associated with cooling and venting the coke drum before coke removal. However, comprehensive data for delayed coking emissions have not been included in available literature.[4-5]

Particulate emission control is accomplished in the decoking operation by wetting down the coke.[5] Generally, there is no control of hydrocarbon emissions from delayed coking. However, some facilities are now collecting coke drum emissions in an enclosed system and routing them to a refinery flare.[4-5]

5.1.2.4 Utilities Plant -

The utilities plant supplies the steam necessary for the refinery. Although the steam can be used to produce electricity by throttling through a turbine, it is primarily used for heating and separating hydrocarbon streams. When used for heating, the steam usually heats the petroleum indirectly in heat exchangers and returns to the boiler. In direct contact operations, the steam can serve as a stripping medium or a process fluid. Steam may also be used in vacuum ejectors to produce a vacuum. Boiler emissions and applicable emission control technology are discussed in much greater detail in Chapter 1.

5.1.2.5 Sulfur Recovery Plant -

Sulfur recovery plants are used in petroleum refineries to convert the hydrogen sulfide (H_2S) separated from refinery gas streams into the more disposable byproduct, elemental sulfur. Emissions from sulfur recovery plants and their control are discussed in Section 8.13, "Sulfur Recovery".

5.1.2.6 Blowdown System -

The blowdown system provides for the safe disposal of hydrocarbons (vapor and liquid) discharged from pressure relief devices.

Most refining processing units and equipment subject to planned or unplanned hydrocarbon discharges are manifolded into a collection unit, called blowdown system. By using a series of flash drums and condensers arranged in decreasing pressure, blowdown material is separated into vapor and liquid cuts. The separated liquid is recycled into the refinery. The gaseous cuts can either be smokelessly flared or recycled.

Uncontrolled blowdown emissions primarily consist of hydrocarbons but can also include any of the other criteria pollutants. The emission rate in a blowdown system is a function of the amount of equipment manifolded into the system, the frequency of equipment discharges, and the blowdown system controls.

Emissions from the blowdown system can be effectively controlled by combustion of the noncondensables in a flare. To obtain complete combustion or smokeless burning (as required by most states), steam is injected in the combustion zone of the flare to provide turbulence and air. Steam injection also reduces emissions of nitrogen oxides by lowering the flame temperature. Controlled emissions are listed in Table 5.1-1.[2,11]

5.1.2.7 Process Heaters -

Process heaters (furnaces) are used extensively in refineries to supply the heat necessary to raise the temperature of feed materials to reaction or distillation level. They are designed to raise petroleum fluid temperatures to a maximum of about 510°C (950°F). The fuel burned may be refinery gas, natural gas, residual fuel oils, or combinations, depending on economics, operating conditions, and emission requirements. Process heaters may also use CO-rich regenerator flue gas as fuel.

All the criteria pollutants are emitted from process heaters. The quantity of these emissions is a function of the type of fuel burned, the nature of the contaminants in the fuel, and the heat duty of the furnace. Sulfur oxides can be controlled by fuel desulfurization or flue gas treatment. Carbon monoxide and hydrocarbons can be controlled by more combustion efficiency. Currently, 4 general techniques or modifications for the control of nitrogen oxides are being investigated: combustion modification, fuel modification, furnace design, and flue gas treatment. Several of these techniques are being applied to large utility boilers, but their applicability to process heaters has not been established.[2,14]

5.1.2.8 Compressor Engines -

Many older refineries run high-pressure compressors with reciprocating and gas turbine engines fired with natural gas. Natural gas has usually been a cheap, abundant source of energy. Examples of refining units operating at high pressure include hydrodesulfurization, isomerization, reforming, and hydrocracking. Internal combustion engines are less reliable and harder to maintain than are steam engines or electric motors. For this reason, and because of increasing natural gas costs, very few such units have been installed in the last few years.

The major source of emissions from compressor engines is combustion products in the exhaust gas. These emissions include CO, hydrocarbons, nitrogen oxides, aldehydes, and ammonia. Sulfur oxides may also be present, depending on the sulfur content of the natural gas. All these emissions are significantly higher in exhaust from reciprocating engines than from turbine engines.

The major emission control technique applied to compressor engines is carburetion adjustment similar to that applied on automobiles. Catalyst systems similar to those of automobiles may also be effective in reducing emissions, but their use has not been reported.

5.1.2.9 Sweetening -

Sweetening of distillates is accomplished by the conversion of mercaptans to alkyl disulfides in the presence of a catalyst. Conversion may be followed by an extraction step for removal of the alkyl disulfides. In the conversion process, sulfur is added to the sour distillate with a small amount of caustic and air. The mixture is then passed upward through a fixed-bed catalyst, counter to a flow of caustic entering at the top of the vessel. In the conversion and extraction process, the sour distillate is washed with caustic and then is contacted in the extractor with a solution of catalyst and caustic. The extracted distillate is then contacted with air to convert mercaptans to disulfides. After oxidation, the distillate is settled, inhibitors are added, and the distillate is sent to storage. Regeneration is accomplished by mixing caustic from the bottom of the extractor with air and then separating the disulfides and excess air.

The major emission problem is hydrocarbons from contact of the distillate product and air in the "air blowing" step. These emissions are related to equipment type and configuration, as well as to operating conditions and maintenance practices.[4]

5.1.2.10 Asphalt Blowing -

The asphalt blowing process polymerizes asphaltic residual oils by oxidation, increasing their melting temperature and hardness to achieve an increased resistance to weathering. The oils, containing a large quantity of polycyclic aromatic compounds (asphaltic oils), are oxidized by blowing heated air through a heated batch mixture or, in a continuous process, by passing hot air countercurrent to the oil flow. The reaction is exothermic, and quench steam is sometimes needed for temperature control. In some cases, ferric chloride or phosphorus pentoxide is used as a catalyst to increase the reaction rate and to impart special characteristics to the asphalt.

Air emissions from asphalt blowing are primarily hydrocarbon vapors vented with the blowing air. The quantities of emissions are small because of the prior removal of volatile hydrocarbons in the distillation units, but the emissions may contain hazardous polynuclear organics. Emissions are 30 kg/megagram (Mg) (60 lb/ton) of asphalt.[13] Emissions from asphalt blowing can be controlled to negligible levels by vapor scrubbing, incineration, or both.[4,13]

5.1.3 Fugitive Emissions And Controls

Fugitive emission sources include leaks of hydrocarbon vapors from process equipment and evaporation of hydrocarbons from open areas, rather than through a stack or vent. Fugitive emission sources include valves of all types, flanges, pump and compressor seals, process drains, cooling towers, and oil/water separators. Fugitive emissions are attributable to the evaporation of leaked or spilled petroleum liquids and gases. Normally, control of fugitive emissions involves minimizing leaks and spills through equipment changes, procedure changes, and improved monitoring, housekeeping, and maintenance practices. Controlled and uncontrolled fugitive emission factors for the following sources are listed in Table 5.1-2:

- Oil/water separators (waste water treatment)
- Storage
- Transfer operations
- Cooling towers

Emission factors for fugitive leaks from the following types of process equipment can be found in *Protocol For Equipment Leak Emission Estimates*, EPA-453/R-93-026, June 1993, or subsequent updates:

- Valves (pipeline, open ended, vessel relief)
- Flanges
- Seals (pump, compressor)
- Process drains

5.1.3.1 Valves, Flanges, Seals, And Drains -

For these sources, a very high correlation has been found between mass emission rates and the type of stream service in which the sources are employed. The four stream service types are (1) hydrocarbon gas/vapor streams (including gas streams with up to 50 percent hydrogen by volume), (2) light liquid and gas/liquid streams, (3) kerosene and heavier liquid streams (includes all crude oils), and (4) gas streams containing more than 50 percent hydrogen by volume. It is found that sources in gas/vapor stream service have higher emission rates than those in heavier stream service. This trend is especially pronounced for valves and pump seals. The size of valves, flanges, pump seals, compressor seals, relief valves, and process drains does not affect their leak rates.[17] The emission factors are independent of process unit or refinery throughput.

Valves, because of their number and relatively high emission factor, are the major emission source. This conclusion is based on an analysis of a hypothetical refinery coupled with the emission rates. The total quantity of fugitive VOC emissions in a typical oil refinery with a capacity of 52,500 m^3 (330,000 bbl) per day is estimated as 20,500 kg (45,000 lb) per day (see Table 5.1-3). This estimate is based on a typical late 1970s refinery without a leak inspection and maintenance (I/M) program. See the *Protocol* document for details on how to estimate emissions for a specific refinery.

Table 5.1-2 (Metric And English Units). FUGITIVE EMISSION FACTORS FOR PETROLEUM REFINERIES[a]

EMISSION FACTOR RATING: D

Emission Source	Emission Factor Units	Emission Factors		Applicable Control Technology
		Uncontrolled Emissions	Controlled Emissions	
Cooling towers[b]	kg/10^6 L cooling water	0.7	0.08	Minimization of hydrocarbon leaks into cooling water system; monitoring of cooling water for hydrocarbons
	lb/10^6 gal cooling water	6	0.7	Minimization of hydrocarbon leaks into cooling water system; monitoring of cooling water for hydrocarbons
Oil/water separators[c]	kg/10^3 L waste water	0.6	0.024	Covered separators and/or vapor recovery systems
	lb/10^3 gal waste water	5	0.2	Covered separators and/or vapor recovery systems
Storage	See Chapter 7 - Liquid Storage Tanks			
Loading	See Section 5.2 - Transportation And Marketing Of Petroleum Liquids			

[a] References 2,4,12-13.

[b] If cooling water rate is unknown (in liters or gallons) assume it is 40 times the refinery feed rate (in liters or gallons). Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column. 1 bbl (oil) = 42 gallons (gal), 1 m^3 = 1000 L.

[c] If waste water flow rate to oil/water separators is unknown (in liters or gallons) assume it is 0.95 times the refinery feed rate (in liters or gallons). Refinery feed rate is defined as the crude oil feed rate to the atmospheric distillation column. 1 bbl (oil) = 42 gal, 1 m^3 = 1000 L.

5.1.3.2 Storage -

All refineries have a feedstock and product storage area, termed a "tank farm", which provides surge storage capacity to ensure smooth, uninterrupted refinery operations. Individual storage tank capacities range from less than 160 m^3 to more than 79,500 m^3 (1,000 to 500,000 bbl). Storage tank designs, emissions, and emission control technology are discussed in detail in AP-42 Chapter 7, and the *TANKS* software program is available to perform the emissions calculations, if desired.

Table 5.1-3 (Metric And English Units). FUGITIVE VOC EMISSIONS FROM AN UNCONTROLLED OIL REFINERY OF 52,500 m^3/day (330,000 bbl/day) CAPACITY[a]

Source	Number	VOC Emissions	
		kg/day	lb/day
Valves	11,500	3,100	6,800
Flanges	46,500	300	600
Pump seals	350	590	1,300
Compressor seals	70	500	1,100
Relief valves	100	200	500
Drains	650	450	1,000
Cooling towers[b]	1	730	1,600
Oil/water separators (uncovered)[b]	1	14,600	32,100
TOTAL	—	20,500	45,000

[a] Reference 17.
[b] Based on limited data.

5.1.3.3 Transfer Operations -

Although most refinery feedstocks and products are transported by pipeline, some are transported by trucks, rail cars, and marine vessels. They are transferred to and from these transport vehicles in the refinery tank farm area by specialized pumps and piping systems. The emissions from transfer operations and applicable emission control technology are discussed in much greater detail in Section 5.2, "Transportation And Marketing Of Petroleum Liquids".

5.1.3.4 Waste Water Treatment Plant -

All refineries employ some form of waste water treatment so water effluents can safely be returned to the environment or reused in the refinery. The design of waste water treatment plants is complicated by the diversity of refinery pollutants, including oil, phenols, sulfides, dissolved solids, and toxic chemicals. Although the treatment processes employed by refineries vary greatly, they generally include neutralizers, oil/water separators, settling chambers, clarifiers, dissolved air flotation systems, coagulators, aerated lagoons, and activated sludge ponds. Refinery water effluents are collected from various processing units and are conveyed through sewers and ditches to the treatment plant. Most of the treatment occurs in open ponds and tanks.

The main components of atmospheric emissions from waste water treatment plants are fugitive VOCs and dissolved gases that evaporate from the surfaces of waste water residing in open process drains, separators, and ponds (Table 5.1-2). Treatment processes that involve extensive contact of waste water and air, such as aeration ponds and dissolved air flotation, have an even greater potential for atmospheric emissions. Section 4.3, "Waste Water Collection, Treatment And Storage", discusses estimation techniques for such water treatment operations. *WATER8* and *SIMS* software models are available to perform the calculations.

The control of waste water treatment plant emissions involves covering systems where emission generation is greatest (such as oil/water separators and settling basins) and removing dissolved gases from water streams with sour water strippers and phenol recovery units before their contact with the atmosphere. These control techniques potentially can achieve greater than 90 percent reduction of waste water system emissions.[13]

5.1.3.5 Cooling Towers -

Cooling towers are used extensively in refinery cooling water systems to transfer waste heat from the cooling water to the atmosphere. The only refineries not employing cooling towers are those with once-through cooling. The increasing scarcity of a large water supply required for once-through cooling is contributing to the disappearance of that form of refinery cooling. In the cooling tower, warm cooling water returning from refinery processes is contacted with air by cascading through packing, Cooling water circulation rates for refineries commonly range from 7 to 70 L/minute per m^3/day (0.3 to 3.0 gal/minute per bbl/day) of refinery capacity.[2,16]

Atmospheric emissions from the cooling tower consist of fugitive VOCs and gases stripped from the cooling water as the air and water come into contact. These contaminants enter the cooling water system from leaking heat exchangers and condensers. Although the predominant contaminants in cooling water are VOCs, dissolved gases such as H_2S and ammonia may also be found (see Table 5.1-2).[2,4,17]

Control of cooling tower emissions is accomplished by reducing contamination of cooling water through the proper maintenance of heat exchangers and condensers. The effectiveness of cooling tower controls is highly variable, depending on refinery configuration and existing maintenance practices.[4]

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5.2 Transportation And Marketing Of Petroleum Liquids[1-3]

5.2.1 General

The transportation and marketing of petroleum liquids involve many distinct operations, each of which represents a potential source of evaporation loss. Crude oil is transported from production operations to a refinery by tankers, barges, rail tank cars, tank trucks, and pipelines. Refined petroleum products are conveyed to fuel marketing terminals and petrochemical industries by these same modes. From the fuel marketing terminals, the fuels are delivered by tank trucks to service stations, commercial accounts, and local bulk storage plants. The final destination for gasoline is usually a motor vehicle gasoline tank. Similar distribution paths exist for fuel oils and other petroleum products. A general depiction of these activities is shown in Figure 5.2-1.

5.2.2 Emissions And Controls

Evaporative emissions from the transportation and marketing of petroleum liquids may be considered, by storage equipment and mode of transportation used, in four categories:

1. Rail tank cars, tank trucks, and marine vessels: loading, transit, and ballasting losses.
2. Service stations: bulk fuel drop losses and underground tank breathing losses.
3. Motor vehicle tanks: refueling losses.
4. Large storage tanks: breathing, working, and standing storage losses. (See Chapter 7, "Liquid Storage Tanks".)

Evaporative and exhaust emissions are also associated with motor vehicle operation, and these topics are discussed in AP-42 *Volume II: Mobile Sources*.

5.2.2.1 Rail Tank Cars, Tank Trucks, And Marine Vessels -

Emissions from these sources are from loading losses, ballasting losses, and transit losses.

5.2.2.1.1 Loading Losses -

Loading losses are the primary source of evaporative emissions from rail tank car, tank truck, and marine vessel operations. Loading losses occur as organic vapors in "empty" cargo tanks are displaced to the atmosphere by the liquid being loaded into the tanks. These vapors are a composite of (1) vapors formed in the empty tank by evaporation of residual product from previous loads, (2) vapors transferred to the tank in vapor balance systems as product is being unloaded, and (3) vapors generated in the tank as the new product is being loaded. The quantity of evaporative losses from loading operations is, therefore, a function of the following parameters:

- Physical and chemical characteristics of the previous cargo;
- Method of unloading the previous cargo;
- Operations to transport the empty carrier to a loading terminal;
- Method of loading the new cargo; and
- Physical and chemical characteristics of the new cargo.

The principal methods of cargo carrier loading are illustrated in Figure 5.2-2, Figure 5.2-3, and Figure 5.2-4. In the splash loading method, the fill pipe dispensing the cargo is lowered only part way into the cargo tank. Significant turbulence and vapor/liquid contact occur during the splash

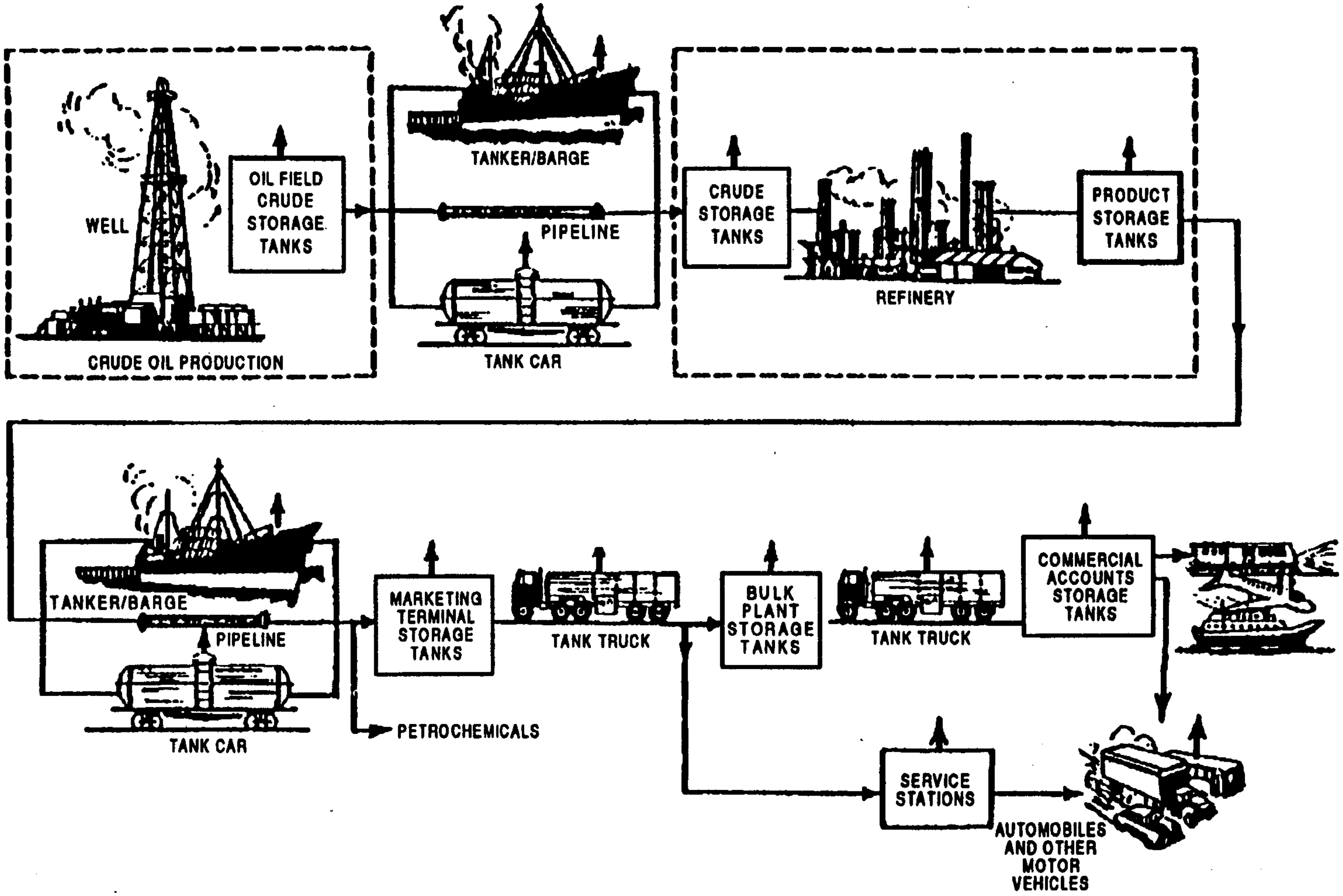

Figure 5.2-1. Flow sheet of petroleum production, refining, and distribution systems. (Points of organic emissions are indicated by vertical arrows.)

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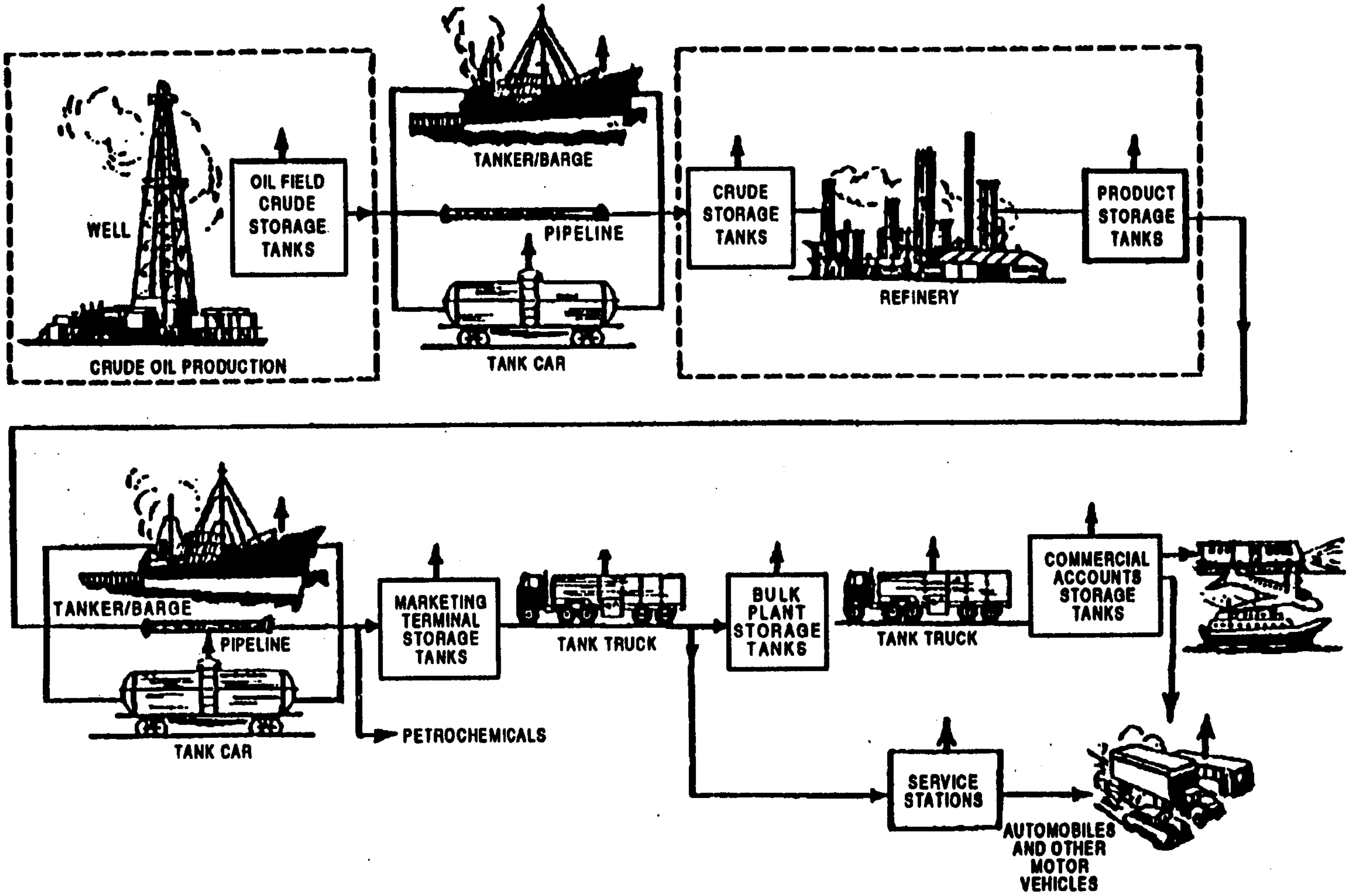

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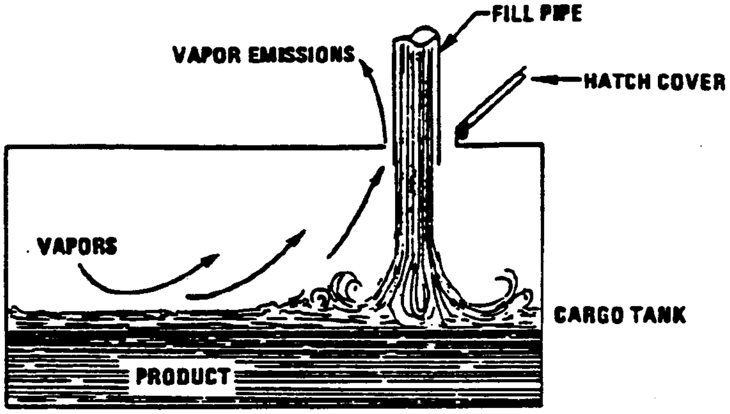

Figure 5.2-2. Splash loading method.

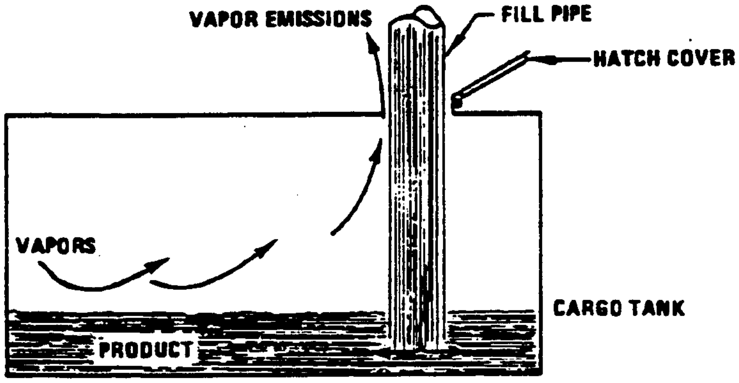

Figure 5.2-3. Submerged fill pipe.

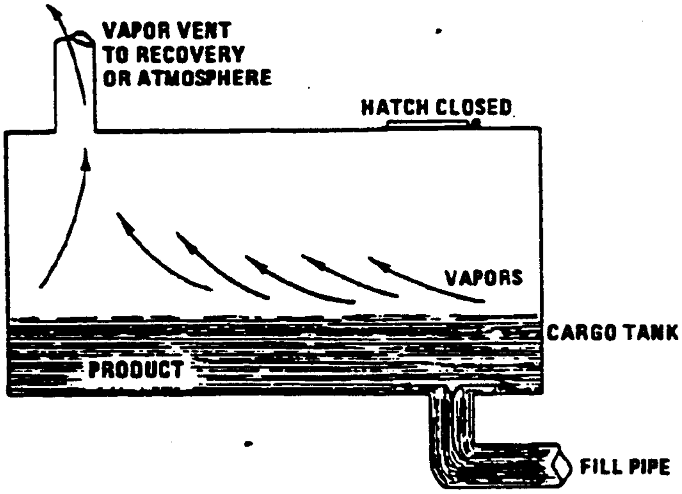

Figure 5.2-4. Bottom loading.

loading operation, resulting in high levels of vapor generation and loss. If the turbulence is great enough, liquid droplets will be entrained in the vented vapors.

A second method of loading is submerged loading. Two types are the submerged fill pipe method and the bottom loading method. In the submerged fill pipe method, the fill pipe extends almost to the bottom of the cargo tank. In the bottom loading method, a permanent fill pipe is attached to the cargo tank bottom. During most of submerged loading by both methods, the fill pipe opening is below the liquid surface level. Liquid turbulence is controlled significantly during submerged loading, resulting in much lower vapor generation than encountered during splash loading.

The recent loading history of a cargo carrier is just as important a factor in loading losses as the method of loading. If the carrier has carried a nonvolatile liquid such as fuel oil, or has just been cleaned, it will contain vapor-free air. If it has just carried gasoline and has not been vented, the air in the carrier tank will contain volatile organic vapors, which will be expelled during the loading operation along with newly generated vapors.

Cargo carriers are sometimes designated to transport only one product, and in such cases are practicing "dedicated service". Dedicated gasoline cargo tanks return to a loading terminal containing air fully or partially saturated with vapor from the previous load. Cargo tanks may also be "switch loaded" with various products, so that a nonvolatile product being loaded may expel the vapors remaining from a previous load of a volatile product such as gasoline. These circumstances vary with the type of cargo tank and with the ownership of the carrier, the petroleum liquids being transported, geographic location, and season of the year.

One control measure for vapors displaced during liquid loading is called "vapor balance service", in which the cargo tank retrieves the vapors displaced during product unloading at bulk plants or service stations and transports the vapors back to the loading terminal. Figure 5.2-5 shows a tank truck in vapor balance service filling a service station underground tank and taking on displaced gasoline vapors for return to the terminal. A cargo tank returning to a bulk terminal in vapor balance service normally is saturated with organic vapors, and the presence of these vapors at the start of submerged loading of the tanker truck results in greater loading losses than encountered during nonvapor balance, or "normal", service. Vapor balance service is usually not practiced with marine vessels, although some vessels practice emission control by means of vapor transfer within their own cargo tanks during ballasting operations, discussed below.

Emissions from loading petroleum liquid can be estimated (with a probable error of ±30 percent)[4] using the following expression:

$$L_L = 12.46 \frac{SPM}{T} \tag{1}$$

where:

L_L = loading loss, pounds per 1000 gallons (lb/10^3 gal) of liquid loaded
S = a saturation factor (see Table 5.2-1)
P = true vapor pressure of liquid loaded, pounds per square inch absolute (psia) (see Figure 7.1-5, Figure 7.1-6, and Table 7.1-2)
M = molecular weight of vapors, pounds per pound-mole (lb/lb-mole) (see Table 7.1-2)
T = temperature of bulk liquid loaded, °R (°F + 460)

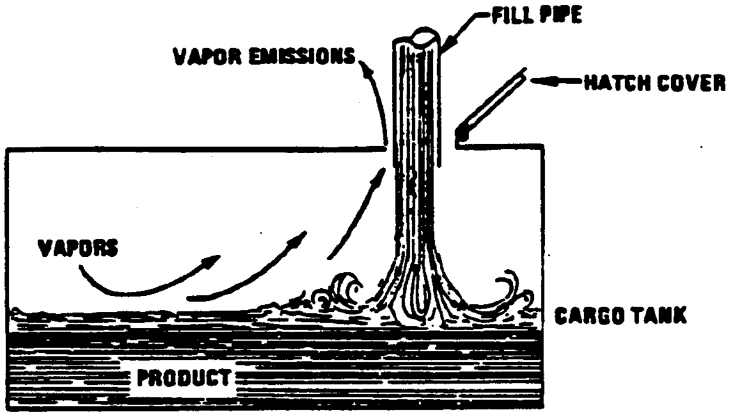

Figure 5.2-2. Splash loading method.

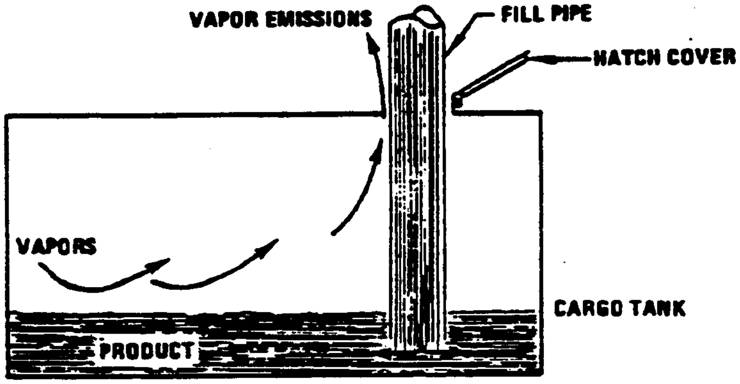

Figure 5.2-3. Submerged fill pipe.

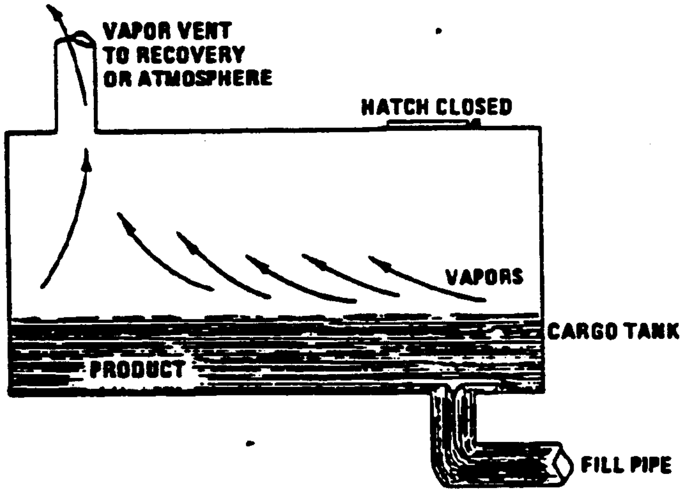

Figure 5.2-4. Bottom loading.

loading operation, resulting in high levels of vapor generation and loss. If the turbulence is great enough, liquid droplets will be entrained in the vented vapors.

A second method of loading is submerged loading. Two types are the submerged fill pipe method and the bottom loading method. In the submerged fill pipe method, the fill pipe extends almost to the bottom of the cargo tank. In the bottom loading method, a permanent fill pipe is attached to the cargo tank bottom. During most of submerged loading by both methods, the fill pipe opening is below the liquid surface level. Liquid turbulence is controlled significantly during submerged loading, resulting in much lower vapor generation than encountered during splash loading.

The recent loading history of a cargo carrier is just as important a factor in loading losses as the method of loading. If the carrier has carried a nonvolatile liquid such as fuel oil, or has just been cleaned, it will contain vapor-free air. If it has just carried gasoline and has not been vented, the air in the carrier tank will contain volatile organic vapors, which will be expelled during the loading operation along with newly generated vapors.

Cargo carriers are sometimes designated to transport only one product, and in such cases are practicing "dedicated service". Dedicated gasoline cargo tanks return to a loading terminal containing air fully or partially saturated with vapor from the previous load. Cargo tanks may also be "switch loaded" with various products, so that a nonvolatile product being loaded may expel the vapors remaining from a previous load of a volatile product such as gasoline. These circumstances vary with the type of cargo tank and with the ownership of the carrier, the petroleum liquids being transported, geographic location, and season of the year.

One control measure for vapors displaced during liquid loading is called "vapor balance service", in which the cargo tank retrieves the vapors displaced during product unloading at bulk plants or service stations and transports the vapors back to the loading terminal. Figure 5.2-5 shows a tank truck in vapor balance service filling a service station underground tank and taking on displaced gasoline vapors for return to the terminal. A cargo tank returning to a bulk terminal in vapor balance service normally is saturated with organic vapors, and the presence of these vapors at the start of submerged loading of the tanker truck results in greater loading losses than encountered during nonvapor balance, or "normal", service. Vapor balance service is usually not practiced with marine vessels, although some vessels practice emission control by means of vapor transfer within their own cargo tanks during ballasting operations, discussed below.

Emissions from loading petroleum liquid can be estimated (with a probable error of ±30 percent)[4] using the following expression:

$$L_L = 12.46 \frac{SPM}{T} \tag{1}$$

where:

L_L = loading loss, pounds per 1000 gallons (lb/10^3 gal) of liquid loaded
S = a saturation factor (see Table 5.2-1)
P = true vapor pressure of liquid loaded, pounds per square inch absolute (psia) (see Figure 7.1-5, Figure 7.1-6, and Table 7.1-2)
M = molecular weight of vapors, pounds per pound-mole (lb/lb-mole) (see Table 7.1-2)
T = temperature of bulk liquid loaded, °R (°F + 460)

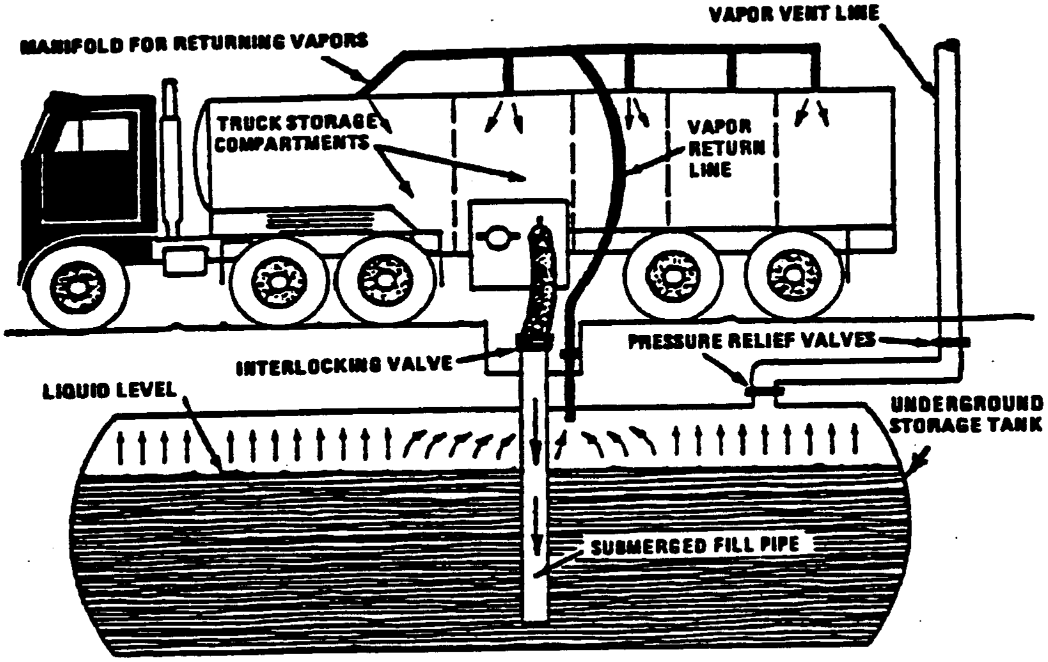

Figure 5.2-5. Tank truck unloading into a service station underground storage tank and practicing "vapor balance" form of emission control.

Table 5.2-1. SATURATION (S) FACTORS FOR CALCULATING PETROLEUM LIQUID LOADING LOSSES

Cargo Carrier	Mode Of Operation	S Factor
Tank trucks and rail tank cars	Submerged loading of a clean cargo tank	0.50
	Submerged loading: dedicated normal service	0.60
	Submerged loading: dedicated vapor balance service	1.00
	Splash loading of a clean cargo tank	1.45
	Splash loading: dedicated normal service	1.45
	Splash loading: dedicated vapor balance service	1.00
Marine vessels[a]	Submerged loading: ships	0.2
	Submerged loading: barges	0.5

[a] For products other than gasoline and crude oil. For marine loading of gasoline, use factors from Table 5.2-2. For marine loading of crude oil, use Equations 2 and 3 and Table 5.2-3.

The saturation factor, S, represents the expelled vapor's fractional approach to saturation, and it accounts for the variations observed in emission rates from the different unloading and loading methods. Table 5.2-1 lists suggested saturation factors.

Emissions from controlled loading operations can be calculated by multiplying the uncontrolled emission rate calculated in Equation 1 by an overall reduction efficiency term:

$$\left[1 - \frac{\text{eff}}{100}\right]$$

The overall reduction efficiency should account for the capture efficiency of the collection system as well as both the control efficiency and any downtime of the control device. Measures to reduce loading emissions include selection of alternate loading methods and application of vapor recovery equipment. The latter captures organic vapors displaced during loading operations and recovers the vapors by the use of refrigeration, absorption, adsorption, and/or compression. The recovered product is piped back to storage. Vapors can also be controlled through combustion in a thermal oxidation unit, with no product recovery. Figure 5.2-6 demonstrates the recovery of gasoline vapors from tank trucks during loading operations at bulk terminals. Control efficiencies for the recovery units range from 90 to over 99 percent, depending on both the nature of the vapors and the type of control equipment used.[5-6] However, only 70 to 90 percent of the displaced vapors reach the control device, because of leakage from both the tank truck and collection system.[6] The collection efficiency should be assumed to be 90 percent for tanker trucks required to pass an annual leak test. Otherwise, 70 percent should be assumed.

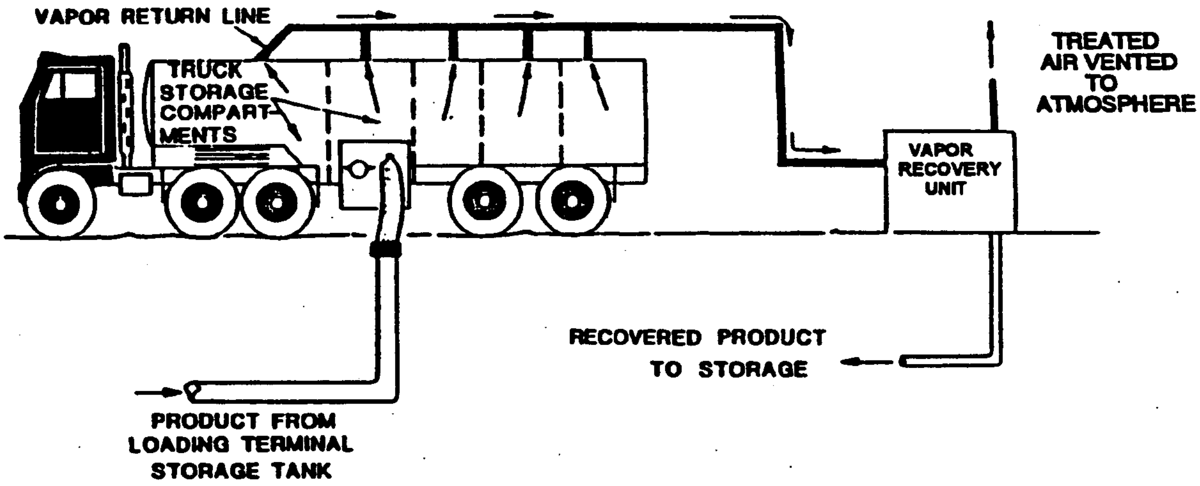

Figure 5.2-6. Tank truck loading with vapor recovery.

Sample Calculation -

Loading losses (L_L) from a gasoline tank truck in dedicated vapor balance service and practicing vapor recovery would be calculated as follows, using Equation 1:

Design basis -

Cargo tank volume is 8000 gal
Gasoline Reid vapor pressure (RVP) is 9 psia
Product temperature is 80°F
Vapor recovery efficiency is 95 percent
Vapor collection efficiency is 90 percent (for vessels passing annual leak test)

Loading loss equation -

$$L_L = 12.46 \frac{SPM}{T} \left[1 - \frac{eff}{100}\right]$$

where:

S = saturation factor (see Table 5.2-1) - 1.00
P = true vapor pressure of gasoline (see Figure 7.1-6) = 6.6 psia
M = molecular weight of gasoline vapors (see Table 7.1-2) = 66
T = temperature of gasoline = 540°R
eff = overall reduction efficiency (95 percent control x 90 percent collection) = 85 percent

$$L_L = 12.46 \frac{(1.00)(6.6)(66)}{540} \left[1 - \frac{85}{100}\right]$$

$$= 1.5 \text{ lb}/10^3 \text{ gal}$$

Total loading losses are:

$$(1.5 \text{ lb}/10^3 \text{ gal})(8.0 \times 10^3 \text{ gal}) = 12 \text{ pounds (lb)}$$

Measurements of gasoline loading losses from ships and barges have led to the development of emission factors for these specific loading operations.[7] These factors are presented in Table 5.2-2 and should be used instead of Equation 1 for gasoline loading operations at marine terminals. Factors are expressed in units of milligrams per liter (mg/L) and pounds per 1000 gallons (lb/10^3 gal).

Table 5.2-2 (Metric And English Units). VOLATILE ORGANIC COMPOUND (VOC) EMISSION FACTORS FOR GASOLINE LOADING OPERATIONS AT MARINE TERMINALS[a]

Vessel Tank Condition	Previous Cargo	Ships/Ocean Barges[b]		Barges[b]	
		mg/L Transferred	lb/10^3 gal Transferred	mg/L Transferred	lb/10^3 gal Transferred
Uncleaned	Volatile[c]	315	2.6	465	3.9
Ballasted	Volatile	205	1.7	—[d]	—[d]
Cleaned	Volatile	180	1.5	ND	ND
Gas-freed	Volatile	85	0.7	ND	ND
Any condition	Nonvolatile	85	0.7	ND	ND
Gas-freed	Any cargo	ND	ND	245	2.0
Typical overall situation[e]	Any cargo	215	1.8	410	3.4

[a] References 2,8. Factors are for both VOC emissions (which excludes methane and ethane) and total organic emissions, because methane and ethane have been found to constitute a negligible weight fraction of the evaporative emissions from gasoline. ND = no data.

[b] Ocean barges (tank compartment depth about 12.2 m [40 ft]) exhibit emission levels similar to tank ships. Shallow draft barges (compartment depth 3.0 to 3.7 m [10 to 12 ft]) exhibit higher emission levels.

[c] Volatile cargoes are those with a true vapor pressure greater than 10 kilopascals (kPa) (1.5 psia).

[d] Barges are usually not ballasted.

[e] Based on observation that 41% of tested ship compartments were uncleaned, 11% ballasted, 24% cleaned, and 24% gas-freed. For barges, 76% were uncleaned.

In addition to Equation 1, which estimates emissions from the loading of petroleum liquids, Equation 2 has been developed specifically for estimating emissions from the loading of crude oil into ships and ocean barges:

$$C_L = C_A + C_G \qquad (2)$$

where:

C_L = total loading loss, lb/10^3 gal of crude oil loaded

C_A = arrival emission factor, contributed by vapors in the empty tank compartment before loading, lb/10^3 gal loaded (see Note below)

C_G = generated emission factor, contributed by evaporation during loading, lb/10^3 gal loaded

Note: Values of C_A for various cargo tank conditions are listed in Table 5.2-3.

5.2-3 (English Units). AVERAGE ARRIVAL EMISSION FACTORS, C_A, FOR CRUDE OIL LOADING EMISSION EQUATION[a]

Ship/Ocean Barge Tank Condition	Previous Cargo	Arrival Emission Factor, lb/10^3 gal
Uncleaned	Volatile[b]	0.86
Ballasted	Volatile	0.46
Cleaned or gas-freed	Volatile	0.33
Any condition	Nonvolatile	0.33

[a] Arrival emission factors (C_A) to be added to generated emission factors (C_G) calculated in Equation 3 to produce total crude oil loading loss (C_L). Factors are for total organic compounds; VOC emission factors average about 15% lower, because VOC does not include methane or ethane.

[b] Volatile cargoes are those with a true vapor pressure greater than 10 kPa (1.5 psia).

This equation was developed empirically from test measurements of several vessel compartments.[7] The quantity C_G can be calculated using Equation 3:

$$C_G = 1.84\ (0.44\ P - 0.42)\ \frac{M\,G}{T} \qquad (3)$$

where:

P = true vapor pressure of loaded crude oil, psia (see Figure 7.1-5 and Table 7.1-2)
M = molecular weight of vapors, lb/lb-mole (see Table 7.1-2)
G = vapor growth factor = 1.02 (dimensionless)
T = temperature of vapors, °R (°F + 460)

Emission factors derived from Equation 3 and Table 5.2-3 represent total organic compounds. Volatile organic compound (VOC) emission factors (which exclude methane and ethane because they are exempted from the regulatory definition of "VOC") for crude oil vapors have been found to range from approximately 55 to 100 weight percent of these total organic factors. When specific vapor composition information is not available, the VOC emission factor can be estimated by taking 85 percent of the total organic factor.[3]

5.2.2.1.2 Ballasting Losses -

Ballasting operations are a major source of evaporative emissions associated with the unloading of petroleum liquids at marine terminals. It is common practice to load several cargo tank compartments with sea water after the cargo has been unloaded. This water, termed "ballast", improves the stability of the empty tanker during the subsequent voyage. Although ballasting practices vary, individual cargo tanks are ballasted typically about 80 percent, and the total vessel 15 to 40 percent, of capacity. Ballasting emissions occur as vapor-laden air in the "empty" cargo tank is displaced to the atmosphere by ballast water being pumped into the tank. Upon arrival at a loading port, tha ballast water is pumped from the cargo tanks before the new cargo is loaded. The ballasting of cargo tanks reduces the quantity of vapors returning in the empty tank, thereby reducing the quantity of vapors emitted during subsequent tanker loading. Regulations administered by the U. S. Coast Guard require that, at marine terminals located in ozone nonattainment areas, large tankers with crude oil washing systems contain the organic vapors from ballasting.[9] This is accomplished principally by displacing the vapors during ballasting into a cargo tank being simultaneously unloaded. In other areas, marine vessels emit organic vapors directly to the atmosphere.

Equation 4 has been developed from test data to calculate the ballasting emissions from crude oil ships and ocean barges[7]:

$$L_B = 0.31 + 0.20\,P + 0.01\,PU_A \qquad (4)$$

where:

L_B = ballasting emission factor, $lb/10^3$ gal of ballast water
P = true vapor pressure of discharged crude oil, psia (see Figure 7.1-5 and Table 7.1-2)
U_A = arrival cargo true ullage, before dockside discharge, measured from the deck, feet; (the term "ullage" here refers to the distance between the cargo surface level and the deck level)

Table 5.2-4 lists average total organic emission factors for ballasting into uncleaned crude oil cargo compartments. The first category applies to "full" compartments wherein the crude oil true ullage just before cargo discharge is less than 1.5 meters (m) (5 ft). The second category applies to lightered, or short-loaded, compartments (part of cargo previously discharged, or original load a partial fill), with an arrival true ullage greater than 1.5 m (5 ft). It should be remembered that these tabulated emission factors are examples only, based on average conditions, to be used when crude oil vapor pressure is unknown. Equation 4 should be used when information about crude oil vapor pressure and cargo compartment condition is available. The following sample calculation illustrates the use of Equation 4.

5.2-4 (Metric And English Units). TOTAL ORGANIC EMISSION FACTORS FOR CRUDE OIL BALLASTING[a]

	Average Emission Factors			
	By Category		Typical Overall[b]	
Compartment Condition Before Cargo Discharge	mg/L Ballast Water	$lb/10^3$ gal Ballast Water	mg/L Ballast Water	$lb/10^3$ gal Ballast Water
Fully loaded[c]	111	0.9	129	1.1
Lightered or previously short loaded[d]	171	1.4		

[a] Assumes crude oil temperature of 16°C (60°F) and RVP of 34 kPa (5 psia). VOC emission factors average about 85% of these total organic factors, because VOCs do not include methane or ethane.
[b] Based on observation that 70% of tested compartments had been fully loaded before ballasting. May not represent average vessel practices.
[c] Assumed typical arrival ullage of 0.6 m (2 ft).
[d] Assumed typical arrival ullage of 6.1 m (20 ft).

Sample Calculation -

Ballasting emissions from a crude oil cargo ship would be calculated as follows, using Equation 4:

Design basis -

Vessel and cargo description:	80,000 dead-weight-ton tanker, crude oil capacity 500,000 barrels (bbl); 20 percent of the cargo capacity is filled with ballast water after cargo discharge. The crude oil has an RVP of 6 psia and is discharged at 75°F.
Compartment conditions:	70 percent of the ballast water is loaded into compartments that had been fully loaded to 2 ft ullage, and 30 percent is loaded into compartments that had been lightered to 15 ft ullage before arrival at dockside.

Ballasting emission equation -

$$L_B = 0.31 + 0.20\ P + 0.01\ PU_A$$

where:

P = true vapor pressure of crude oil (see Figure 7.1-5)
= 4.6 psia
U_A = true cargo ullage for the full compartments = 2 ft, and true cargo ullage for the lightered compartments = 15 ft

$$\begin{aligned} L_B &= 0.70\ [0.31 + (0.20)\ (4.6) + (0.01)\ (4.6)\ (2)] \\ &\quad + 0.30\ [0.31 + (0.20)\ (4.6) + (0.01)\ (4.6)\ (15)] \\ &= 1.5\ \text{lb}/10^3\ \text{gal} \end{aligned}$$

Total ballasting emissions are:

$$(1.5\ \text{lb}/10^3\ \text{gal})\ (0.20)\ (500{,}000\ \text{bbl})\ (42\ \text{gal/bbl}) = 6{,}300\ \text{lb}$$

Since VOC emissions average about 85 percent of these total organic emissions, emissions of VOCs are about: (0.85)(6,300 lb) = 5,360 lb

5.2.2.1.3 Transit Losses -

In addition to loading and ballasting losses, losses occur while the cargo is in transit. Transit losses are similar in many ways to breathing losses associated with petroleum storage (see Section 7.1, "Organic Liquid Storage Tanks"). Experimental tests on ships and barges[4] have indicated that transit losses can be calculated using Equation 5:

$$L_T = 0.1\ PW \qquad (5)$$

where:

L_T = transit loss from ships and barges, lb/week-10^3 gal transported
P = true vapor pressure of the transported liquid, psia (see Figure 7.1-5, Figure 7.1-6, and Table 7.1-2)
W = density of the condensed vapors, lb/gal (see Table 7.1-2)

Emissions from gasoline truck cargo tanks during transit have been studied by a combination of theoretical and experimental techniques, and typical emission values are presented in Table 5.2-5.[10-11] Emissions depend on the extent of venting from the cargo tank during transit, which in turn depends on the vapor tightness of the tank, the pressure relief valve settings, the pressure in the tank at the start of the trip, the vapor pressure of the fuel being transported, and the degree of fuel vapor saturation of the space in the tank. The emissions are not directly proportional to the time spent in transit. If the vapor leakage rate of the tank increases, emissions increase up to a point, and then the rate changes as other determining factors take over. Truck tanks in dedicated vapor balance service usually contain saturated vapors, and this leads to lower emissions during transit because no additional fuel evaporates to raise the pressure in the tank to cause venting. Table 5.2-5 lists "typical" values for transit emissions and "extreme" values that could occur in the unlikely event that all determining factors combined to cause maximum emissions.

Table 5.2-5 (Metric And English Units). TOTAL UNCONTROLLED ORGANIC EMISSION FACTORS FOR PETROLEUM LIQUID RAIL TANK CARS AND TANK TRUCKS

Emission Source	Gasoline[a]	Crude Oil[b]	Jet Naphtha (JP-4)	Jet Kerosene	Distillate Oil No. 2	Residual Oil No. 6
Loading operations[c]						
Submerged loading - Dedicated normal service[d]						
mg/L transferred	590	240	180	1.9	1.7	0.01
lb/10^3 gal transferred	5	2	1.5	0.016	0.014	0.0001
Submerged loading - Vapor balance service[d]						
mg/L transferred	980	400	300	—[e]	—[e]	—[e]
lb/10^3 gal transferred	8	3	2.5	—[e]	—[e]	—[e]
Splash loading - Dedicated normal service						
mg/L transferred	1,430	580	430	5	4	0.03
lb/10^3 gal transferred	12	5	4	0.04	0.03	0.0003
Splash loading - Vapor balance service						
mg/L transferred	980	400	300	—[e]	—[e]	—[e]
lb/10^3 gal transferred	8	3	2.5	—[e]	—[e]	—[e]

Table 5.2-5 (cont.).

Emission Source	Gasoline[a]	Crude Oil[b]	Jet Naphtha (JP-4)	Jet Kerosene	Distillate Oil No. 2	Residual Oil No. 6
Transit losses						
Loaded with product						
mg/L transported						
Typical	0 - 1.0	ND	ND	ND	ND	ND
Extreme	0 - 9.0	ND	ND	ND	ND	ND
lb/10^3 gal transported						
Typical	0 - 0.01	ND	ND	ND	ND	ND
Extreme	0 - 0.08	ND	ND	ND	ND	ND
Return with vapor						
mg/L transported						
Typical	0 - 13.0	ND	ND	ND	ND	ND
Extreme	0 - 44.0	ND	ND	ND	ND	ND
lb/10^3 gal transported						
Typical	0 - 0.11	ND	ND	ND	ND	ND
Extreme	0 - 0.37	ND	ND	ND	ND	ND

[a] Reference 2. Gasoline factors represent emissions of VOC as well as total organics, because methane and ethane constitute a negligible weight fraction of the evaporative emissions from gasoline. VOC factors for crude oil can be assumed to be 15% lower than the total organic factors, to account for the methane and ethane content of crude oil evaporative emissions. All other products should be assumed to have VOC factors equal to total organics. The example gasoline has an RVP of 69 kPa (10 psia). ND = no data.

[b] The example crude oil has an RVP of 34 kPa (5 psia).

[c] Loading emission factors are calculated using Equation 1 for a dispensed product temperature of 16°C (60°F).

[d] Reference 2.

[e] Not normally used.

In the absence of specific inputs for Equations 1 through 5, the typical evaporative emission factors presented in Tables 5.2-5 and 5.2-6 should be used. It should be noted that, although the crude oil used to calculate the emission values presented in these tables has an RVP of 5, the RVP of crude oils can range from less than 1 up to 10. Similarly, the RVP of gasolines ranges from 7 to 13. In areas where loading and transportation sources are major factors affecting air quality, it is advisable to obtain the necessary parameters and to calculate emission estimates using Equations 1 through 5.

5.2.2.2 Service Stations -

Another major source of evaporative emissions is the filling of underground gasoline storage tanks at service stations. Gasoline is usually delivered to service stations in 30,000-liter (8,000-gal) tank trucks or smaller account trucks. Emissions are generated when gasoline vapors in the

Table 5.2-6 (Metric And English Units). TOTAL ORGANIC EMISSION FACTORS FOR PETROLEUM MARINE VESSEL SOURCES[a]

Emission Source	Gasoline[b]	Crude Oil[c]	Jet Naphtha (JP-4)	Jet Kerosene	Distillate Oil No. 2	Residual Oil No. 6
Loading operations						
Ships/ocean barges						
mg/L transferred	—[d]	73	60	0.63	0.55	0.004
lb/10^3 gal transferred	—[d]	0.61	0.50	0.005	0.005	0.00004
Barges						
mg/L transferred	—[d]	120	150	1.60	1.40	0.011
lb/10^3 gal transferred	—[d]	1.0	1.2	0.013	0.012	0.00009
Tanker ballasting						
mg/L ballast water	100	—[e]	ND	ND	ND	ND
lb/10^3 gal ballast water	0.8	—[e]	ND	ND	ND	ND
Transit						
mg/week-L transported	320	150	84	0.60	0.54	0.003
lb/week-10^3 gal transported	2.7	1.3	0.7	0.005	0.005	0.00003

[a] Factors are for a dispensed product of 16°C (60°F). ND = no data.

[b] Factors represent VOC as well as total organic emissions, because methane and ethane constitute a negligible fraction of gasoline evaporative emissions. All products other than crude oil can be assumed to have VOC factors equal to total organic factors. The example gasoline has an RVP of 69 kPa (10 psia).

[c] VOC emission factors for a typical crude oil are 15% lower than the total organic factors shown, in order to account for methane and ethane. The example crude oil has an RVP of 34 kPa (5 psia).

[d] See Table 5.2-2 for these factors.

[e] See Table 5.2-4 for these factors.

underground storage tank are displaced to the atmosphere by the gasoline being loaded into the tank. As with other loading losses, the quantity of loss in service station tank filling depends on several variables, including the method and rate of filling, the tank configuration, and the gasoline temperature, vapor pressure and composition. An average emission rate for submerged filling is 880 mg/L (7.3 lb/1000 gal) of transferred gasoline, and the rate for splash filling is 1380 mg/L (11.5 lb/1000 gal) transferred gasoline (see Table 5.2-7).[5]

Emissions from underground tank filling operations at service stations can be reduced by the use of a vapor balance system such as in Figure 5.2-5 (termed Stage I vapor control). The vapor balance system employs a hose that returns gasoline vapors displaced from the underground tank to the tank truck cargo compartments being emptied. The control efficiency of the balance system ranges from 93 to 100 percent. Organic emissions from underground tank filling operations at a service station employing a vapor balance system and submerged filling are not expected to exceed 40 mg/L (0.3 lb/1000 gal) of transferred gasoline.

Table 5.2-7 (Metric And English Units). EVAPORATIVE EMISSIONS FROM GASOLINE SERVICE STATION OPERATIONS[a]

Emission Source	Emission Rate	
	mg/L Throughput	$lb/10^3$ gal Throughput
Filling underground tank (Stage I)		
Submerged filling	880	7.3
Splash filling	1,380	11.5
Balanced submerged filling	40	0.3
Underground tank breathing and emptying[b]	120	1.0
Vehicle refueling operations (Stage II)		
Displacement losses (uncontrolled)[c]	1,320	11.0
Displacement losses (controlled)	132	1.1
Spillage	80	0.7

[a] Factors are for VOC as well as total organic emissions, because of the methane and ethane content of gasoline evaporative emissions is negligible.
[b] Includes any vapor loss between underground tank and gas pump.
[c] Based on Equation 6, using average conditions.

A second source of vapor emissions from service stations is underground tank breathing. Breathing losses occur daily and are attributable to gasoline evaporation and barometric pressure changes. The frequency with which gasoline is withdrawn from the tank, allowing fresh air to enter to enhance evaporation, also has a major effect on the quantity of these emissions. An average breathing emission rate is 120 mg/L (1.0 lb/1000 gal) of throughput.

5.2.2.3 Motor Vehicle Refueling -

Service station vehicle refueling activity also produces evaporative emissions. Vehicle refueling emissions come from vapors displaced from the automobile tank by dispensed gasoline and from spillage. The quantity of displaced vapors depends on gasoline temperature, auto tank temperature, gasoline RVP, and dispensing rate. Equation 6 can be used to estimate uncontrolled displacement losses from vehicle refueling for a particular set of conditions.[13]

$$E_R = 264.2\ [(-5.909) - 0.0949\ (\Delta T) + 0.0884\ (T_D) + 0.485\ (RVP)] \qquad (6)$$

where:

E_R = refueling emissions, mg/L
ΔT = difference between temperature of fuel in vehicle tank and temperature of dispensed fuel, °F
T_D = temperature of dispensed fuel, °F
RVP = Reid vapor pressure, psia

Note that this equation and the spillage loss factor are incorporated into the *MOBILE* model. The *MOBILE* model allows for disabling of this calculation if it is desired to include these emissions in the stationary area source portion of an inventory rather than in the mobile source portion. It is estimated that the uncontrolled emissions from vapors displaced during vehicle refueling average 1320 mg/L (11.0 lb/1000 gal) of dispensed gasoline.[5,12]

Spillage loss is made up of contributions from prefill and postfill nozzle drip and from spit-back and overflow from the vehicles's fuel tank filler pipe during filling. The amount of spillage loss can depend on several variables, including service station business characteristics, tank configuration, and operator techniques. An average spillage loss is 80 mg/L (0.7 lb/1000 gal) of dispensed gasoline.[5,12]

Control methods for vehicle refueling emissions are based on conveying the vapors displaced from the vehicle fuel tank to the underground storage tank vapor space through the use of a special hose and nozzle, as depicted in Figure 5.2-7 (termed Stage II vapor control). In "balance" vapor control systems, the vapors are conveyed by natural pressure differentials established during refueling. In "vacuum assist" systems, the conveyance of vapors from the auto fuel tank to the underground storage tank is assisted by a vacuum pump. Tests on a few systems have indicated overall systems control efficiencies in the range of 88 to 92 percent.[5,12] When inventorying these emissions as an area source, rule penetration and rule effectiveness should also be taken into account. *Procedures For Emission Inventory Preparation, Volume IV: Mobile Sources*, EPA-450/4-81-026d, provides more detail on this.

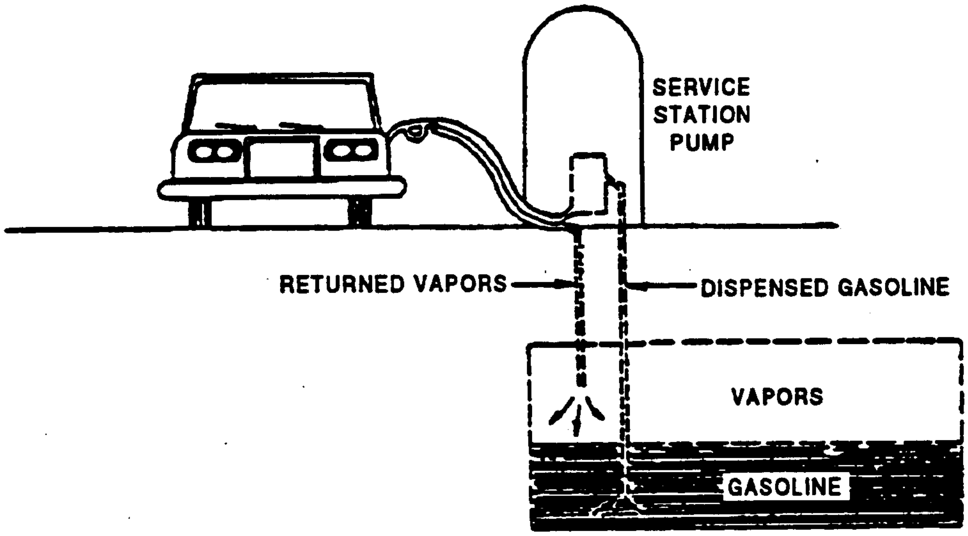

Figure 5.2-7. Automobile refueling vapor recovery system.

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5.3 Natural Gas Processing

5.3.1 General[1]

Natural gas from high-pressure wells is usually passed through field separators at the well to remove hydrocarbon condensate and water. Natural gasoline, butane, and propane are usually present in the gas, and gas processing plants are required for the recovery of these liquefiable constituents (see Figure 5.3-1). Natural gas is considered "sour" if hydrogen sulfide (H_2S) is present in amounts greater than 5.7 milligrams per normal cubic meters (mg/$\underline{N}m^3$) (0.25 grains per 100 standard cubic feet [gr/100 scf]). The H_2S must be removed (called "sweetening" the gas) before the gas can be utilized. If H_2S is present, the gas is usually sweetened by absorption of the H_2S in an amine solution. Amine processes are used for over 95 percent of all gas sweetening in the United States. Other methods, such as carbonate processes, solid bed absorbents, and physical absorption, are employed in the other sweetening plants. Emission data for sweetening processes other than amine types are very meager, but a material balance on sulfur will give accurate estimates for sulfur dioxide (SO_2).

The major emission sources in the natural gas processing industry are compressor engines, acid gas wastes, fugitive emissions from leaking process equipment and if present, glycol dehydrator vent streams. Compressor engine emissions are discussed in Section 3.3.2. Fugitive leak emissions are detailed in *Protocol For Equipment Leak Emission Estimates*, EPA-453/R-93-026, June 1993. Regeneration of the glycol solutions used for dehydrating natural gas can release significant quantities of benzene, toluene, ethylbenzene, and xylene, as well as a wide range of less toxic organics. These emissions can be estimated by a thermodynamic software model (*GRI-DEHY*) available from the Gas Research Institute. Only the SO_2 emissions from gas sweetening operations are discussed here.

5.3.2 Process Description[2-3]

Many chemical processes are available for sweetening natural gas. At present, the amine process (also known as the Girdler process), is the most widely used method for H_2S removal. The process is summarized in reaction 1 and illustrated in Figure 5.3-2.

$$2\ RNH_2 + H_2S \rightarrow (RNH_3)_2S \qquad (1)$$

where:

R = mono, di, or tri-ethanol
N = nitrogen
H = hydrogen
S = sulfur

The recovered hydrogen sulfide gas stream may be: (1) vented, (2) flared in waste gas flares or modern smokeless flares, (3) incinerated, or (4) utilized for the production of elemental sulfur or sulfuric acid. If the recovered H_2S gas stream is not to be utilized as a feedstock for commercial applications, the gas is usually passed to a tail gas incinerator in which the H_2S is oxidized to SO_2 and is then passed to the atmosphere out a stack. For more details, the reader should consult Reference 8.

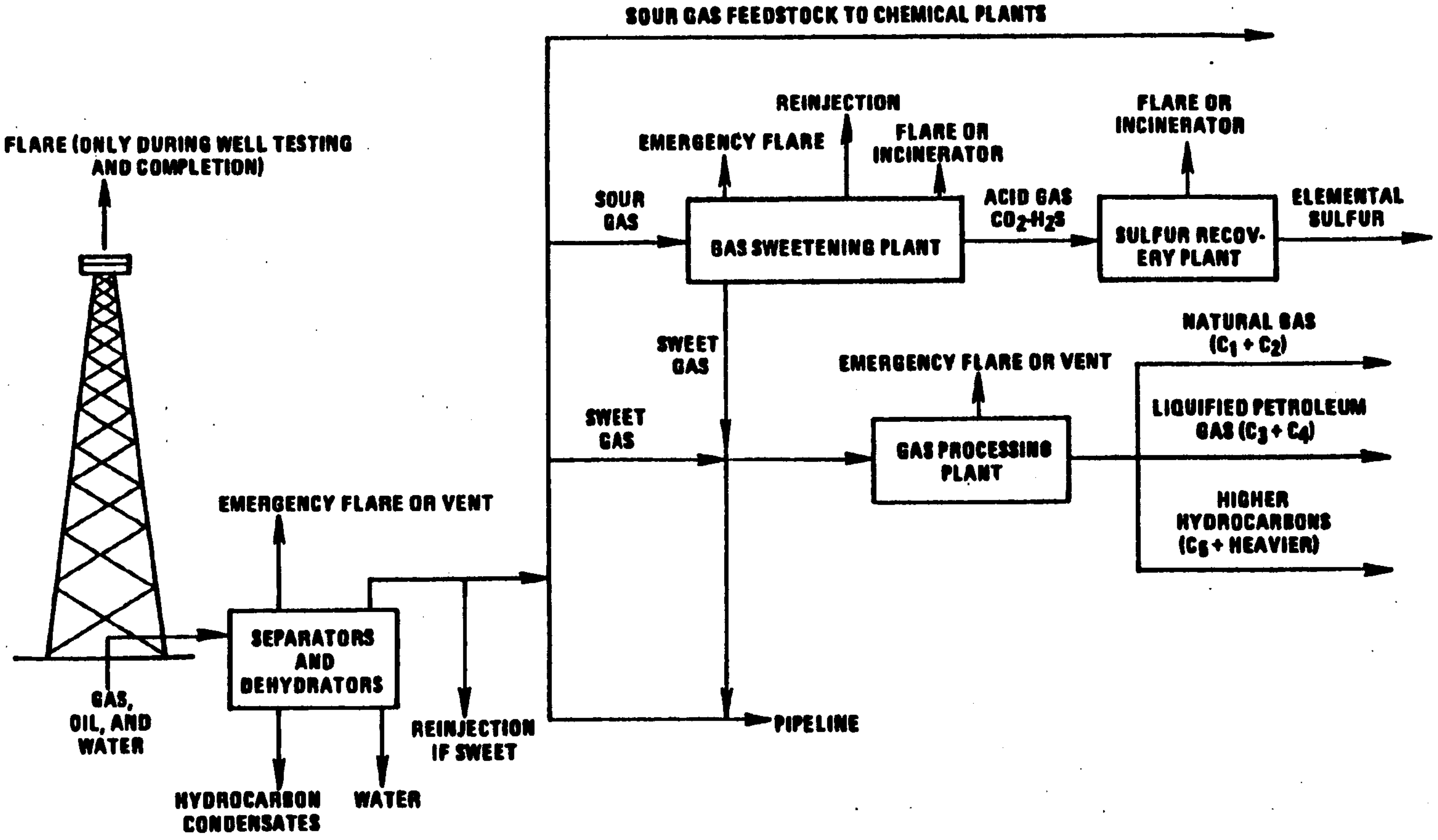

Figure 5.3-1. General flow diagram of the natural gas industry.

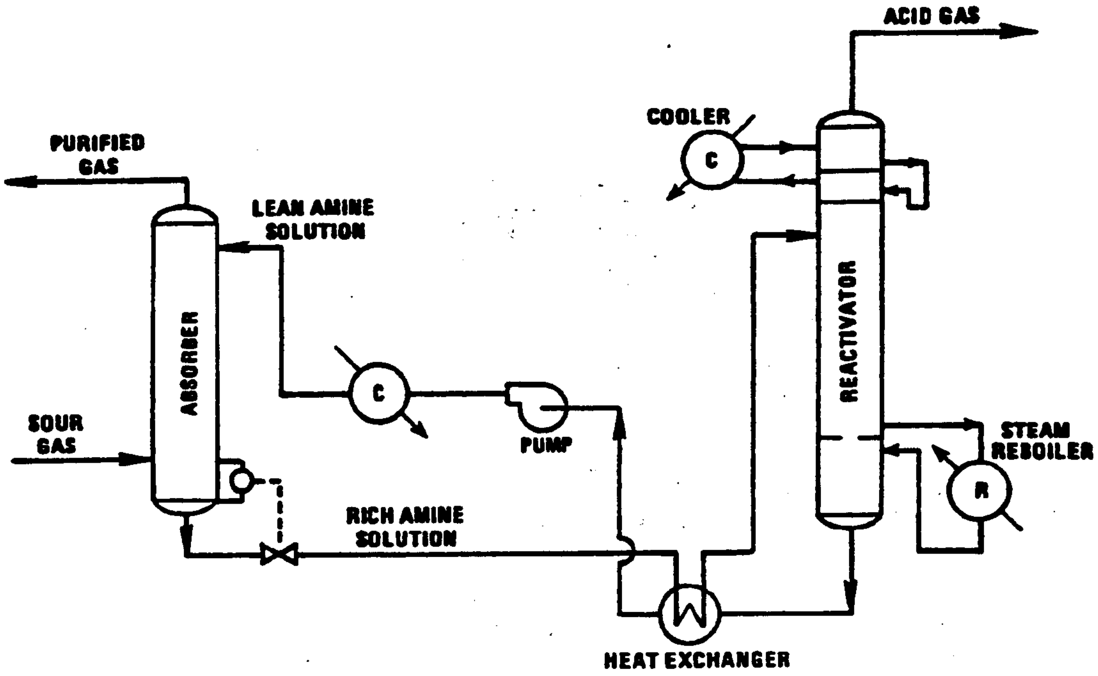

Figure 5.3-2. Flow diagram of the amine process for gas sweetening.

5.3.3 Emissions[4-5]

Emissions will result from gas sweetening plants only if the acid waste gas from the amine process is flared or incinerated. Most often, the acid waste gas is used as a feedstock in nearby sulfur recovery or sulfuric acid plants. See Sections 8.13 "Sulfur Recovery", or 8.10, "Sulfuric Acid", respectively, for these associated processes.

When flaring or incineration is practiced, the major pollutant of concern is SO_2. Most plants employ elevated smokeless flares or tail gas incinerators for complete combustion of all waste gas constituents, including virtually 100 percent conversion of H_2S to SO_2. Little particulate, smoke, or hydrocarbons result from these devices, and because gas temperatures do not usually exceed 650°C (1200°F), significant quantities of nitrogen oxides are not formed. Emission factors for gas sweetening plants with smokeless flares or incinerators are presented in Table 5.3-1. Factors are expressed in units of kilograms per 1000 cubic meters (kg/10^3 m^3) and pounds per million standard cubic feet (lb/10^6 scf).

Some plants still use older, less-efficient waste gas flares. Because these flares usually burn at temperatures lower than necessary for complete combustion, larger emissions of hydrocarbons and particulate, as well as H_2S, can occur. No data are available to estimate the magnitude of these emissions from waste gas flares.

Table 5.3.1 (Metric And English Units). EMISSION FACTORS FOR GAS SWEETENING PLANTS[a]

EMISSION FACTOR RATING: SULFUR OXIDES: A
ALL OTHERS: C

Process[b]	Particulate	Sulfur Oxides[c] (SO_2)	Carbon Monoxide	Hydrocarbons	Nitrogen Oxides
Amine					
$kg/10^3\ m^3$ gas processed	Neg	26.98 S[d]	Neg	—[e]	Neg
$lb/10^6$ scf gas processed	Neg	1685 S[d]	Neg	—[e]	Neg

[a] Factors are presented only for smokeless flares and tail gas incinerators on the amine gas sweetening process with no sulfur recovery or sulfuric acid production present. Too little information exists to characterize emissions from older, less-efficient waste gas flares on the amine process or from other, less common gas sweetening processes. Factors for various internal combustion engines used in a gas processing plant are given in Section 3.3, "Gasoline and Diesel Industrial Engines". Factors for sulfuric acid plants and sulfur recovery plants are given in Section 8.10, "Sulfuric Acid", and Section 8.13, "Sulfur Recovery", respectively.
Neg = negligible.

[b] References 2,4-7. Factors are for emissions after smokeless flares (with fuel gas and steam injection) or tail gas incinerators.

[c] Assumes that 100% of the H_2S in the acid gas stream is converted to SO_2 during flaring or incineration and that the sweetening process removes 100% of the H_2S in the feedstock.

[d] S is the H_2S content of the sour gas entering the gas sweetening plant, in mole or volume percent. For example, if the H_2S content is 2%, the emission factor would be 26.98 times 2, or 54.0 kg/1000 m^3 (3370 $lb/10^6$ scf) of sour gas processed. If the H_2S mole % is unknown, average values from Table 5.3-2 may be substituted. Note: If H_2S contents are reported in ppm or grains (gr) per 100 scf, use the following factors to convert to mole %:

10,000 ppm H_2S = 1 mole % H_2S
627 gr H_2S/100 scf = 1 mole % H_2S

The m^3 or scf are to be measured at 60°F and 760 mm Hg for this application (1 lb-mol = 379.5 scf).

[e] Flare or incinerator stack gases are expected to have negligible hydrocarbon emissions. To estimate fugitive hydrocarbon emissions from leaking compressor seals, valves, and flanges, see *"Protocol For Equipment Leak Emission Estimates"*, EPA-453/R-93-026, June 1993 (or updates).

Table 5.3-2. AVERAGE HYDROGEN SULFIDE CONCENTRATIONS IN NATURAL GAS BY AIR QUALITY CONTROL REGION[a]

State	AQCR Name	AQCR Number	Average H_2S, mole %
Alabama	Mobile-Pensacola-Panama City-Southern Mississippi (FL, MS)	5	3.30
Arizona	Four Corners (CO, NM, UT)	14	0.71
Arkansas	Monroe-El Dorado (LA)	19	0.15
	Shreveport-Texarkana-Tyler (LA, OK, TX)	22	0.55
California	Metropolitan Los Angeles	24	2.09
	San Joaquin Valley	31	0.89
	South Central Coast	32	3.66
	Southeast Desert	33	1.0
Colorado	Four Corners (AZ, NM, UT)	14	0.71
	Metropolitan Denver	36	0.1
	Pawnee	37	0.49
	San Isabel	38	0.3
	Yampa	40	0.31
Florida	Mobile-Pensacola-Panama City-Southern Mississippi (AL, MS)	5	3.30
Kansas	Northwest Kansas	97	0.005
	Southwest Kansas	100	0.02
Louisiana	Monroe-El Dorado (AZ)	19	0.15
	Shreveport-Texarkana-Tyler (AZ, OK, TX)	22	0.55
Michigan	Upper Michigan	126	0.5
Mississippi	Mississippi Delta	134	0.68
	Mobile-Pensacola-Panama City-Southern Mississippi (AL, FL)	5	3.30
Montana	Great Falls	141	3.93
	Miles City	143	0.4
New Mexico	Four Corners (AZ, CO, UT)	14	0.71
	Pecos-Permian Basin	155	0.83
North Dakota	North Dakota	172	1.74[b]

Table 5.3-2 (cont.).

State	AQCR Name	AQCR Number	Average H_2S, mole %
Oklahoma	Northwestern Oklahoma	187	1.1
	Shreveport-Texarkana-Tyler (AZ, LA, TX)	22	0.55
	Southeastern Oklahoma	188	0.3
Texas	Abilene-Wichita Falls	210	0.055
	Amarillo-Lubbock	211	0.26
	Austin-Waco	212	0.57
	Corpus Christi-Victoria	214	0.59
	Metropolitan Dallas-Fort Worth	215	2.54
	Metropolitan San Antonio	217	1.41
	Midland-Odessa-San Angelo	218	0.63
	Shreveport-Texarkana-Tyler (AZ, LA, OK)	22	0.55
Utah	Four Corners (AZ, CO, NM)	14	0.71
Wyoming	Casper	241	1.262
	Wyoming (except Park, Bighorn, and Washakie Counties)	243	2.34[c]

[a] Reference 9. AQCR = Air Quality Control Region.

[b] Sour gas only reported for Burke, Williams, and McKenzie Counties, ND.

[c] Park, Bighorn, and Washakie Counties, WY, report gas with an average H_2S content of 23 mole %.

References For Section 5.3

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6. ORGANIC CHEMICAL PROCESS INDUSTRY

Possible emissions from the manufacture of chemicals and chemical products are significant, but for economic necessity are usually recovered. In some cases, the manufacturing operation either is a closed system or is vented to a combustion device with little or no process vent emissions to the atmosphere. Emission sources from chemical processes include heaters and boilers; valves, flanges, pumps and compressors; storage and transfer of products and intermediates; waste water handling; and emergency vents.

Emissions reaching the atmosphere from chemical processes are generally gaseous and are controlled by incineration, adsorption or absorption. Particulate emissions also could be a problem, since the particulate emitted is usually extremely small, requiring very efficient treatment for removal.

Emission data from chemical processes are sparse. It has been frequently necessary, therefore, to make estimates of emission factors on the basis of material balances, yields or process similarities.

6.1 Carbon Black

6.1.1 Process Description

Carbon black is produced by the reaction of a hydrocarbon fuel such as oil or gas with a limited supply of combustion air at temperatures of 1320 to 1540°C (2400 to 2800°F). The unburned carbon is collected as an extremely fine black fluffy particle, 10 to 500 nanometers (nm) in diameter. The principal uses of carbon black are as a reinforcing agent in rubber compounds (especially tires) and as a black pigment in printing inks, surface coatings, paper, and plastics. Two major processes are presently used in the United States to manufacture carbon black, the oil furnace process and the thermal process. The oil furnace process accounts for about 90 percent of production, and the thermal, about 10 percent. Two others, the lamp process for production of lamp black and the cracking of acetylene to produce acetylene black, are each used at 1 plant in the U. S. However, these are small-volume specialty black operations that constitute less than 1 percent of total production in this country. The gas furnace process is being phased out, and the last channel black plant in the U. S. was closed in 1976.

6.1.1.1 Oil Furnace Process -

In the oil furnace process (Figure 6.1-1 and Table 6.1-1), an aromatic liquid hydrocarbon feedstock is heated and injected continuously into the combustion zone of a natural gas-fired furnace, where it is decomposed to form carbon black. Primary quench water cools the gases to 500°C (1000°F) to stop the cracking. The exhaust gases entraining the carbon particles are further cooled to about 230°C (450°F) by passage through heat exchangers and direct water sprays. The black is then separated from the gas stream, usually by a fabric filter. A cyclone for primary collection and particle agglomeration may precede the filter. A single collection system often serves several manifolded furnaces.

The recovered carbon black is finished to a marketable product by pulverizing and wet pelletizing to increase bulk density. Water from the wet pelletizer is driven off in a gas-fired rotary dryer. Oil or process gas can be used. From 35 to 70 percent of the dryer combustion gas is charged directly to the interior of the dryer, and the remainder acts as an indirect heat source for the dryer. The dried pellets are then conveyed to bulk storage. Process yields range from 35 to 65 percent, depending on the feed composition and the grade of black produced. Furnace designs and operating conditions determine the particle size and the other physical and chemical properties of the black. Generally, yields are highest for large particle blacks and lowest for small particle blacks.

6.1.1.2 Thermal Process -

The thermal process is a cyclic operation in which natural gas is thermally decomposed (cracked) into carbon particles, hydrogen, and a mixture of other organics. Two furnaces are used in normal operation. The first cracks natural gas and makes carbon black and hydrogen. The effluent gas from the first reactor is cooled by water sprays to about 125°C (250°F), and the black is collected in a fabric filter. The filtered gas (90 percent hydrogen, 6 percent methane, and 4 percent higher hydrocarbons) is used as a fuel to heat a second reactor. When the first reactor becomes too cool to crack the natural gas feed, the positions of the reactors are reversed, and the second reactor is used to crack the gas while the first is heated. Normally, more than enough hydrogen is produced to make the thermal black process self-sustaining, and the surplus hydrogen is used to fire boilers that supply process steam and electric power.

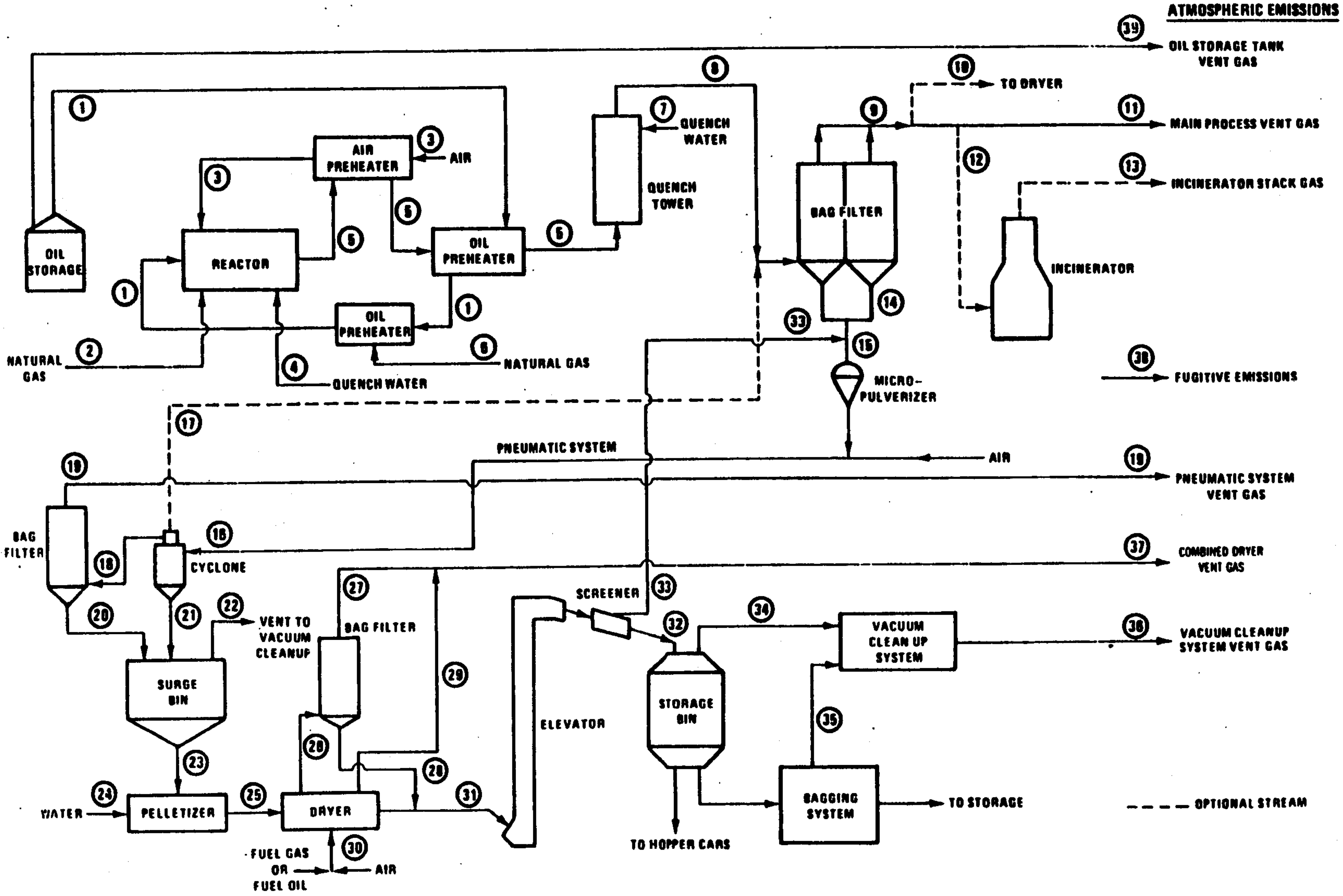

Figure 6.1-1. Flow diagram for the oil furnace carbon black process.

Table 6.1-1. STREAM IDENTIFICATION FOR THE OIL FURNACE PROCESS (FIGURE 6.1-1)

Stream	Identification
1	Oil feed
2	Natural gas feed
3	Air to reactor
4	Quench water
5	Reactor effluent
6	Gas to oil preheater
7	Water to quench tower
8	Quench tower effluent
9	Bag filter effluent
10	Vent gas purge for dryer fuel
11	Main process vent gas
12	Vent gas to incinerator
13	Incinerator stack gas
14	Recovered carbon black
15	Carbon black to micropulverizer
16	Pneumatic conveyor system
17	Cyclone vent gas recycle
18	Cyclone vent gas
19	Pneumatic system vent gas
20	Carbon black from bag filter
21	Carbon black from cyclone
22	Surge bin vent
23	Carbon black to pelletizer
24	Water to pelletizer
25	Pelletizer effluent
26	Dryer direct heat source vent
27	Dryer heat exhaust after bag filter
28	Carbon black from dryer bag filter
29	Dryer indirect heat source vent
30	Hot gases to dryer

Table 6.1-1 (cont.).

Stream	Identification
31	Dried carbon black
32	Screened carbon black
33	Carbon black recycle
34	Storage bin vent gas
35	Bagging system vent gas
36	Vacuum cleanup system vent gas
37	Combined dryer vent gas
38	Fugitive emissions
39	Oil storage tank vent gas

The collected thermal black is pulverized and pelletized to a final product in much the same manner as is furnace black. Thermal process yields are generally high (35 to 60 percent), but the relatively coarse particles produced, 180 to 470 nm, do not have the strong reinforcing properties required for rubber products.

6.1.2 Emissions And Controls

6.1.2.1 Oil Furnace Process -

Emissions from carbon black manufacture include particulate matter, carbon monoxide (CO), organics, nitrogen oxides, sulfur compounds, polycyclic organic matter (POM), and trace elements.

The principal source of emissions in the oil furnace process is the main process vent. The vent stream consists of the reactor effluent and the quench water vapor vented from the carbon black recovery system. Gaseous emissions may vary considerably according to the grade of carbon black being produced. Organic and CO emissions tend to be higher for small particle production, corresponding with the lower yields obtained. Sulfur compound emissions are a function of the feed sulfur content. Tables 6.1-2, 6.1-3, and 6.1-4 show the normal emission ranges to be expected, with typical average values.

The combined dryer vent (stream 37 in Figure 6.1-1) emits carbon black from the dryer bag filter and contaminants from the use of the main process vent gas if the gas is used as a supplementary fuel for the dryer. It also emits contaminants from the combustion of impurities in the natural gas fuel for the dryer. These contaminants include sulfur oxides, nitrogen oxides, and the unburned portion of each of the species present in the main process vent gas (see Table 6.1-2). The oil feedstock storage tanks are a source of organic emissions. Carbon black emissions also occur from the pneumatic transport system vent, the plantwide vacuum cleanup system vent, and from cleaning, spills, and leaks (fugitive emissions).

Gaseous emissions from the main process vent may be controlled with CO boilers, incinerators, or flares. The pellet dryer combustion furnace, which is, in essence, a thermal incinerator, may also be employed in a control system. CO boilers, thermal incinerators, or combinations of these devices can achieve essentially complete oxidation of organics and can oxidize

Table 6.1-2 (Metric And English Units). EMISSION FACTORS FOR CHEMICAL SUBSTANCES FROM OIL FURNACE CARBON BLACK MANUFACTURE[a]

Chemical Substance	Main Process Vent Gas[b]	
	kg/Mg	lb/ton
Carbon disulfide	30	60
Carbonyl sulfide	10	20
Methane	25 (10 - 60)	50 (20 - 120)
Nonmethane VOC		
Acetylene	45 (5 - 130)	90 (10 - 260)
Ethane	0[c]	0[c]
Ethylene	1.6	3.2
Propylene	0[c]	0[c]
Propane	0.23	0.46
Isobutane	0.10	0.20
n-Butane	0.27	0.54
n-Pentane	0[c]	0[c]
POM	0.002	0.004
Trace elements[d]	<0.25	<0.50

[a] Expressed in terms of weight of emissions per unit weight of carbon black produced. VOC = volatile organic compounds.

[b] These chemical substances are emitted only from the main process vent. Average values are based on 6 sampling runs made at a representative plant (Reference 1). Ranges given in parentheses are based on results of a survey of operating plants (Reference 4).

[c] Below detection limit of 1 ppm.

[d] Beryllium, lead, and mercury, among several others.

sulfur compounds in the process flue gas. Combustion efficiencies of 99.6 percent for hydrogen sulfide and 99.8 percent for CO have been measured for a flare on a carbon black plant. Particulate emissions may also be reduced by combustion of some of the carbon black particles, but emissions of sulfur dioxide and nitrogen oxides are thereby increased.

6.1.2.2 Thermal Process -

Emissions from the furnaces in this process are very low because the offgas is recycled and burned in the next furnace to provide heat for cracking, or sent to a boiler as fuel. The carbon black is recovered in a bag filter between the 2 furnaces. The rest is recycled in the offgas. Some adheres to the surface of the checkerbrick where it is burned off in each firing cycle.

Table 6.1-3 (Metric Units). EMISSION FACTORS FOR CARBON BLACK MANUFACTURE[a]

EMISSION FACTOR RATING: C

Process	Particulate[b]	Carbon Monoxide	Nitrogen Oxides	Sulfur Oxides	Methane	Nonmethane VOC[c]	Hydrogen Sulfide
Oil furnace process							
Main process vent	3.27^d (0.1 - 5)	$1,400^e$ (700 - 2,200)	0.28^e (1 - 2.8)	$0^{e,f}$ (0 - 12)	25^e (10 - 60)	50^e (10 - 159)	30^e $(5S - 13S)^g$
Flare	1.35 (1.2 - 1.5)	122 (108 - 137)	ND	25 (21.9 - 28)		1.85 (1.7 - 2)	1
CO boiler and incinerator	1.04	0.88	4.65	17.5		0.99	0.11
Combined dryer vent[h]							
Bag filter	0.12 (0.01 - 0.40)		0.36 (0.12 - 0.61)	0.26 (0.03 - 0.54)			
Scrubber	0.36 (0.01 - 0.70)		1.10	0.20			
Pneumatic system vent[h]							
Bag filter	0.29 (0.06 - 0.70)						
Oil storage tank vent[i]							
Uncontrolled						0.72	
Vacuum cleanup system vent[h]							
Bag filter	0.03 (0.01 - 0.05)						
Fugitive emissions[h]	0.10						
Solid waste incinerator[j]	0.12	0.01	0.04	0.01		0.01	
Thermal process[k]	Neg	Neg	ND	Neg		Neg	Neg

Table 6.1-3 (cont.).

[a] Expressed in terms of weight of emissions per unit weight of carbon black produced. Blanks indicate no emissions. Most plants use bag filters on all process trains for product recovery except solid waste incineration. Some plants may use scrubbers on at least one process train. ND = no data.

[b] The particulate matter is carbon black.

[c] Emission factors do not include organic sulfur compounds that are reported separately in Table 6.1-2. Individual organic species comprising the nonmethane VOC emissions are included in Table 6.1-2.

[d] Average values based on surveys of plants (References 4-5).

[e] Average values based on results of 6 sampling runs conducted at a representative plant with a mean production rate of 5.1 x 10 Mg/yr (5.6 x 10 ton/yr). Ranges of values are based on a survey of 15 plants (Reference 4). Controlled by bag filter.

[f] Not detected at detection limit of 1 ppm.

[g] S is the weight % sulfur in the feed.

[h] Average values and corresponding ranges of values are based on a survey of plants (Reference 4) and on the public files of Louisiana Air Control Commission.

[i] Emission factor calculated using empirical correlations for petrochemical losses from storage tanks (vapor pressure = 0.7 kPa). Emissions are mostly aromatic oils.

[j] Based on emission rates obtained from the National Emissions Data System. All plants do not use solid waste incineration. See Section 2.1.

[k] Emissions from the furnaces are negligible. Emissions from the dryer vent, pneumatic system vent, vacuum cleanup system, and fugitive sources are similar to those for the oil furnace process.

Table 6.1-4 (English Units). EMISSION FACTORS FOR CARBON BLACK MANUFACTURE^a

EMISSION FACTOR RATING: C

Process	Particulate^b	Carbon Monoxide	Nitrogen Oxides	Sulfur Oxides	Methane	Nonmethane VOC^c	Hydrogen Sulfide
Oil furnace process							
Main process vent	6.53^d (0.2 - 10)	2,800^e (1,400 - 4,400)	0.56^e (2 - 5.6)	0^{e,f} (0 - 24)	50^e (20 - 120)	100^e (20 - 300)	60^e (10S - 26S)^g
Flare	2.70 (2.4 - 3)	245 (216 - 274)	ND	50 (44 - 56)		3.7 (3.4 - 4)	2
CO boiler and incinerator	2.07	1.75	9.3	35.2		1.98	0.22
Combined dryer vent^h							
Bag filter	0.24 (0.02 - 0.80)		0.73 (0.24 - 1.22)	0.52 (0.06 - 1.08)			
Scrubber	0.71 (0.02 - 1.40)		2.20	0.40			
Pneumatic system vent^h							
Bag filter	0.58 (0.12 - 1.40)						
Oil storage tank vent^i							
Uncontrolled						1.44	
Vacuum cleanup system vent^h							
Bag filter	0.06 (0.02 - 0.10)						
Fugitive emissions^h	0.20						
Solid waste incinerator^j	0.24	0.02	0.08	0.02		0.02	
Thermal process^k	Neg	Neg	ND	Neg		Neg	Neg

Table 6.1-4 (cont.).

[a] Expressed in terms of weight of emissions per unit weight of carbon black produced. Blanks indicate no emissions. Most plants use bag filters on all process trains for product recovery except solid waste incineration. Some plants may use scrubbers on at least one process train. ND = no data.

[b] The particulate matter is carbon black.

[c] Emission factors do not include organic sulfur compounds that are reported separately in Table 6.1-2. Individual organic species comprising the nonmethane VOC emissions are included in Table 6.1-2.

[d] Average values based on surveys of plants (References 4-5).

[e] Average values based on results of 6 sampling runs conducted at a representative plant with a mean production rate of 5.1 x 10 Mg/yr (5.6 x 10 tons/yr). Ranges of values are based on a survey of 15 plants (Reference 4). Controlled by bag filter.

[f] Not detected at detection limit of 1 ppm.

[g] S is the weight % sulfur in the feed.

[h] Average values and corresponding ranges of values are based on a survey of plants (Reference 4) and on the public files of Louisiana Air Control Commission.

[i] Emission factor calculated using empirical correlations for petrochemical losses from storage tanks (vapor pressure = 0.7 kPa). Emissions are mostly aromatic oils.

[j] Based on emission rates obtained from the National Emissions Data System. All plants do not use solid waste incineration. See Section 2.1.

[k] Emissions from the furnaces are negligible. Emissions from the dryer vent, pneumatic system vent, vacuum cleanup system, and fugitive sources are similar to those for the oil furnace process.

Emissions from the dryer vent, the pneumatic transport system vent, the vacuum cleanup system vent, and fugitive sources are similar to those for the oil furnace process, since the operations that give rise to these emissions in the 2 processes are similar. There is no emission point in the thermal process that corresponds to the oil storage tank vents in the oil furnace process. Also in the thermal process, sulfur compounds, POM, trace elements, and organic compound emissions are negligible, because low-sulfur natural gas is used, and the process offgas is burned as fuel.

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6.2 Adipic Acid

6.2.1 General[1,3-5]

Adipic acid, $HOOC(CH_2)_4COOH$, is a white crystalline solid used primarily in the manufacture of nylon-6,6 polyamide and is produced in 4 facilities in the U. S. Worldwide demand for adipic acid in 1989 was nearly 2 billion megagrams (Mg) (2 billion tons), with growth continuing at a steady rate.

Adipic acid historically has been manufactured from either cyclohexane or phenol, but shifts in hydrocarbon markets have nearly resulted in the elimination of phenol as a feedstock in the U. S. This has resulted in experimentation with alternative feedstocks, which may have commercial ramifications.

6.2.2 Process Description[1,4-5]

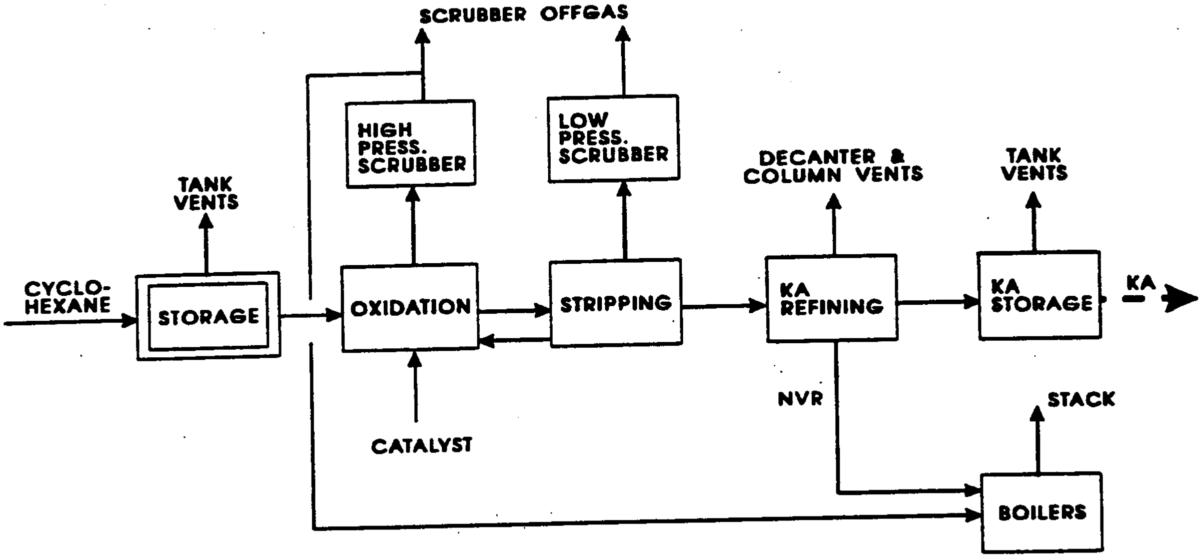
Adipic acid is manufactured from cyclohexane in two major reactions. The first step, shown in Figure 6.2-1, is the oxidation of cyclohexane to produce cyclohexanone (a ketone) and cyclohexanol (an alcohol). This ketone-alcohol (KA) mixture is then converted to adipic acid by oxidation with nitric acid in the second reaction, as shown in Figure 6.2-2. Following these 2 reaction stages, the wet adipic acid crystals are separated from water and nitric acid. The product is dried and cooled before packaging and shipping. Dibasic acids (DBA) may be recovered from the nitric acid solution and sold as a coproduct. The remaining nitric acid is then recycled to the second reactor.

The predominant method of cyclohexane oxidation is metal-catalyzed oxidation, which employs a small amount of cobalt, chromium, and/or copper, with moderate temperatures and pressures. Air, catalyst, cyclohexane, and in some cases small quantities of benzene are fed into either a multiple-stage column reactor or a series of stirred tank reactors, with a low conversion rate from feedstock to oxidized product. This low rate of conversion necessitates effective recovery and recycling of unreacted cyclohexane through distillation of the oxidizer effluent.

The conversion of the intermediates cyclohexanol and cyclohexanone to adipic acid uses the same fundamental technology as that developed and used since the early 1940s. It entails oxidation with 45 to 55 percent nitric acid in the presence of copper and vanadium catalysts. This results in a very high yield of adipic acid. The reaction is exothermic, and can reach an autocatalytic runaway state if temperatures exceed 150°C (300°F). Process control is achieved by using large amounts of nitric acid. Nitrogen oxides (NO_x) are removed by bleaching with air, water is removed by vacuum distillation, and the adipic acid is separated from the nitric acid by crystallization. Further refining, typically recrystallization from water, is needed to achieve polymer-grade material.

6.2.3 Emissions And Controls[1-2,4-7]

Emissions from the manufacture of adipic acid consist primarily of organic compounds and carbon monoxide (CO) from the first reaction, NO_x from the second reaction, and particulate matter from product cooling, drying, storage, and loading. Tables 6.2-1 and 6.2-2 present emission factors for the processes in Figure 6.2-1 and Figure 6.6-2, respectively. Emissions estimation of in-process



KA = ketone-alcohol mixture

Figure 6.2-1. Adipic acid manufacturing process: Oxidation of cyclohexane.

combustion products, fractional distillation evaporation losses, oxidizer effluent streams, and storage of volatile raw or intermediate materials, is addressed in Chapter 12, "Metallurgical Industry".

The waste gas stream from cyclohexane oxidation, after removal of most of the valuable unreacted cyclohexane by 1 or more scrubbers, will still contain CO, carbon dioxide (CO_2), and organic compounds. In addition, the most concentrated waste stream, which comes from the final distillation column (sometimes called the "nonvolatile residue"), will contain metals, residues from catalysts, and volatile and nonvolatile organic compounds. Both the scrubbed gas stream and the nonvolatile residue may be used as fuel in process heating units. If a caustic soda solution is used as a final purification step for the KA, the spent caustic waste can be burned or sold as a recovered byproduct. Analyses of gaseous effluent streams at 2 plants indicate that compounds containing cobalt and chromium, in addition to normal products of combustion, are emitted when nonvolatile residue is burned. Caproic, valeric, butyric, and succinic acids are emitted from tanks storing the nonvolatile residue. Cyclohexanone, cyclohexanol, and hexanol are among the organic compounds emitted from the cyclohexane recovery equipment (such as decanters and distillation columns.)

The nitric acid oxidation of the KA results in 2 main streams. The liquid effluent, which contains primarily water, nitric acid, and adipic acid, contains significant quantities of NO_x, which are considered part of the process stream with recoverable economic value. These NO_x are stripped

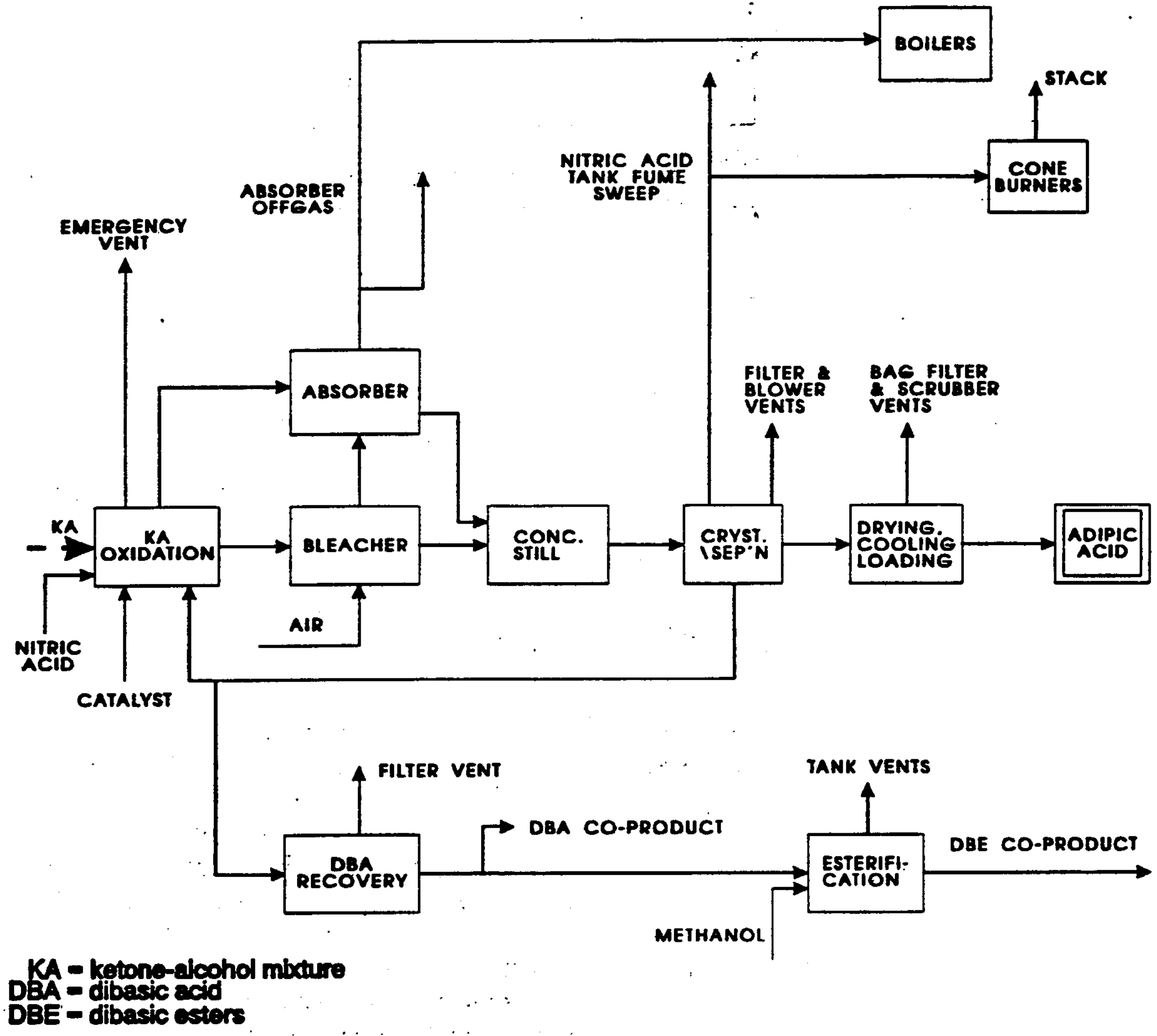


Figure 6.2-2. Adipic acid manufacturing process: Nitric acid oxidation of ketone-alcohol mixture.

Table 6.2-1 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR PRIMARY OXIDATION ADIPIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: D

Source (Cyclohexane → KA)	TNMOC[b]		CO		CO_2		CH_4	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
High-pressure scrubber	7.0[c]	14[b]	25	49	14	28	0.08	0.17
Low-pressure scrubber	1.4[d]	2.8[c]	9.0	18	3.7	7.4	0.05	0.09

[a] Factors are kilograms per megagram (kg/Mg) and pounds per ton (lb/ton) of adipic acid. KA = ketone-alcohol mixture. TNMOC = total nonmethane organic compounds.

[b] One TNMOC composition analysis at a third plant utilizing only 1 scrubber yielded the following speciation: 46% butane, 16% pentane, 33% cyclohexane, 5% other; this test not used in total TNMOC emission factor calculation.

[c] Multiple TNMOC composition analyses from 2 reactors within 1 plant yielded the following average speciation: 1.6% ethane, 1.2% ethylene, 6.7% propane, 63% butane, 16% pentane, 11% cyclohexane.

[d] Multiple TNMOC composition analyses from 2 reactors within 1 plant yielded the following average speciation: 2.3% ethane, 1.7% ethylene, 5.2% propane, 54% butane, 10% pentane, 26% cyclohexane.

from the stream in a bleaching column using air. The gaseous effluent from oxidation contains NO_x, CO_2, CO, nitrous oxide (N_2O), and DBAs. The gaseous effluent from both the bleacher and the oxidation reactor typically is passed through an absorption tower to recover most of the NO_x, but this process does not significantly reduce the concentration of N_2O in the stream. The absorber offgases and the fumes from tanks storing solutions high in nitric acid content are controlled by extended absorption at 1 of the 3 plants utilizing cyclohexane oxidation, and by thermal reduction at the remaining 2. Extended absorption is accomplished by simply increasing the volume of the absorber, by extending the residence time of the NO_x-laden gases with the absorbing water, and by providing sufficient cooling to remove the heat released by the absorption process. Thermal reduction involves reacting the NO_x with excess fuel in a reducing atmosphere, which is less economical than extended absorption.

Both scrubbers and bag filters are used commonly to control adipic acid dust particulate emissions from product drying, cooling, storage, and loading operations. Nitric acid emissions occur from the product blowers and from the centrifuges and/or filters used to recover adipic acid crystals from the effluent stream leaving the second reactor. When chlorine is added to product cooling towers, all of it can typically be assumed to be emitted to the atmosphere. If DBA are recovered from the nitric acid solution and converted to dibasic esters (DBE) using methanol, methanol emissions will also occur.

Table 6.2-2 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR SECONDARY OXIDATION ADIPIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: E (except as noted)

Source (KA → Adipic Acid)	TNMOC		CO		CO_2		N_2O		NO_x		PM	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Oxidation reactor[b,c]	0.28	0.55	0.25	0.49	60	120	290	590	7.0	14	NA	NA
Nitric acid tank fume sweep[d]	0.007	0.014	0.14	0.28	2.6	5.2	1.3	2.6	0.81	1.6	NA	NA
Adipic acid refining[e]	0.3	0.5	0	0	NA	NA	NA	NA	0.3	0.6	0.1[g]	0.1[f]
Adipic acid drying/cooling/ storage	0	0	0	0	NA	NA	NA	NA	0	0	0.4[g]	0.1[f]

[a] Factors are kilograms per megagram (kg/Mg) and pounds per ton (lb/ton) of adipic acid. KA = ketone-alcohol mixture. TNMOC = total nonmethane organic compounds. NA = not applicable.

[b] EMISSION FACTOR RATING: D

[c] Derived from multiple gas-stream composition analyses at 2 plants, 1 of which can use extended absorption to lower NO_x emissions to 3.2 lb/ton adipic acid.

[d] Derived from gas-stream composition analysis during 1 stack test.

[e] Includes chilling, crystallization, and centrifuging.

[f] Factors are after baghouse control device, no efficiency given.

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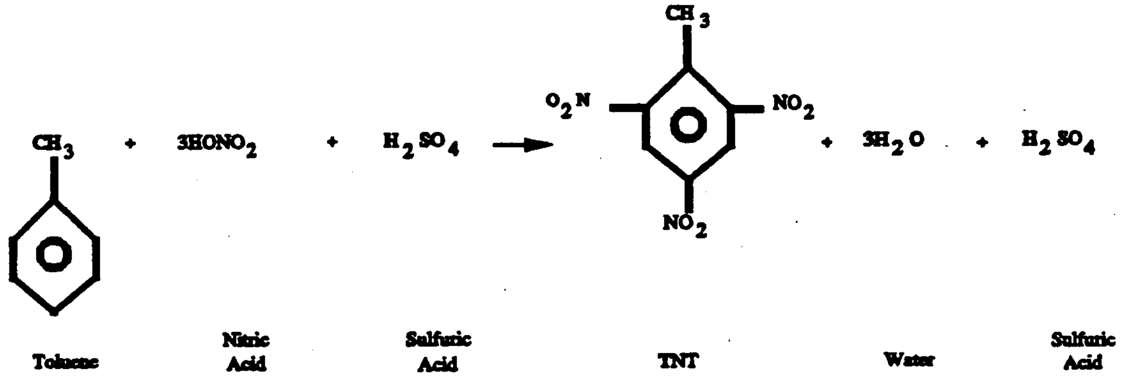
6.3 Explosives

6.3.1 General[1]

An explosive is a material that, under the influence of thermal or mechanical shock, decomposes rapidly and spontaneously with the evolution of large amounts of heat and gas. There are two major categories, high explosives and low explosives. High explosives are further divided into initiating, or primary, high explosives and secondary high explosives. Initiating high explosives are very sensitive and are generally used in small quantities in detonators and percussion caps to set off larger quantities of secondary high explosives. Secondary high explosives, chiefly nitrates, nitro compounds, and nitramines, are much less sensitive to mechanical or thermal shock, but they explode with great violence when set off by an initiating explosive. The chief secondary high explosives manufactured for commercial and military use are ammonium nitrate blasting agents and 2,4,6,-trinitrotoluene (TNT). Low explosives, such as black powder and nitrocellulose, undergo relatively slow autocombustion when set off and evolve large volumes of gas in a definite and controllable manner. Many different types of explosives are manufactured. As examples of high and low explosives, the production of TNT and nitrocellulose (NC) are discussed below.

6.3.2 TNT Production[1-3,6]

TNT may be prepared by either a continuous or a batch process, using toluene, nitric acid (HNO_3) and sulfuric acid as raw materials. The production of TNT follows the same chemical process, regardless of whether batch or continuous method is used. The flow chart for TNT production is shown in Figure 6.3-1. The overall chemical reaction may be expressed as:



The production of TNT by nitration of toluene is a 3-stage process performed in a series of reactors, as shown in Figure 6.3-2. The mixed acid stream is shown to flow countercurrent to the flow of the organic stream. Toluene and spent acid fortified with a 60 percent HNO_3 solution are fed into the first reactor. The organic layer formed in the first reactor is pumped into the second reactor, where it is subjected to further nitration with acid from the third reactor fortified with additional HNO_3. The product from the second nitration step, a mixture of all possible isomers of dinitrotoluene (DNT), is pumped to the third reactor. In the final reaction, the DNT is treated with a fresh feed of nitric acid and oleum (a solution of sulfur trioxide [SO_3] in anhydrous sulfuric acid). The crude TNT from this third nitration consists primarily of 2,4,6-trinitrotoluene. The crude TNT is washed to remove free acid, and the wash water (yellow water) is recycled to the early nitration stages. The washed TNT is

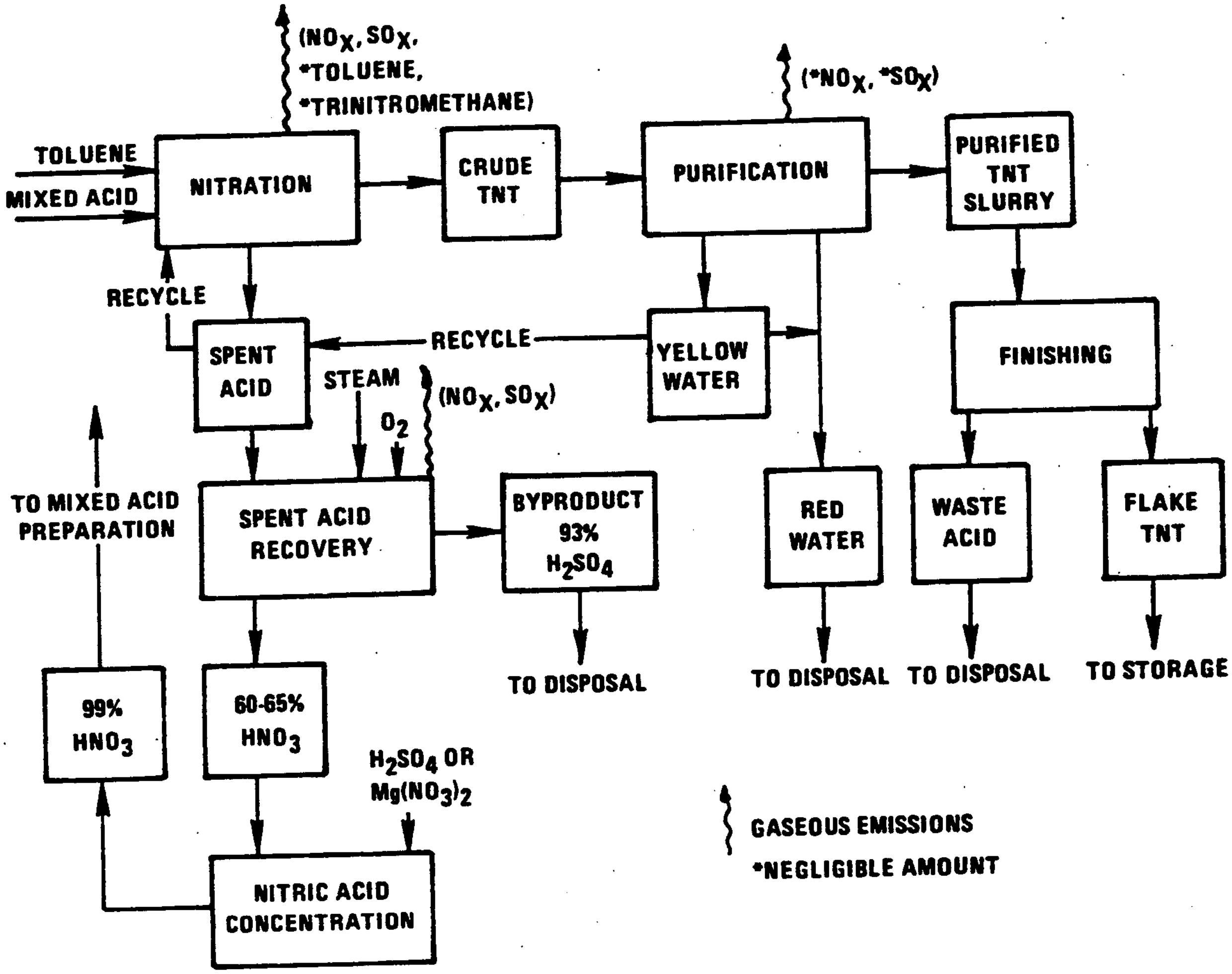


Figure 6.3-1. TNT production.

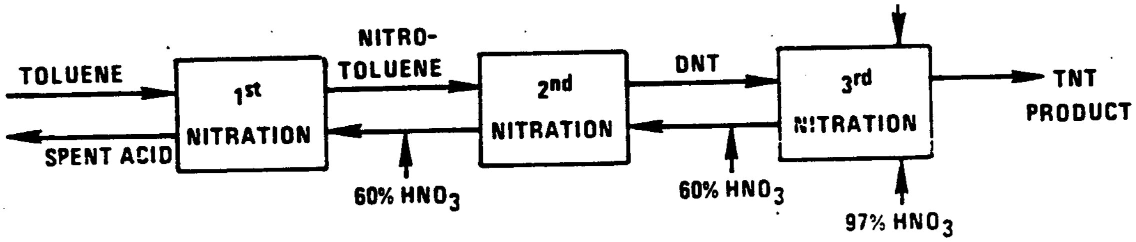


Figure 6.3-2. Nitration of toluene to form trinitrotoluene.

discharged directly as a liquid waste stream, is collected and sold, or is concentrated to a slurry and incinerated. Finally, the TNT crystals are melted and passed through hot air dryers, where most of the water is evaporated. The dehydrated product is solidified, and the TNT flakes packaged for transfer to a storage or loading area.

6.3.3 Nitrocellulose Production[1,6]

Nitrocellulose is commonly prepared by the batch-type mechanical dipper process. A newly developed continuous nitration processing method is also being used. In batch production, cellulose in the form of cotton linters, fibers, or specially prepared wood pulp is purified by boiling and bleaching. The dry and purified cotton linters or wood pulp are added to mixed nitric and sulfuric acid in metal reaction vessels known as dipping pots. The reaction is represented by:

$$\underset{\text{Cellulose}}{(C_6H_7O_2(OH)_3)_x} + \underset{\text{Nitric Acid}}{3HONO_2} + \underset{\text{Sulfuric Acid}}{H_2SO_4} \longrightarrow \underset{\text{Nitrocellulose}}{(C_6H_7O_2(ONO_2)_3)_x} + \underset{\text{Water}}{3H_2O} + \underset{\text{Sulfuric Acid}}{H_2SO_4}$$

Following nitration, the crude NC is centrifuged to remove most of the spent nitrating acids and is put through a series of water washing and boiling treatments to purify the final product.

6.3.4 Emissions And Controls[2-3,5-7]

Oxides of nitrogen (NO_x) and sulfur (SO_x) are the major emissions from the processes involving the manufacture, concentration, and recovery of acids in the nitration process of explosives manufacturing. Emissions from the manufacture of nitric and sulfuric acid are discussed in other sections. Trinitromethane (TNM) is a gaseous byproduct of the nitration process of TNT manufacture. Volatile organic compound (VOC) emissions result primarily from fugitive vapors from various solvent recovery operations. Explosive wastes and contaminated packaging material are regularly disposed of by open burning, and such results in uncontrolled emissions, mainly of NO_x and particulate matter. Experimental burns of several explosives to determine "typical" emission factors for the open burning of TNT are presented in Table 6.3-1.

Table 6.3-1 (English Units). EMISSION FACTORS FOR THE OPEN BURNING OF TNT[a,b]
(lb pollution/ton TNT burned)

Type Of Explosive	Particulates	Nitrogen Oxides	Carbon Monoxide	Volatile Organic Compounds
TNT	180.0	150.0	56.0	1.1

[a] Reference 7. Particulate emissions are soot. VOC is nonmethane.

[b] The burns were made on very small quantities of TNT, with test apparatus designed to simulate open burning conditions. Since such test simulations can never replicate actual open burning, it is advisable to use the factors in this Table with caution.

In the manufacture of TNT, emissions from the nitrators containing NO, NO_2, N_2O, TNM, and some toluene are passed through a fume recovery system to extract NO_x as nitric acid, and then are vented through scrubbers to the atmosphere. Final emissions contain quantities of unabsorbed NO_x and TNM. Emissions may also come from the production of Sellite solution and the incineration of red water. Red water incineration results in atmospheric emissions of NO_x, SO_2, and ash (primarily Na_2SO_4.)

In the manufacture of nitrocellulose, emissions from reactor pots and centrifuges are vented to a NO_x water absorber. The weak HNO_3 solution is transferred to the acid concentration system. Absorber emissions are mainly NO_x. Another possible source of emissions is the boiling tubs, where steam and acid vapors vent to the absorber.

The most important fact affecting emissions from explosives manufacture is the type and efficiency of the manufacturing process. The efficiency of the acid and fume recovery systems for TNT manufacture will directly affect the atmospheric emissions. In addition, the degree to which acids are exposed to the atmosphere during the manufacturing process affects the NO_x and SO_x emissions. For nitrocellulose production, emissions are influenced by the nitrogen content and the desired product quality. Operating conditions will also affect emissions. Both TNT and nitrocellulose can be produced in batch processes. Such processes may never reach steady state, emission concentrations may vary considerably with time, and fluctuations in emissions will influence the efficiency of control methods.

Several measures may be taken to reduce emissions from explosive manufacturing. The effects of various control devices and process changes, along with emission factors for explosives manufacturing, are shown in Tables 6.3-2 and 6.3-3. The emission factors are all related to the amount of product produced and are appropriate either for estimating long-term emissions or for evaluating plant operation at full production conditions. For short time periods, or for plants with intermittent operating schedules, the emission factors in Tables 6.3-2 and 6.3-3 should be used with caution because processes not associated with the nitration step are often not in operation at the same time as the nitration reactor.

Table 6.3-2 (Metric Units). EMISSION FACTORS FOR EXPLOSIVES MANUFACTURING[a,b]

EMISSION FACTOR RATING: C

Process	Particulates	Sulfur Oxides (SO_2)	Nitrogen Oxides (NO_2)	Nitric Acid Mist (100% HNO_3)	Sulfur Acid Mist (100% H_2SO_4)
TNT - Batch process[c]					
Nitration reactors					
Fume recovery	—	—	12.5 (3 - 19)	0.5 (0.15 - 0.95)	—
Acid recovery	—	—	27.5 (0.5 - 68)	46 (0.005 - 137)	—
Nitric acid concentrators	—	—	18.5 (8 - 36)	—	4.5 (0.15 - 13.5)
Sulfuric acid concentrators[d]					
Electrostatic precipitator (exit)	—	7 (2 - 20)	20 (1 - 40)	—	32.5 (0.5 - 94)
Electrostatic precipitator with scrubber[e]	—	Neg	20 (1 - 40)	—	2.5 (2 - 3)
Red water incinerator					
Uncontrolled[f]	12.5 (0.015 - 63)	1 (0.025 - 1.75)	13 (0.75 - 50)	—	—
Wet scrubber[g]	0.5	1 (0.025 - 1.75)	2.5	—	—
Sellite exhaust	—	29.5 (0.005 - 88)	—	—	3 (0.3 - 8)
TNT - Continuous process[h]					
Nitration reactors					
Fume recovery	—	—	4 (3.35 - 5)	0.5 (0.15 - 0.95)	—
Acid recovery	—	—	1.5 (0.5 - 2.25)	0.01 (0.005 - 0.015)	—

Table 6.3-2 (cont.).

Process	Particulates	Sulfur Oxides (SO_2)	Nitrogen Oxides (NO_2)	Nitric Acid Mist (100% HNO_3)	Sulfur Acid Mist (100% H_2SO_4)
Red water incinerator	0.13 (0.015 - 0.25)	0.12 (0.025 - 0.22)	3.5 (3 - 4.2)	—	—
Nitrocellulose[h]					
Nitration reactors[i]	—	0.7 (0.04 - 1)	7 (1.85 - 17)	9.5 (0.25 - 18)	—
Nitric acid concentrator	—	—	7 (5 - 9)	—	—
Sulfuric acid concentrator	—	34 (0.2 - 67)	—	—	0.3
Boiling tubs	—	—	1	—	—

[a] For some processes, considerable variations in emissions have been reported. Average of reported values is shown first; ranges in parentheses. Where only 1 number is given, only 1 source test was available. Emission factors are in units of kg of pollutant per Mg of TNT or nitrocellulose produced.

[b] Significant emissions of VOCs have not been reported for the explosives industry. However, negligible emissions of toluene and TNM from nitration reactors have been reported in TNT manufacture. Also, fugitive VOC emissions may result from various solvent recovery operations. See Reference 6.

[c] Reference 5.

[d] Acid mist emissions influenced by nitrobody levels and type of furnace fuel.

[e] No data available for NO_x emissions after scrubber. NO_x emissions are assumed to be unaffected by scrubber.

[f] Use low end of range for modern efficient units, high end for less efficient units.

[g] Apparent reductions in NO_x and particulate after control may not be significant because these values are based on only 1 test result.

[h] Reference 4.

[i] For product with low nitrogen content (12%), use high end of range. For products with higher nitrogen content, use lower end of range.

Table 6.3-3 (English Units). EMISSION FACTORS FOR EXPLOSIVES MANUFACTURING[a,b]

EMISSION FACTOR RATING: C

Process	Particulates	Sulfur Oxides (SO_2)	Nitrogen Oxides (NO_2)	Nitric Acid Mist (100% HNO_3)	Sulfur Acid Mist (100% H_2SO_4)
TNT - Batch process[c]					
Nitration reactors					
Fume recovery	—	—	25 (6 - 38)	1 (0.3 - 1.9)	—
Acid recovery	—	—	55 (1 - 136)	92 (0.02 - 275)	—
Nitric acid concentrators	—	—	37 (16 - 72)	—	9 (0.3 - 27)
Sulfuric acid concentrators[d]					
Electrostatic precipitator (exit)	—	14 (4 - 40)	40 (2 - 80)	—	65 (1 - 188)
Electrostatic precipitator with scrubber[e]	—	Neg	40 (2 - 80)		5 (4 - 6)
Red water incinerator					
Uncontrolled[f]	25 (0.03 - 126)	2 (0.05 - 3.5)	26 (1.5 - 101)	—	—
Wet scrubber[g]	1	2 (0.05 - 3.5)	5	—	—
Sellite exhaust	—	59 (0.01 - 177)	—	—	6 (0.6 - 16)
TNT - Continuous process[h]					
Nitration reactors					
Fume recovery	—	—	8 (6.7 - 10)	1 (0.3 - 1.9)	—
Acid recovery	—	—	3 (1 - 4.5)	0.02 (0.01 - 0.03)	—

Table 6.3-3 (cont.).

Process	Particulates	Sulfur Oxides (SO_2)	Nitrogen Oxides (NO_2)	Nitric Acid Mist (100% HNO_3)	Sulfur Acid Mist (100% H_2SO_4)
Red water incinerator	0.25 (0.03 - 0.5)	0.24 (0.05 - 0.43)	7 (6.1 - 8.4)	—	—
Nitrocellulose[h]					
Nitration reactors[i]	—	1.4 (0.8 - 2)	14 (3.7 - 34)	19 (0.5 - 36)	—
Nitric acid concentrator	—	—	14 (10 - 18)	—	—
Sulfuric acid concentrator	—	68 (0.4 - 135)	—	—	0.6
Boiling tubs	—	—	2	—	—

[a] For some processes, considerable variations in emissions have been reported. Average of reported values is shown first, ranges in parentheses. Where only 1 number is given, only 1 source test was available. Emission factors are in units of pounds of pollutant per ton of TNT or nitrocellulose produced.

[b] Significant emissions of VOCs have not been reported for the explosives industry. However, negligible emissions of toluene and TNM from nitration reactors have been reported in TNT manufacture. Also, fugitive VOC emissions may result from various solvent recovery operations. See Reference 6.

[c] Reference 5.

[d] Acid mist emissions influenced by nitrobody levels and type of furnace fuel.

[e] No data available for NO_x emissions after scrubber. NO_x emissions are assumed to be unaffected by scrubber.

[f] Use low end of range for modern efficient units, high end for less efficient units.

[g] Apparent reductions in NO_x and particulate after control may not be significant because these values are based on only 1 test result.

[h] Reference 4.

[i] For product with low nitrogen content (12%), use high end of range. For products with higher nitrogen content, use lower end of range.

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6.4 Paint And Varnish

6.4.1 Paint Manufacturing[1]

The manufacture of paint involves the dispersion of a colored oil or pigment in a vehicle, usually an oil or resin, followed by the addition of an organic solvent for viscosity adjustment. Only the physical processes of weighing, mixing, grinding, tinting, thinning, and packaging take place. No chemical reactions are involved.

These processes take place in large mixing tanks at approximately room temperature.

The primary factors affecting emissions from paint manufacture are care in handling dry pigments, types of solvents used, and mixing temperature. About 1 or 2 percent of the solvent is lost even under well-controlled conditions. Particulate emissions amount to 0.5 to 1.0 percent of the pigment handled.

Afterburners can reduce emitted volatile organic compounds (VOC) by 99 percent and particulates by about 90 percent. A water spray and oil filter system can reduce particulate emissions from paint blending by 90 percent.

6.4.2 Varnish Manufacturing[1-3,5]

The manufacture of varnish also involves the mixing and blending of various ingredients to produce a wide range of products. However in this case, chemical reactions are initiated by heating. Varnish is cooked in either open or enclosed gas-fired kettles for periods of 4 to 16 hours at temperatures of 93 to 340°C (200 to 650°F).

Varnish cooking emissions, largely in the form of volatile organic compounds, depend on the cooking temperatures and times, the solvent used, the degree of tank enclosure and the type of air pollution controls used. Emissions from varnish cooking range from 1 to 6 percent of the raw material.

To reduce organic compound emissions from the manufacture of paint and varnish, control techniques include condensers and/or adsorbers on solvent handling operations, and scrubbers and afterburners on cooking operations. Afterburners can reduce volatile organic compounds by 99 percent. Emission factors for paint and varnish are shown in Table 6.4-1.

Table 6.4-1 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR PAINT AND VARNISH MANUFACTURING[a,b]

EMISSION FACTOR RATING: C

Type Of Product	Particulate		Nonmethane VOC[c]	
	kg/Mg Pigment	lb/ton Pigment	kg/Mg Of Product	lb/ton Of Product
Paint[d]	10	20	15	30
Varnish				
Bodying oil	—	—	20	40
Oleoresinous	—	—	75	150
Alkyd	—	—	80	160
Acrylic	—	—	10	20

[a] References 2,4-8.

[b] Afterburners can reduce VOC emissions by 99% and particulates by about 90%. A water spray and oil filter system can reduce particulates by about 90%.

[c] Expressed as undefined organic compounds whose composition depends upon the type of solvents used in the manufacture of paint and varnish.

[d] Reference 4. Particulate mater (0.5 - 1.0%) is emitted from pigment handling.

References For Section 6.4

1. *Air Pollutant Emission Factors*, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

2. R. L. Stenburg, "Controlling Atmospheric Emissions From Paint And Varnish Operations, Part I", *Paint And Varnish Production*, September 1959.

3. Private communication between Resources Research, Inc., Reston, VA, And National Paint, Varnish And Lacquer Association, Washington, DC, September 1969.

4. Unpublished engineering estimates based on plant visits in Washington, DC, Resources Research, Inc., Reston, VA, October 1969.

5. *Air Pollution Engineering Manual*, Second Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1973.

6. E. G. Lunche, *et al.*, "Distribution Survey Of Products Emitting Organic Vapors In Los Angeles County", *Chemical Engineering Progress*, *53*(8):371-376, August 1957.

7. Communication on emissions from paint and varnish operations between Resources Research, Inc., Reston, VA, and G. Sallee, Midwest Research Institute, Kansas City, MO, December 17, 1969.

8. Communication between Resources Research, Inc., Reston, VA, and Roger Higgins, Benjamin Moore Paint Company, June 25, 1968.

6.5 Phthalic Anhydride

6.5.1 General[1]

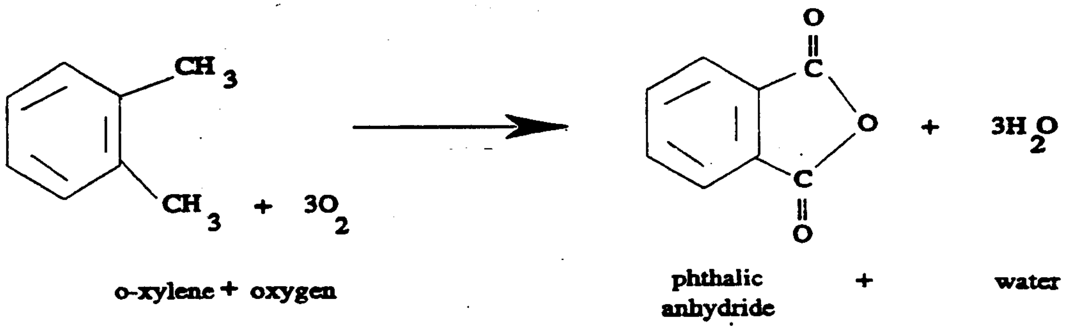
Phthalic anhydride (PAN) production in the United States in 1972 was 0.9 billion pounds per year; this total is estimated to increase to 2.2 billion pounds per year by 1985. Of the current production, 50 percent is used for plasticizers, 25 percent for alkyd resins, 20 percent for unsaturated polyester resins, and 5 percent for miscellaneous and exports. PAN is produced by catalytic oxidation of either orthoxylene or naphthalene. Since naphthalene is a higher-priced feedstock and has a lower feed utilization (about 1.0 lb PAN/lb o-xylene versus 0.97 lb PAN/lb naphthalene), future production growth is predicted to utilize o-xylene. Because emission factors are intended for future as well as present application, this report will focus mainly on PAN production utilizing o-xylene as the main feedstock.

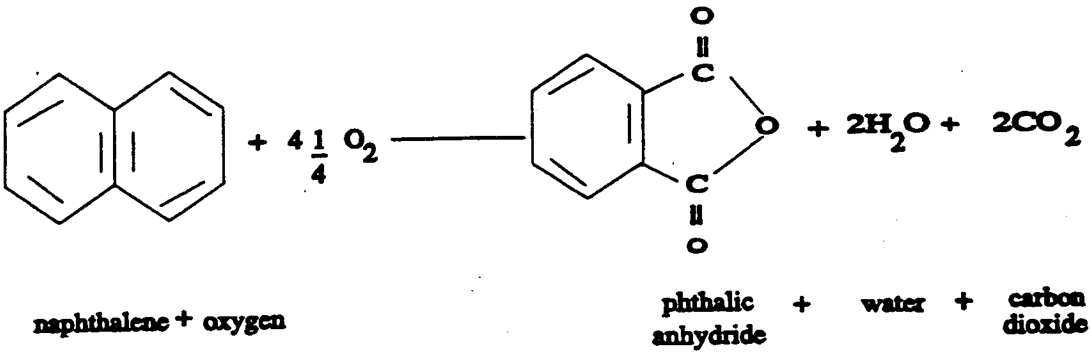
The processes for producing PAN by o-xylene or naphthalene are the same except for reactors, catalyst handling, and recovery facilities required for fluid bed reactors.

In PAN production using o-xylene as the basic feedstock, filtered air is preheated, compressed, and mixed with vaporized o-xylene and fed into the fixed-bed tubular reactors. The reactors contain the catalyst, vanadium pentoxide, and are operated at 650 to 725°F (340 to 385°C). Small amounts of sulfur dioxide are added to the reactor feed to maintain catalyst activity. Exothermic heat is removed by a molten salt bath circulated around the reactor tubes and transferred to a steam generation system.

Naphthalene-based feedstock is made up of vaporized naphthalene and compressed air. It is transferred to the fluidized bed reactor and oxidized in the presence of a catalyst, vanadium pentoxide, at 650 to 725°F (340 to 385°C). Cooling tubes located in the catalyst bed remove the exothermic heat, which is used to produce high-pressure steam. The reactor effluent consists of PAN vapors, entrained catalyst, and various byproducts and nonreactant gas. The catalyst is removed by filtering and returned to the reactor.

The chemical reactions for air oxidation of o-xylene and naphthalene are as follows.





The reactor effluent containing crude PAN plus products from side reactions and excess oxygen passes to a series of switch condensers where the crude PAN cools and crystallizes. The condensers are alternately cooled and then heated, allowing PAN crystals to form and then melt from the condenser tube fins.

The crude liquid is transferred to a pretreatment section in which phthalic acid is dehydrated to anhydride. Water, maleic anhydride, and benzoic acid are partially evaporated. The liquid then goes to a vacuum distillation section where pure PAN (99.8 wt. percent pure) is recovered. The product can be stored and shipped either as a liquid or a solid (in which case it is dried, flaked, and packaged in multi-wall paper bags). Tanks for holding liquid PAN are kept at 300°F (150°C) and blanketed with dry nitrogen to prevent the entry of oxygen (fire) or water vapor (hydrolysis to phthalic acid).

Maleic anhydride is currently the only byproduct being recovered.

Figure 6.5-1 and Figure 6.5-2 show the process flow for air oxidation of o-xylene and naphthalene, respectively.

6.5.2 Emissions And Controls[1]

Emissions from o-xylene and naphthalene storage are small and presently are not controlled.

The major contributor of emissions is the reactor and condenser effluent which is vented from the condenser unit. Particulate, sulfur oxides (for o-xylene-based production), and carbon monoxide make up the emissions, with carbon monoxide comprising over half the total. The most efficient (96 percent) system of control is the combined usage of a water scrubber and thermal incinerator. A thermal incinerator alone is approximately 95 percent efficient in combustion of pollutants for o-xylene-based production, and 80 percent efficient for naphthalene-based production. Thermal incinerators with steam generation show the same efficiencies as thermal incinerators alone. Scrubbers have a 99 percent efficiency in collecting particulates, but are practically ineffective in reducing carbon monoxide emissions. In naphthalene-based production, cyclones can be used to control catalyst dust emissions with 90 to 98 percent efficiency.

Pretreatment and distillation emissions—particulates and hydrocarbons—are normally processed through the water scrubber and/or incinerator used for the main process stream (reactor and condenser) or scrubbers alone, with the same efficiency percentages applying.

Product storage in the liquid phase results in small amounts of gaseous emissions. These gas streams can either be sent to the main process vent gas control devices or first processed through sublimation boxes or devices used to recover escaped PAN. Flaking and bagging emissions are negligible, but can be sent to a cyclone for recovery of PAN dust. Exhaust from the cyclone presents no problem.

Table 6.5-1 gives emission factors for controlled and uncontrolled emissions from the production of PAN.

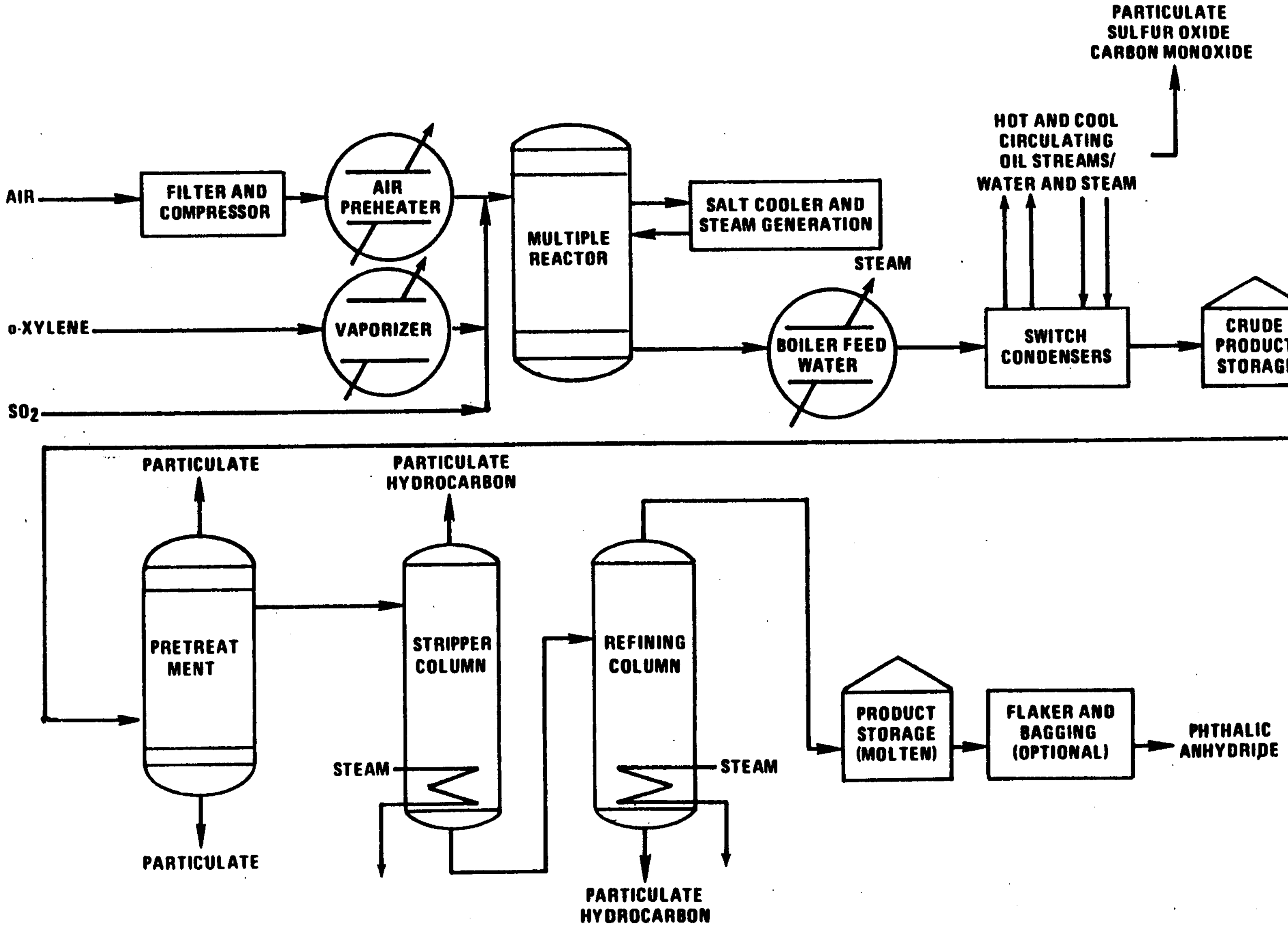


Figure 6.5-1. Flow diagram for phthalic anhydride using o-xylene as basic feedstock.[1]

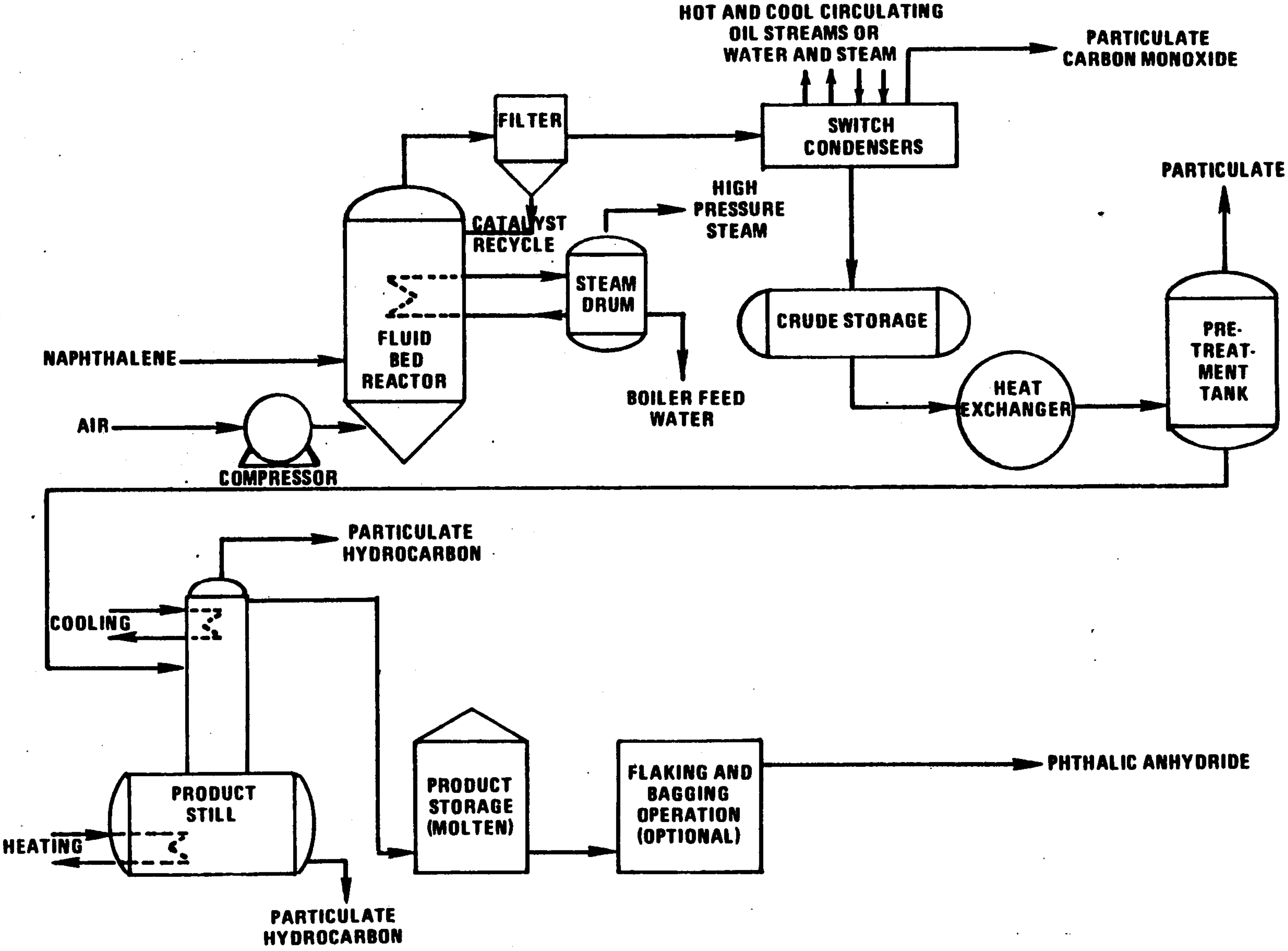


Figure 6.5-2. Flow diagram for phthalic anhydride using naphthalene as basic feedstock.[1]

Table 6.5-1 (Metric And English Units). EMISSION FACTORS FOR PHTHALIC ANHYDRIDE[a]

EMISSION FACTOR RATING: B

Process	Particulate		SO_x		Nonmethane VOC[b]		CO	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Oxidation of o-xylene[c]								
Main process stream[d]								
Uncontrolled	69[e]	138[e]	4.7[f]	9.4[f]	0	0	151	301
W/scrubber and thermal incinerator	3	6	4.7	9.4	0	0	6	12
W/thermal incinerator	4	7	4.7	9.4	0	0	8	15
W/incinerator with steam generator	4	7	4.7	9.4	0	0	8	15
Pretreatment								
Uncontrolled	6.4[g]	13[g]	0	0	0	0	0	0
W/scrubber and thermal incinerator	0.3	0.5	0	0	0	0	0	0
W/thermal incinerator	0.4	0.7	0	0	0	0	0	0
Distillation								
Uncontrolled	45[e]	89[e]	0	0	1.2[e,h]	2.4[e,h]	0	0
W/scrubber and thermal incinerator	2	4	0	0	<0.1	<0.1	0	0
W/thermal incinerator	2	4	0	0	<0.1	0.1	0	0
Oxidation of naphthalene[c]								
Main process stream[d]								
Uncontrolled	28[j,k]	56[j,k]	0	0	0	0	50	100
W/thermal incinerator	6	11	0	0	0	0	10	20
W/scrubber	0.3	0.6	0	0	0	0	50	100
Pretreatment								
Uncontrolled	2.5[m]	5[m]	0	0	0	0	0	0
W/thermal incinerator	0.5	1	0	0	0	0	0	0
W/scrubber	<0.1	<0.1	0	0	0	0	0	0

Table 6.5-1 (cont.).

Process	Particulate		SO_x		Nonmethane VOC[b]		CO	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Distillation								
Uncontrolled	19[j]	38[j]	0	0	5[h,j]	10[h,j]	0	0
W/thermal incinerator	4	8	0	0	1	2	0	0
W/scrubber	0.2	0.4	0	0	<0.1	0.1	0	0

[a] Reference 1. Factors are in kg of pollutant/Mg (lb/ton) of phthalic athydride produced.

[b] Emissions contain no methane.

[c] Control devices listed are those currently being used by phthalic anhydride plants.

[d] Main process stream includes reactor and multiple switch condensers as vented through condenser unit.

[e] Consists of phthalic anhydride, maleic anhydride, benzoic acid.

[f] Value shown corresponds to relatively fresh catalyst, which can change with catalyst age. Can be 9.5 - 13 kg/Mg (19 - 25 lb/ton) for aged catalyst.

[g] Consists of phthalic anhydride and maleic anhydride.

[h] Normally a vapor, but can be present as a particulate at low temperature.

[j] Consists of phthalic anhydride, maleic anhydride, naphthaquinone.

[k] Does not include catalyst dust, controlled by cyclones with efficiency of 90 - 98%.

[m] Particulate is phthalic anhydride.

Reference For Section 6.5

1. *Engineering And Cost Study Of Air Pollution Control For The Petrochemical Industry, Vol. 7: Phthalic Anhydride Manufacture From Ortho-xylene*, EPA-450/3-73-006g, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1975.

6.6 Plastics

6.6.1 Polyvinyl Chloride

6.6.2 Poly(ethylene Terephthalate)

6.6.3 Polystyrene

6.6.1 Polyvinyl Chloride

6.6.1.1 Process Description[1]

The manufacture of most resins or plastics begins with the polymerization or linking of the basic compound (monomer), usually a gas or liquid, into high molecular weight noncrystalline solids. The manufacture of the basic monomer is not considered part of the plastics industry and is usually accomplished at a chemical or petroleum plant.

The manufacture of most plastics involves an enclosed reaction or polymerization step, a drying step, and a final treating and forming step. These plastics are polymerized or otherwise combined in completely enclosed stainless steel or glass-lined vessels. Treatment of the resin after polymerization varies with the proposed use. Resins for moldings are dried and crushed or ground into molding powder. Resins such as the alkyd to be used for protective coatings are usually transferred to an agitated thinning tank, where they are thinned with some type of solvent and then stored in large steel tanks equipped with water-cooled condensers to prevent loss of solvent to the atmosphere. Still other resins are stored in latex form as they come from the kettle.

6.6.1.2 Emissions And Controls[1]

The major sources of air contamination in plastics manufacturing are the raw materials or monomers, solvents, or other volatile liquids emitted during the reaction; sublimed solids such as phthalic anhydride emitted in alkyd production; and solvents lost during storage and handling of thinned resins. Emission factors for the manufacture of polyvinyl chloride are shown in Table 6.6.1-1.

Table 6.6.1-1 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR PLASTICS MANUFACTURING[a]

EMISSION FACTOR RATING: E

Type of Plastic	Particulate		Gases	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Polyvinyl chloride	17.5[b]	35[b]	8.5[c]	17[c]

[a] References 2-3.
[b] Usually controlled with fabric filter, efficiency of 98-99%.
[c] As vinyl chloride.

Much of the control equipment used in this industry is a basic part of the system serving to recover a reactant or product. These controls include floating roof tanks or vapor recovery systems on volatile material, storage units, vapor recovery systems (adsorption or condensers), purge lines venting to a flare system, and vacuum exhaust line recovery systems.

References For Section 6.6.1

1. *Air Pollutant Emission Factors, Final Report*, Resources Research, Inc., Reston, VA, Prepared for National Air Pollution Control Administration, Durham, NC, under Contract Number CPA-22-69-119, April 1970.

2. Unpublished data, U. S. Department of Health and Human Services, National Air Pollution Control Administration, Durham, NC, 1969.

3. Communication between Resources Research, Inc., Reston, VA, and State Department Of Health, Baltimore, MD, November 1969.

6.6.2 Poly(ethylene Terephthalate)[1-2]

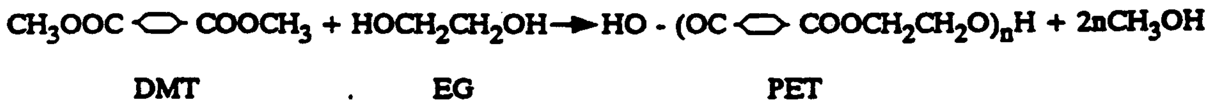
6.6.2.1 General

Poly(ethylene terephthalate), or PET, is a thermoplastic polyester resin. Such resins may be classified as low-viscosity or high-viscosity resins. Low-viscosity PET typically has an intrinsic viscosity of less than 0.75, while high-viscosity PET typically has an intrinsic viscosity of 0.9 or higher. Low-viscosity resins, which are sometimes referred to as "staple" PET (when used in textile applications), are used in a wide variety of products, such as apparel fiber, bottles, and photographic film. High-viscosity resins, sometimes referred to as "industrial" or "heavy denier" PET, are used in tire cord, seat belts, and the like.

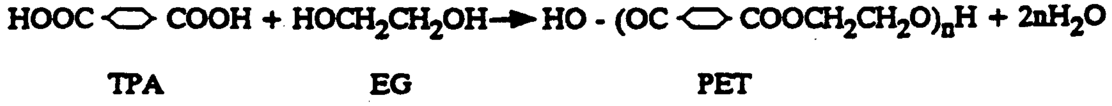
PET is used extensively in the manufacture of synthetic fibers (i. e., polyester fibers), which compose the largest segment of the synthetic fiber industry. Since it is a pure and regulated material meeting FDA food contact requirements, PET is also widely used in food packaging, such as beverage bottles and frozen food trays that can be heated in a microwave or conventional oven. PET bottles are used for a variety of foods and beverages, including alcohol, salad dressing, mouthwash, syrups, peanut butter, and pickled food. Containers made of PET are being used for toiletries, cosmetics, and household and pharmaceutical products (e. g., toothpaste pumps). Other applications of PET include molding resins, X-ray and other photographic films, magnetic tape, electrical insulation, printing sheets, and food packaging film.

6.6.2.2 Process Description[3-15]

PET resins are produced commercially from ethylene glycol (EG) and either dimethyl terephthalate (DMT) or terephthalic acid (TPA). DMT and TPA are solids. DMT has a melting point of 140°C (284°F), while TPA sublimes (goes directly from the solid phase to the gaseous phase). Both processes first produce the intermediate bis-(2-hydroxyethyl)-terephthalate (BHET) monomer and either methanol (DMT process) or water (TPA process). The BHET monomer is then polymerized under reduced pressure with heat and catalyst to produce PET resins. The primary reaction for the DMT process is:



The primary reaction for the TPA process is:



Both processes can produce low- and high-viscosity PET. Intrinsic viscosity is determined by the high polymerizer operating conditions of: (1) vacuum level, (2) temperature, (3) residence time, and (4) agitation (mechanical design).

The DMT process is the older of the two processes. Polymerization grade TPA has been available only since 1963. The production of methanol in the DMT process creates the need for methanol recovery and purification operations. In addition, this methanol can produce major VOC emissions. To avoid the need to recover and purify the methanol and to eliminate the potential VOC emissions, newer plants tend to use the TPA process.

DMT Process -

Both batch and continuous operations are used to produce PET using DMT. There are three basic differences between the batch process and continuous process: (1) a column-type reactor replaces the kettle reactor for esterification (ester exchange between DMT and ethylene glycol), (2) "no-back-mix" (i. e., no stirred tank) reactor designs are required in the continuous operation, and (3) different additives and catalysts are required to ensure proper product characteristics (e. g., molecular weight, molecular weight distribution).

Figure 6.6.2-1 is a schematic representation of the PET/DMT continuous process, and the numbers and letters following refer to this figure. Ethylene glycol is drawn from raw material storage (1) and fed to a mix tank (2), where catalysts and additives are mixed in. From the mix tank, the mixture is fed, along with DMT, to the esterifiers, also known as ester exchange reactors (3). About 0.6 pounds (lb) of ethylene glycol and 1.0 lb of DMT are used for each pound of PET product. In the esterifiers, the first reaction step occurs at an elevated temperature (between 170 and 230°C [338 and 446°F]) and at or above atmospheric pressure. This reaction produces the intermediate BHET monomer and the byproduct methanol. The methanol vapor must be removed from the esterifiers to shift the conversion to produce more BHET.

The vent from the esterifiers is fed to the methanol recovery system (11), which separates the methanol by distillation in a methanol column. The recovered methanol is then sent to storage (12). Vapor from the top of the methanol column is sent to a cold water (or refrigerated) condenser, where the condensate returns to the methanol column, and noncondensables are purged with nitrogen before being emitted to the atmosphere. The bottom product of methanol column, mostly ethylene glycol from the column's reboiler, is reused.

The BHET monomer, with other esterifier products, is fed to a prepolymerization reactor (4) where the temperature is increased to 230 to 285°C (446 to 545°F), and the pressure is reduced to between 1 and 760 millimeters (mm) of mercury (Hg) (typically, 100 to 200 mm Hg). At these operating conditions, residual methanol and ethylene glycol are vaporized, and the reaction that produces PET resin starts.

Product from the prepolymerizer is fed to one or more polymerization reactors (5), in series. In the polymerization reactors, sometimes referred to as end finishers, the temperature is further increased to 260 to 300°C (500 to 572°F). The pressure is further reduced (e. g., to an absolute pressure of 4 to 5 mm Hg). The final temperature and pressure depend on whether low- or high-viscosity PET is being produced. For high-viscosity PET, the pressure in the final (or second) end finisher is less than 2 mm Hg. With high-viscosity PET, more process vessels are used than low-viscosity PET to achieve the higher temperatures and lower pressures needed.

The vapor (ethylene glycol, methanol, and other trace hydrocarbons from the prepolymerization and polymerization reactors) typically is evacuated through scrubbers (spray condensers) using spent ethylene glycol. The recovered ethylene glycol is recirculated in the scrubber system, and part of the spent ethylene glycol from the scrubber system is sent to storage in process tanks (13), after which it is sent to the ethylene glycol recovery system (14).

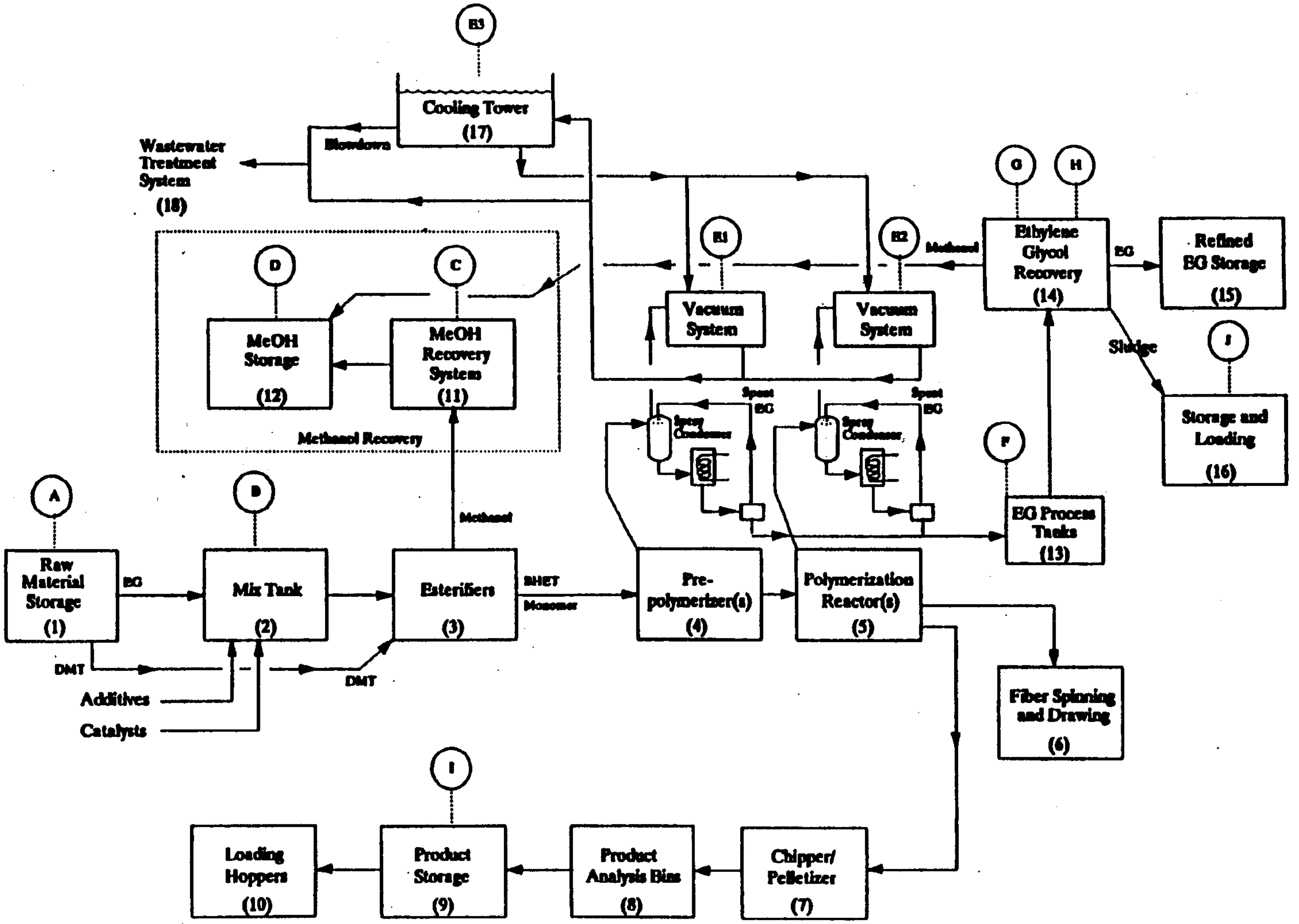


Figure 6.6.2-1. Simplified flow diagram of PET/DMT continuous process.

The ethylene glycol recovery system (14) usually is a distillation system composed of a low boiler column, a refining column, and associated equipment. In such a system, the ethylene glycol condensate is fed to the low boiler column. The top product from this column is sent to a condenser, where methanol is condensed and sent to methanol storage. The noncondensable vent (from the low boiler condenser) is purged with nitrogen and sent to the atmosphere (Stream G in the flow diagram). The bottom product of the low boiler column goes to its reboiler, with the vapor recycled back to the low boiler column and the underflow sent to the refining column. The refining column is under vacuum and is evacuated to the atmosphere. Top product from the refining column goes through a condenser, and the condensate is collected in a reflux tank. Part of the ethylene glycol condensate returns to the refining column. The remaining liquid goes to refined ethylene glycol storage (15). The reflux tank is purged with nitrogen. (The purge gas vented to the atmosphere from the reflux tank consists of only nitrogen.) The bottom product of the refining column goes to a reboiler, vapor returns to the column, and what remains is a sludge byproduct (16).

The vacuum conditions in the prepolymerization and polymerization reactors are created by means of multistage steam jet ejector (venturi) systems. The vacuum system typically is composed of a series of steam jets, with condensers on the discharge side of the steam jet to cool the jets and to condense the steam. The condensed steam from the vacuum jets and the evacuated vapors are combined with the cooling water during the condensation process. This stream exiting the vacuum system goes either to a cooling tower (17), where the water is cooled and then recirculated through the vacuum system, or to a waste water treatment plant (once-through system) (18).

Product from the polymerization reactor (referred to as the polymer melt) may be sent directly to fiber spinning and drawing operations (6). Alternatively, the polymer melt may be chipped or pelletized (7), put into product analysis bins (8), and then sent to product storage (9) before being loaded into hoppers (10) for shipment to the customer.

TPA Process -

Figure 6.6.2-2 is a schematic diagram of a continuous PET/TPA process, and the numbers and letters following refer to this figure. Raw materials are brought on site and stored (1). Terephthalic acid, in powder form, may be stored in silos. The ethylene glycol is stored in tanks. The terephthalic acid and ethylene glycol, containing catalysts, are mixed in a tank (2) to form a paste. In the mix tank, ethylene glycol flows into a manifold that sprays the glycol through many small slots around the periphery of the vent line. The terephthalic acid and ethylene glycol are mixed by kneading elements working in opposite directions. Combining these materials into a paste is a simple means of introducing them to the process, allowing more accurate control of the feed rates to the esterification vessels. A portion of the paste is recycled to the mix tank. This paste recycle and feed rates of TPA and ethylene glycol are used to maintain an optimum paste density or weight percent of terephthalic acid.

The paste from the mix tanks is fed, using gear pumps to meter the flow, to a series of esterification vessels (referred to as esterifiers, or ester exchange reactors). Two or more esterifiers may be used. Residence time is controlled by valves in the transfer lines between each vessel. These esterifiers are closed, pressurized reactors. Pressure and temperature operating conditions in the primary esterifier (3) are between 30 and 50 pounds per square inch gauge (psig) and 230 to 260°C (446 to 500°F), respectively. Vapors, primarily water (steam) and glycol, are vented to a reflux column or distillation column. A heat exchanger cools the vapors. Recovered glycol is returned to the primary esterifier. The water vapor is condensed using 29°C (85°F) cooling water in a shell-and-tube condenser and then is discharged to the waste water treatment system. The monomer formed in the primary esterifier and the remaining reactants are pumped to the secondary esterifier.

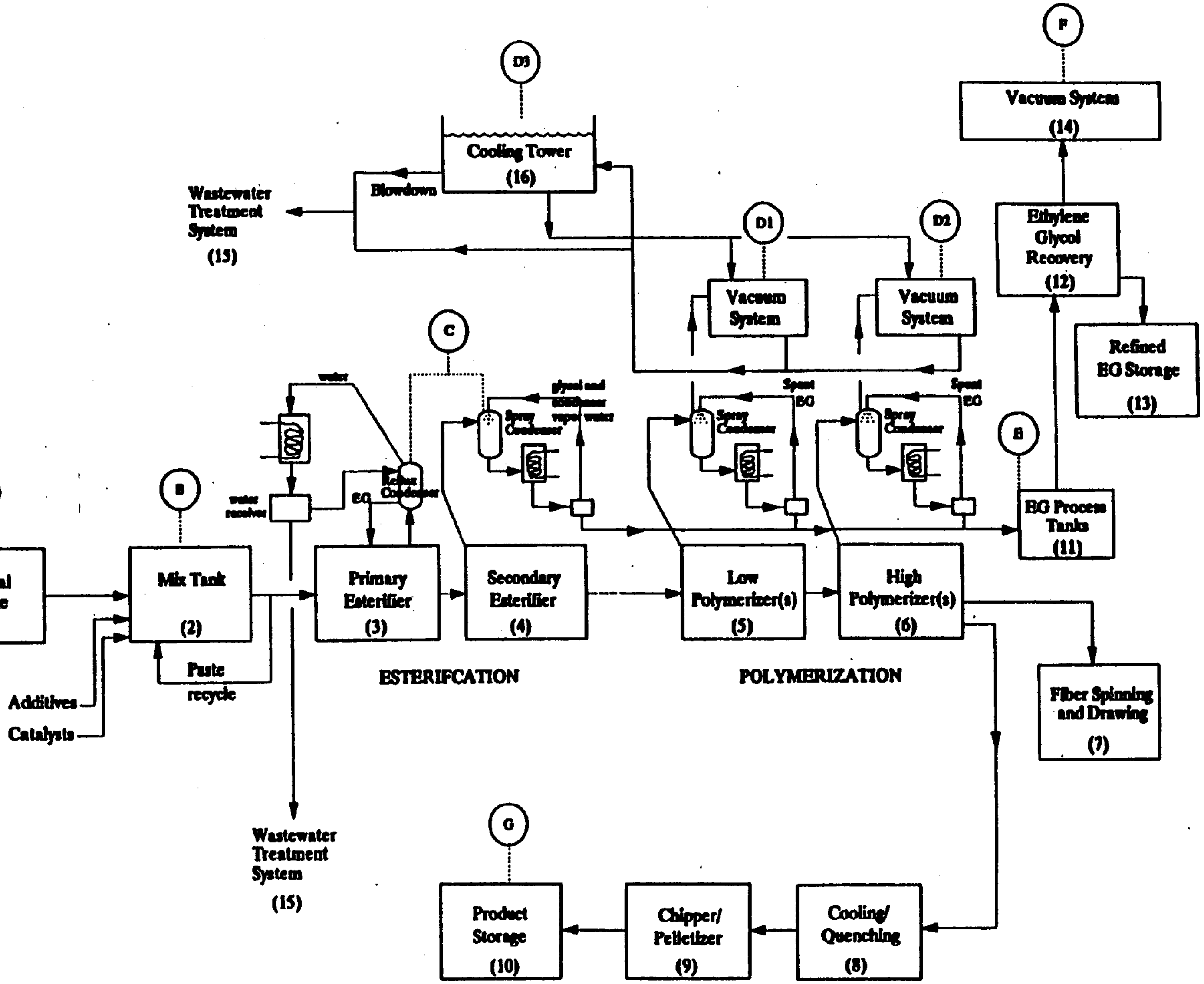


Figure 6.6.2-2. Simplified flow diagram of PET/TPA continuous process.

The secondary esterifier (4) is operated at atmospheric pressure and at a temperature of 250 to 270°C (482 to 518°F). The vapors from the secondary esterifier, primarily water vapor, are vented to a spray condenser, and this condensate is sent to a central ethylene glycol recovery unit (12). The condensate water is cooled by cooling water in a shell-and-tube heat exchanger and then recycled.

At one plant, the secondary esterifiers for the staple PET lines have a manhole (or rotary valve on some lines) through which chips and reworked yarn pellets are recycled. These manholes are not present on the secondary esterifiers for the industrial PET lines. Water vapor and monomer are emitted from the manholes, and the monomer sublimates on piping near the manhole.

Monomer (BHET) from the secondary esterifier is then pumped to the polymerization reactors. The number of reactors and their operating conditions depends on the type of PET being produced. Typically, there will be at least two polymerization reaction vessels in series, an initial (low) polymerizer and a final (high) polymerizer. The former is sometimes referred to as a prepolymerizer or a prepolycondensation reactor. The latter is sometimes called an end finisher. In producing high-viscosity PET, a second end finisher is sometimes used.

In the initial (low) polymerizer (5), esterification is completed and polymerization occurs (i. e., the joining of short molecular chains). Polymerization is "encouraged" by the removal of ethylene glycol. This reactor is operated under pressures of 20 to 40 mm Hg and at 270 to 290°C (518 to 554°F) for staple (low-viscosity) PET, and 10 to 20 mm Hg and 280 to 300°C (536 to 572°F) for industrial filament PET. The latter conditions produce a longer molecule, with the greater intrinsic viscosity and tenacity required in industrial fibers. Glycol released in the polymerization process and any excess or unreacted glycol are drawn into a contact spray condenser (scrubber) countercurrent to a spent ethylene glycol spray. (At one facility, both the low and high polymerizer spray condensers have four spray nozzles, with rods to clear blockage by solidified polymer. Care is taken to ensure that the spray pattern and flow are maintained.) Recovered glycol is pumped to a central glycol recovery unit, a distillation column. Vacuum on the reactors is maintained by a series of steam jets with barometric intercondensers. At one plant, a two-stage steam ejector system with a barometric intercondenser is used to evacuate the low polymerizer. The condensate from the intercondensers and the last steam jets is discharged to an open recirculating water system, which includes an open trough (referred to as a "hot well") and cooling tower. The recirculation system supplies cooling water to the intercondensers.

In the production of high-viscosity PET, the polymer from the low polymerizer is pumped to a high polymerizer vessel (6). In the high polymerizer, the short polymer chains formed in the low polymerizer are lengthened. Rotating wheels within these vessels are used to create large surface exposure for the polymer to facilitate removal of ethylene glycol produced by the interchange reaction between the glycol ester ends. The high polymerizer is operated at a low absolute pressure (high vacuum), 0.1 to 1.0 mm Hg, and at about 280 to 300°C (536 to 572°F). Vapors evolved in the high polymerizer, including glycol, are drawn through a glycol spray condenser. If very "hard" vacuums are drawn (e. g., 0.25 mm Hg), such spray condensers are very difficult, if not impossible, to use. At least one facility does not use any spray condensers off the polymerizers (low and high). Recovered glycol is collected in a receiver and is pumped to a central ethylene glycol recovery unit. At one plant, chilled water between -3.9 and 1.7°C (25 and 35°F) is used on the heat exchanger associated with the high polymerizer spray condenser.

At least one facility uses two high polymerizers (end finishers) to produce high-viscosity PET. At this plant, the first end finisher is usually operated with an intermediate vacuum level of about 2 mm Hg. The polymer leaving this reactor then enters a second end finisher, which may have a vacuum level as low as 0.25 mm Hg.

Vapors from the spray condenser off the high polymerizers are also drawn through a steam jet ejector system. One facility uses a five-jet system. After the first three ejectors, there is a barometric intercondenser. Another barometric intercondenser is located between the fourth and fifth ejectors. The ejectors discharge to the cooling water hot well. The stream exiting the vacuum system is sent either to a cooling tower (16) where the water is recirculated through the vacuum system, or to a waste water treatment plant (once-through system) (15).

Vacuum pumps were installed at one plant as an alternative to the last two ejectors. These pumps were installed as part of an energy conservation program and are used at the operator's discretion. The vacuum pumps are operated about 50 percent of the time. The vacuum system was designed for a maximum vapor load of about 10 kilograms per hour (kg/hr). If vacuum is lost, or is insufficient in the low or high polymerizers, off-specification product results. Each process line has a dual vacuum system. One five-stage ejector/vacuum pump system is maintained as a standby for each industrial filament (high-viscosity) process line. The staple (low-viscosity) lines have a standby ejector system, but with only one vacuum pump per process line. Steam ejectors reportedly recover faster from a slug of liquid carryover than do vacuum pumps, but the spare system is used in the production of either high- or low-viscosity PET.

At many facilities, molten PET from the high polymerizer is pumped at high pressure directly through an extruder spinerette, forming polyester filaments (7). The filaments are air cooled and then either cut into staple or wound onto spools. Molten PET can also be pumped out to form blocks as it cools and solidifies (8), which are then cut into chips or are pelletized (9). The chips or pellets are stored (10) before being shipped to the customer, where they are remelted for end-product fabrication.

Ethylene glycol recovery (12) generally involves a system similar to that of the DMT process. The major difference is the lack of a methanol recovery step. At least one TPA facility has a very different process for ethylene glycol recovery. At this plant, ethylene glycol emissions from the low and high polymerizers are allowed to pass directly to the vacuum system and into the cooling tower. The ethylene glycol is then recovered from the water in the cooling tower. This arrangement allows for a higher ethylene glycol concentration in the cooling tower.

6.6.2.3 Emissions And Controls[3,5,11,13,16-21]

Table 6.6.2-1 shows the VOC and particulate emissions for the PET/DMT continuous process, with similar levels expected for batch processes. The extensive use of spray condensers and other ethylene glycol and methanol recovery systems is economically essential to PET production, and these are not generally considered "controls".

Total VOC emissions will depend greatly on the type of system used to recover the ethylene glycol from the prepolymerizers and polymerization reactors, which give rise to emission streams E1, E2, E3, F, G, H, and J. The emission streams from the prepolymerizers and polymerization reactors are primarily ethylene glycol, with small amounts of methanol vapors and volatile impurities in the raw materials. Of these emission streams, the greatest emission potential is from the cooling tower (Stream E3). The amount of emissions from the cooling tower depends on a number of factors, including ethylene glycol concentration and windage rate. The ethylene glycol concentration depends on a number of factors, including use of spray condensers off the polymerization vessels, circulation rate of the cooling water in the cooling tower, blowdown rate (the rate are which water is drawn out of the cooling tower), and sources of water to cooling tower (e. g., dedicated cooling tower versus plant-side cooling tower).

Table 6.6.2-1 (Metric Units). EMISSION FACTORS FOR PET/DMT PROCESS[a]

Stream Identification	Emission Stream	Nonmethane VOC[b]	Particulate	EMISSION FACTOR RATING	References
A	Raw material storage	0.1	0.165[c]	C	17
B	Mix tanks	negligible[d]	ND	C	13
C	Methanol recovery system	0.3[e]	ND	C	3, 17
D	Recovered methanol storage	0.09[f]	ND	C	3, 17
E	Polymerization reaction				
E1	Prepolymerizer vacuum system	0.009	ND	C	17
E2	Polymerization reactor vacuum system	0.005	ND	C	17
E3	Cooling tower[g]	0.2 3.4	ND	C	18 - 19
F	Ethylene glycol process tanks	0.0009	ND	C	17
G	Ethylene glycol recovery condenser	0.01	ND	C	17
H	Ethylene glycol recovery vacuum system	0.0005	ND	C	17
I	Product storage	ND	0.0003[h]	C	17
J	Sludge storage and loading	0.02	ND	C	17
Total Plant		0.73[j] 3.9[k]	0.17		

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[a] Stream identification refers to Figure 6.6.2-1. Units are grams per kilogram of product. ND = no data.

[b] Rates reflect extensive use of condensers and other recovery equipment as part of normal industry economical practice.

[c] From storage of DMT.

[d] Assumed same as for TPA process.

[e] Reference 3. For batch PET production process, estimated to be 0.15 grams VOC per kilogram of product.

[f] Reflects control by refrigerated condensers.

[g] Based on ethylene glycol concentrations at two PET/TPA plants. The lower estimate reflects emissions where spray condensers are used off the prepolymerizers and the polymerization reactors. The higher estimate reflects emissions where spray condensers are not used off the prepolymerizers and the polymerization reactors. A site-specific calculation is highly recommended for all cooling towers, because of the many variables. The following equation may be used to estimate windage emissions from cooling towers:

$$E = [EG_{wt\%} \times CT_{cr} \times 60 \times WR] \times [(4.2 \times EG_{wt\%}) + (3.78 \times H_2O_{wt\%})]$$

Table 6.6.2-1 (cont.).

where:

E = Mass of VOC emitted (kilograms per hour)
$EG_{wt\%}$ = Concentration of ethylene glycol, weight percent (fraction)
60 = Minutes per hour
CT_{cr} = Cooling tower circulation rate, gallons per minute
WR = Windage rate, fraction
4.2 = Density of ethylene glycol (kilograms per gallon)
3.78 = Density of water (kilograms per gallon)
$H_2O_{wt\%}$ = Concentration of water, weight percent (fraction)

Example: The VOC emissions from a cooling tower with an ethylene glycol concentration of 8.95% by weight, a water concentration of 91.05% by weight, a cooling tower circulation rate of 1270 gallons per minute, and a windage rate of 0.03% are estimated to be:

$$E = [0.0895 \times 1270 \times 60 \times 0.0003] \times [(4.2 \times 0.0895) + (3.78 \times 0.9105)]$$

$$= 7.8 \text{ kilograms per hour}$$

[h] Emission rate is for "controlled" emissions. Without controls, the estimated emission rate is 0.4 grams per kilogram of product.
[j] With spray condensers off all prepolymerizers and the polymerization reactors.
[k] With no spray condensers off all prepolymerizers and the polymerization reactors.

Most plants recover the ethylene glycol by using a spent ethylene glycol spray scrubber condenser directly off these process vessels and before the stream passes through the vacuum system. The condensed ethylene glycol may then be recovered through distillation. This type of recovery system results in relatively low concentrations of ethylene glycol in the cooling water at the tower, which in turn lowers emission rates for the cooling tower and the process as a whole. At one PET/TPA plant, a typical average concentration of about 0.32 weight percent ethylene glycol was reported, from which an emission rate of 0.2 grams VOC per kilogram (gVOC/kg) of product was calculated.

Alternatively, a plant may send the emission stream directly through the vacuum system (typically steam ejectors) without using spent ethylene glycol spray condensers. The steam ejectors used to produce a vacuum will produce contaminated water, which is then cooled for reuse. In this system, ethylene glycol is recovered from the water in the cooling tower by drawing off water from the tower (blowdown) and sending the blowdown to distillation columns. This method of recovering ethylene glycol can result in much higher concentrations of ethylene glycol in the cooling tower than when the ethylene glycol is recovered with spray condensers directly off the process vessels. (The actual concentration of ethylene glycol in the cooling water depends, in part, on the blowdown rate.) Higher concentrations in the cooling tower result in greater ethylene glycol emissions from the cooling tower and, in turn, from the process as a whole. At one PET/TPA plant recovering the ethylene glycol from the cooling tower, emissions from the cooling tower were approximately 3.4 gVOC/kg of product.

Next to the cooling tower, the next largest potential emission source in the PET/DMT process is the methanol recovery system. Methanol recovery system emissions (Stream C) from a plant using a continuous process are estimated to be approximately 0.3 gVOC/kg of product and about 0.09 gVOC/kg of product from the recovered methanol storage tanks. The emissions from the methanol recovery system (Stream C) for a batch process were reported to be 0.15 gVOC/kg of product, and typically are methanol and nitrogen.

The other emission streams related to the prepolymerizer and polymerization reactors are collectively relatively small, being about 0.04 gVOC/kg of product. VOC emissions from raw material storage (mostly ethylene glycol) are estimated to be about 0.1 gVOC/kg of product. Fixed roof storage tanks (ethylene glycol) and bins (DMT) are used throughout the industry. Emissions are vapors of ethylene glycol and DMT result from vapor displacement and tank breathing. Emissions from the mix tank are believed to be negligible.

Particulate emissions occur from storage of both raw material (DMT) and end product. Those from product storage may be controlled before release to the atmosphere. Uncontrolled particulate emissions from raw material storage are estimated to be approximately 0.17 g/kg of product. Particulate emissions from product storage are estimated to be approximately 0.0003 g/kg of product after control and approximately 0.4 g/kg of product before control.

Total VOC emissions from a PET/DMT continuous process are approximately 0.74 gVOC/kg of product if spray condensers are used off all of the prepolymerizers and polymerization reaction vessels. For a batch process, this total decreases to approximately 0.59 gVOC/kg of product. If spray condensers are not used, the ethylene glycol concentration in the cooling tower is expected to be higher, and total VOC emissions will be greater. Calculation of cooling tower emissions for site-specific plants is recommended. Total particulate emissions are approximately 0.17 g/kg of product, if product storage emissions are controlled.

Table 6.6.2-2 summarizes VOC and particulate emissions for the PET/TPA continuous process, and similar emission levels are expected for PET/TPA batch processes. VOC emissions are generally "uncontrolled", in that the extensive use of spray condensers and other ethylene glycol recovery systems are essential to the economy of PET production.

Emissions from raw material storage include losses from the raw materials storage and transfer (e. g., ethylene glycol). Fixed roof storage tanks and bins with conservation vents are used throughout the process. The emissions, vapors of ethylene glycol, TPA, and TPA dust, are from working and breathing losses. The VOC emission estimate for raw materials storage is assumed to be the same as that for the PET/DMT process. No emission estimate was available for the storage and transfer of TPA.

VOC emissions from the mix tank are believed to be negligible. They are emitted at ambient temperatures through a vent line from the mixer.

VOC emissions from the esterifiers occur from the condensers/distillation columns on the esterifiers. Emissions, which consist primarily of steam and ethylene glycol vapors, with small amounts of feed impurities and volatile side reaction products, are estimated to be 0.04 gVOC/kg of product. Exit temperature is reported to be approximately 104°C (220°F). At least one plant controls the primary esterifier condenser vent with a second condenser. At this plant, emissions were 0.0008 gVOC/kg of product with the second condenser operating, and 0.037 gVOC/kg of product without the second condenser operating. The temperature for the emission stream from the second

Table 6.6.2-2 (Metric Units). EMISSION FACTORS FOR PET/TPA PROCESS[a]

Stream Identification	Emission Stream	Nonmethane VOC[b]	Particulate	EMISSION FACTOR RATING	References
A	Raw material storage	0.1[c]	ND	C	17
B	Mix tanks	negligible	ND	C	13
C	Esterification	0.04[d]	ND	A	20 - 21
D	Polymerization reaction				
D1	Prepolymerizer vacuum system	0.009[c]	ND	C	17
D2	Polymerization reactor vacuum system	0.005[c]	ND	C	17
D3	Cooling tower[e]	0.2 3.4	ND	C	18 - 19
E	Ethylene glycol process tanks	0.0009[c]	ND	C	17
F	Ethylene glycol recovery vacuum system	0.0005[c]	ND	C	17
G	Product storage	ND	0.0003[c,f]	C	17
Total Plant		0.36[g] 3.6[h]			

[a] Stream identification refers to Figure 6.6.2-2. Units are grams per kilogram of product. ND = no data.

[b] Rates reflect extensive use of condensers and other recovery equipment as part of normal industry economical practice.

[c] Assumed same as for DMT process.

[d] At least one plant controls the primary esterifier condenser vent with a second condenser. Emissions were 0.0008 grams VOC per kilogram of product with the second condenser operating, and 0.037 grams VOC per kilogram of product without the second condenser operating.

[e] Based on ethylene glycol concentrations at two PET/TPA plants. The lower estimate reflects emissions where spray condensers are used off the prepolymerizers and the polymerization reactors. The higher estimate reflects emissions where spray condensers are not used off the prepolymerizers and the polymerization reactors. It is highly recommended that a site-specific calculation be done for all cooling towers as many variables affect actual emissions. The equation found in footnote g for Table 6.6.2-1 may be used to estimate windage emissions from cooling towers.

[f] Reflects control of product storage emissions. Without controls, the estimated emission rate is 0.4 grams per kilogram of product.

[g] With spray condensers off all prepolymerizers and the polymerization reactors.

[h] With no use of spray condensers off all prepolymerizers and the polymerization reactors.

condenser was reported to be 27 to 38°C (80 to 100°F). The emissions from the second condenser were composed of di-iso-propyl amine (DIPA) and acetaldehyde, with small amounts of ethylene.

Emissions from the prepolymerizers and polymerization reaction vessels in both PET/TPA and PET/DMT processes should be very similar. The emissions were discussed earlier under the DMT process.

The estimates of VOC emissions from the ethylene glycol process tanks and the ethylene glycol recovery system, and of particulate emissions from product storage, are assumed to be the same as for the DMT process.

Total VOC emissions from the PET/TPA process are approximately 0.36 gVOC/kg of product if spray condensers are used with all of the prepolymerizers and polymerization reaction vessels. If spray condensers are not used with all of these process vessels, the concentration in the cooling tower can be expected to be higher, and total VOC emissions will be greater. For example, at one plant, emissions from the cooling tower were calculated to be approximately 3.4 gVOC/kg of product, resulting in a plantwide estimate of 3.6 gVOC/kg of product. Calculation of cooling tower emissions for site-specific plants is recommended. Excluding TPA particulate emissions (no estimate available), total particulate emissions are expected to be small.

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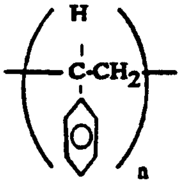
6.6.3 Polystyrene[1-2]

6.6.3.1 General

Styrene readily polymerizes to polystyrene by a relatively conventional free radical chain mechanism. Either heat or initiators will begin the polymerization. Initiators thermally decompose, thereby forming active free radicals that are effective in starting the polymerization process. Typically initiators used in the suspension process include benzoyl peroxide and di-tert-butyl per-benzoate. Potassium persulfate is a typical initiator used in emulsion polymerizations. In the presence of inert materials, styrene monomer will react with itself to form a homopolymer. Styrene monomer will react with a variety of other monomers to form a number of copolymers.

Polystyrene is an odorless, tasteless, rigid thermoplastic. Pure polystyrene has the following structure.



The homopolymers of styrene are also referred to as general purpose, or crystal, polystyrene. Because of the brittleness of crystal polystyrene, styrene is frequently polymerized in the presence of dissolved polybutadiene rubber to improve the strength of the polymer. Such modified polystyrene is called high-impact, or rubber-modified, polystyrene. The styrene content of high-impact polystyrene varies from about 88 to 97 percent. Where a blowing (or expanding) agent is added to the polystyrene, the product is referred to as an expandable polystyrene. The blowing agent may be added during the polymerization process (as in the production of expandable beads), or afterwards as part of the fabrication process (as in foamed polystyrene applications).

Polystyrene is the fourth largest thermoplastic by production volume. It is used in applications in the following major markets (listed in order of consumption): packaging, consumer/institutional goods, electrical/electronic goods, building/construction, furniture, industrial/machinery, and transportation.

Packaging applications using crystal polystyrene biaxial film include meat and vegetable trays, blister packs, and other packaging where transparency is required. Extruded polystyrene foam sheets are formed into egg carton containers, meat and poultry trays, and fast food containers requiring hot or cold insulation. Solid polystyrene sheets are formed into drinking cups and lids, and disposable packaging of edibles. Injection molded grades of polystyrene are used extensively in the manufacture of cosmetic and personal care containers, jewelry and photo equipment boxes, and photo film packages. Other formed polystyrene items include refrigerator door liners, audio and video cassettes, toys, flower pots, picture frames, kitchen utensils, television and radio cabinets, home smoke detectors, computer housings, and profile moldings in the construction/home-building industry.

6.6.3.2 General Purpose And High Impact Polystyrene[1-2]

Homopolymers and copolymers can be produced by bulk (or mass), solution (a modified bulk), suspension, or emulsion polymerization techniques. In solution (or modified bulk) polymerization, the reaction takes place as the monomer is dissolved in a small amount of solvent, such as ethylbenzene. Suspension polymerization takes place with the monomer suspended in a water phase. The bulk and solution polymerization processes are homogenous (taking place in one phase), whereas the suspension and emulsion polymerization processes are heterogeneous (taking place in more than one phase). The bulk (mass) process is the most widely used process for polystyrene today. The suspension process is also common, especially in the production of expandable beads. Use of the emulsion process for producing styrene homopolymer has decreased significantly since the mid-1940s.

6.6.3.2.1 Process Descriptions[1-3] -

Batch Process -

Various grades of polystyrene can be produced by a variety of batch processes. Batch processes generally have a high conversion efficiency, leaving only small amounts of unreacted styrene to be emitted should the reactor be purged or opened between batches. A typical plant will have multiple process trains, each usually capable of producing a variety of grades of polystyrene.

Figure 6.6.3-1 is a schematic representation of the polystyrene batch bulk polymerization process, and the following numbered steps refer to that figure. Pure styrene monomer (and comonomer, if a copolymer product is desired) is pumped from storage (1) to the feed dissolver (2). For the production of impact-grade polystyrene, chopped polybutadiene rubber is added to the feed dissolver, where it is dissolved in the hot styrene. The mixture is agitated for 4 to 8 hours to complete rubber dissolution. From the feed dissolver, the mixture usually is fed to an agitated tank (3), often a prepolymerization reactor, for mixing the reactants. Small amounts of mineral oil (as a lubricant and plasticizer), the dimer of alpha-methylstyrene (as a polymerization regulator), and an antioxidant are added. The blended or partially polymerized feed is then pumped into a batch reactor (4). During the reactor filling process, some styrene vaporizes and is vented through an overflow vent drum (5). When the reactor is charged, the vent and reactor are closed. The mixture in the reactor is heated to the reaction temperature to initiate (or continue) the polymerization. The reaction may also be begun by introducing a free radical initiator into the feed dissolver (2) along with other reactants. After polymerization is complete, the polymer melt (molten product) containing some unreacted styrene monomer, ethylbenzene (an impurity from the styrene feed), and low molecular weight polymers (dimers, trimers, and other oligomers), is pumped to a vacuum devolatilizer (6). Here, the residual styrene monomer, ethylbenzene, and the low molecular weight polymers are removed, condensed (7), passed through a devolatilizer condensate tank (9), and then sent to the byproduct recovery unit. Overhead vapors from the condenser are usually exhausted through a vacuum system (8). Molten polystyrene from the bottom of the devolatilizer, which may be heated to 250 to 280°C (482 to 536°F), is extruded (10) through a stranding die plate (a plate with numerous holes to form strands), and then immersed in a cold water bath. The cooled strands are pelletized (10) and sent to product storage (11).

Continuous Process -

As with the batch process, various continuous steps are used to make a variety of grades of polystyrene or copolymers of styrene. In continuous processes, the chemical reaction does not approach completion as efficiently as in batch processes. As a result, a lower percentage of styrene is converted to polystyrene, and larger amounts of unreacted styrene may be emitted from continuous

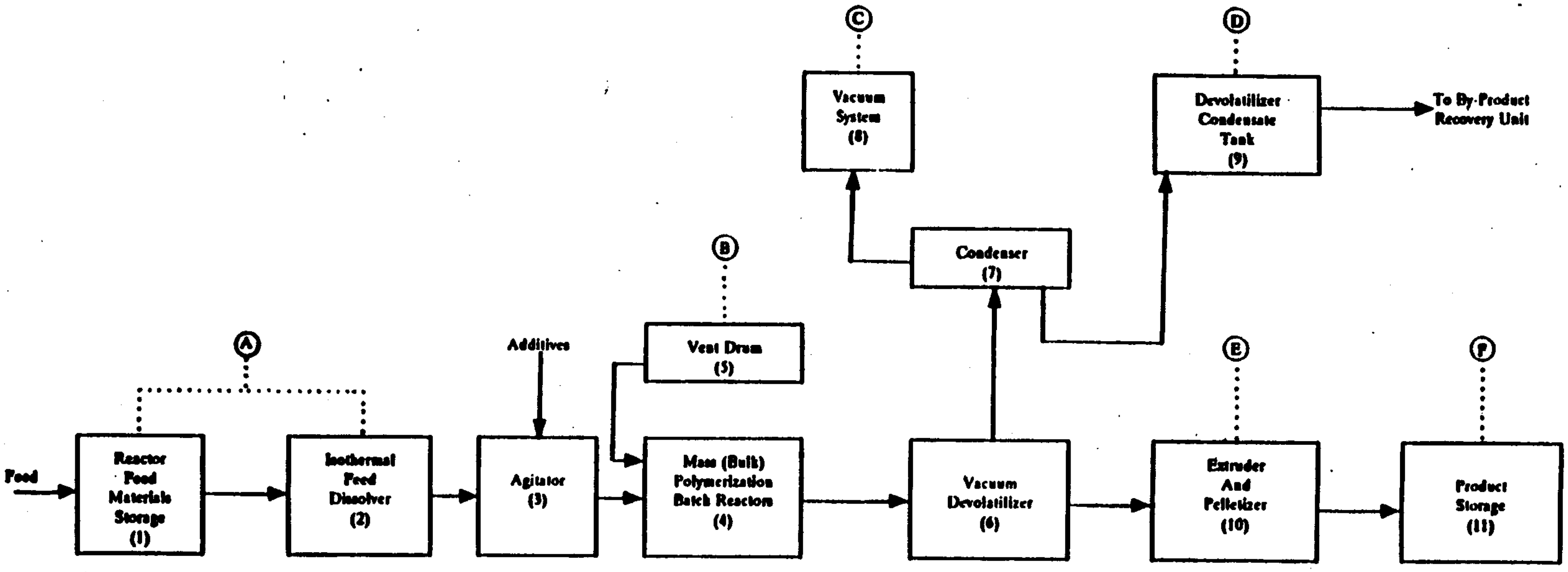


Figure 6.6.3-1. Simplified flow diagram of a batch polystyrene process.

process sources. A typical plant may contain more than one process line, producing either the same or different grades of polymer or copolymer.

A typical bulk (mass) continuous process is represented in Figure 6.6.3-2. Styrene, polybutadiene (if an impact-grade product is desired), mineral oil (lubricant and plasticizer), and small amounts of recycled polystyrene, antioxidants, and other additives are charged from storage (1) into the feed dissolver mixer (2) in proportions that vary according to the grade of resin to be produced. Blended feed is pumped continuously to the reactor system (3) where it is thermally polymerized to polystyrene. A process line usually employs more than one reactor in series. Some polymerization occurs in the initial reactor, often referred to as the prepolymerizer. Polymerization to successively higher levels occurs in subsequent reactors in the series, either stirred autoclaves or tower reactors. The polymer melt, which contains unreacted styrene monomer, ethylbenzene (an impurity from the styrene feed), and low molecular weight polymers, is pumped to a vacuum devolatilizer (4). Here, most of the monomer, ethylbenzene, and low molecular weight polymers are removed, condensed (5), and sent to the styrene recovery unit (8 and 9). Noncondensables (overhead vapors) from the condenser typically are exhausted through a vacuum pump (10). Molten polystyrene from the bottom of the devolatilizer is pumped by an extruder (6) through a stranding die plate into a cold water bath. The solidified strands are then pelletized (6) and sent to storage (7).

In the styrene recovery unit, the crude styrene monomer recovered from the condenser (5) is purified in a distillation column (8). The styrene overhead from the tower is condensed (9) and returned to the feed dissolver mixer. Noncondensables are vented through a vacuum system (11). Column bottoms containing low molecular weight polymers are used sometimes as a fuel supplement.

6.6.3.2.2 Emissions And Controls[3-9] -

As seen in Figure 6.6.3-1, six emission streams have been identified for batch processes: (1) the monomer storage and feed dissolver vent (Stream A); (2) the reactor vent drum vent (Stream B); (3) the devolatilizer condenser vent (Stream C); (4) the devolatilizer condensate tank (Stream D); (5) the extruder quench vent (Stream E); and (6) product storage emissions (Stream F). Table 6.6.3-1 summarizes the emission factors for these streams.

Table 6.6.3-1 (Metric Units). EMISSION FACTORS FOR BATCH PROCESS POLYSTYRENE[a]

EMISSION FACTOR RATING: C

Stream Identification	Emission Stream	Nonmethane VOC	References
A	Monomer storage and feed dissolver tanks	0.09[b]	3
B	Reactor vent drum vent	0.12 - 1.35[c]	3 - 4
C	Devolatilizer condenser vent	0.25 - 0.75[c]	3 - 4
D	Devolatilizer condensate tank	0.002[b]	3
E	Extruder quench vent	0.15 - 0.3[c]	3 - 4
F	Product storage	negligible	3
Total Plant		0.6 - 2.5	

[a] Stream identification refers to Figure 6.6.3-1. Units are grams VOC per kilogram of product.

[b] Based on fixed roof design.

[c] Reference 4. The higher factors are more likely during the manufacture of lower molecular weight products. Factor for any given process train will change with product grade.

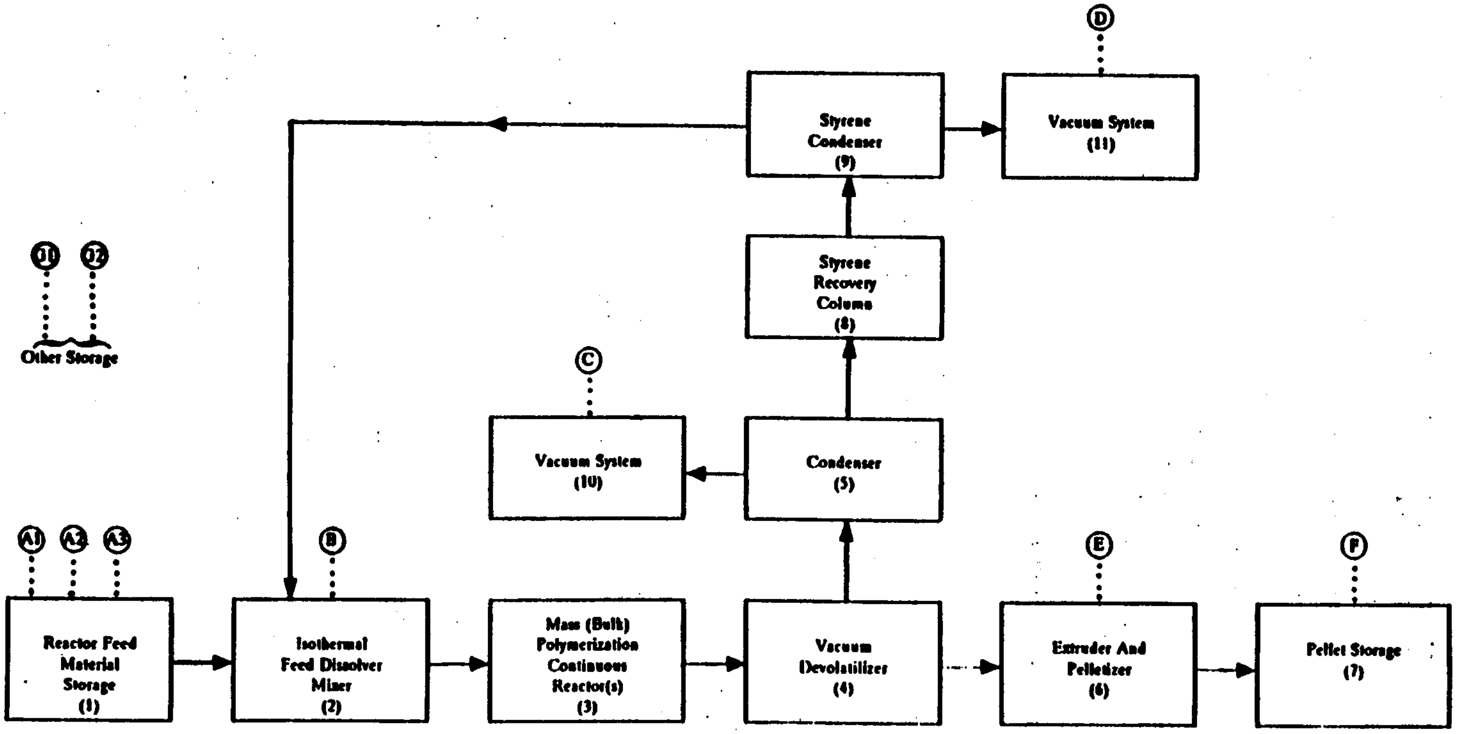


Figure 6.6.3-2. Simplified flow diagram of a continuous polystyrene process.

The major vent is the devolatilizer condenser vent (Stream C). This continuous offgas vent emits 0.25 to 0.75 grams of VOC per kilogram (gVOC/kg) of product depending on the molecular weight of the polystyrene product being produced. The higher emission factor is more likely during the manufacture of lower molecular weight products. The emissions are unreacted styrene, which is flashed from the product polymer in the vacuum devolatilizer, and it is extremely diluted in air through leakage. The stream is exhausted through a vacuum system and then through an oil demister to the atmosphere. The oil demister is used primarily to separate out organic mist.

The second largest vent stream is likely to be the reactor vent drum vent, with an emission rate ranging from 0.12 to 1.35 gVOC/kg of product, this range also being associated with the molecular weight of the polystyrene product being produced. The higher emission factor is more likely during the manufacture of lower molecular weight products. These emissions, which are the only intermittent emissions from the process, occur only during reactor filling periods and they are vented to the atmosphere. The rate of 0.12 gVOC/kg of product is based on a facility having two batch reactors that are operated alternately on 24-hour cycles.

Stream E, the extruder quench vent, is the third largest emission stream, with an emission rate of 0.15 to 0.3 gVOC/kg of product. This stream, composed of styrene in water vapor, is formed when the hot, extruded polystyrene strands from the stranding die plate contact the cold water in the quenching bath. The resulting stream of steam with styrene is usually vented through a forced draft hood located over the water bath and then passed through a mist separator or electrostatic precipitator before venting to the atmosphere.

The other emission streams are relatively small continuous emissions. Streams A and D represent emissions from various types of tanks and dissolver tanks. Emissions from these streams are estimated, based on fixed roof tanks. Emissions from product storage, Stream F, have been reported to be negligible.

There are no VOC control devices typically used at polystyrene plants employing batch processes. The condenser (7) off the vacuum devolatilizer (6) typically is used for process reasons (recovery of unreacted styrene and other reactants). This condenser reduces VOC emissions, and its operating characteristics will affect the quantity of emissions associated with batch processes (Stream C in particular).

Total process uncontrolled emissions are estimated to range from 0.6 to 2.5 gVOC/kg of product. The higher emission rates are associated with the manufacture of lower molecular weight polystyrene. The emission factor for any given process line will change with changes in the grade of the polystyrene being produced.

Emission factors for the continuous polystyrene process are presented in Table 6.6.3-2, and the following numbered steps refer to Figure 6.6.3-2. Emissions from the continuous process are similar to those for the batch process, although the continuous process lacks a reactor vent drum. The emission streams, all of which are continuous, are: (1) various types of storage (Streams A and G); (2) the feed dissolver vent (Stream B); (3) the devolatilizer condenser vent (Stream C); (4) the styrene recovery unit condenser vent (Stream D); (5) the extruder quench vent (Stream E); and (6) product storage emissions (Stream F).

Industry's experience with continuous polystyrene plants indicates a wide range of emission rates from plant to plant depending in part on the type of vacuum system used. Two types are now used in the industry, one relying on steam ejectors and the other on vacuum pumps. Where steam ejectors are used, the overheads from the devolatilizer condenser vent and the styrene recovery unit

Table 6.6.3-2 (Metric Units). EMISSION FACTORS FOR CONTINUOUS PROCESS POLYSTYRENE[a]

EMISSION FACTOR RATING: C

Stream Identification	Emission Stream	Nonmethane VOC		References
		Uncontrolled	Controlled	
A1	Styrene monomer storage	0.08		3, 5
A2	Additives			
	General purpose	0.002		5
	High impact	0.001		5 - 6
A3	Ethylbenzene storage	0.001		5
B	Dissolvers	0.008		3, 5
C	Devolatilizer condenser vent[b]	0.05[c] 2.96[e]	0.04[d]	4 - 5, 7 3
D	Styrene recovery unit condenser vent	0.05[c] 0.13[e]		4, 7 3
C+D		0.024 - 0.3[f]	0.004[g]	5 - 6, 8
E	Extruder quench vent	0.01[c] 0.15[e,g,h]		4 3
F	Pellet storage	negligible		3
	Other storage			
G1	General purpose	0.008		3, 5
G2	High impact	0.007		3, 5
Total Plant		0.21[c] 3.34[e]		

[a] Stream identification refers to Figure 6.6.3-2. Units are grams VOC per kilogram of product.

[b] Reference 9. Larger plants may route this stream to the styrene recovery section. Smaller plants may find this too expensive.

[c] For plants using vacuum pumps.

[d] Condenser is used downstream of primary process condensers; includes emissions from dissolvers. Plant uses vacuum pumps.

[e] For plants using steam jets.

[f] Lower value based on facility using refrigerated condensers as well as conventional cooling water exchangers; vacuum pumps in use. Higher value for facility using vacuum pumps.

[g] Plant uses an organic scrubber to reduce emissions. Nonsoluble organics are burned as fuel.

[h] This factor may vary significantly depending on overall process. Reference 6 indicates an emission factor of 0.0012 gVOC/kg product at a plant whose process design is "intended to minimize emissions".

condenser vent are composed mainly of steam. Some companies have recently replaced these steam ejectors with mechanical vacuum pumps. Emissions from vacuum pumps usually are lower than from steam ejectors.

It is estimated that the typical total VOC emission rate for plants using steam ejectors is about 3.34 gVOC/kg of product, with the largest emission stream being the devolatilizer condenser vent (2.96 gVOC/kg of product). Emissions from the styrene recovery unit condenser vent and the extruder quench vent are estimated to be 0.13 and 0.15 gVOC/kg of product, respectively, although the latter may vary significantly depending on overall plant design. One plant designed to minimize emissions reported an emission factor of 0.0012 gVOC/kg product for the extruder quench vent.

For plants using vacuum pumps, it is estimated that the total VOC emission rate is about 0.21 gVOC/kg of product. In these plants, emissions from the devolatilizer condenser vent and the styrene recovery unit condenser vent are each estimated to be 0.05 gVOC/kg of product. Styrene monomer and other storage emissions can be the largest emission sources at such plants, approximately 0.1 gVOC/kg of product. Some plants combine emissions from the dissolvers with those from the devolatilizer condenser vent. Other plants may combine the dissolver, devolatilizer condenser vent, and styrene recovery unit condenser vent emissions. One plant uses an organic scrubber to reduce these emissions to 0.004 gVOC/kg of product.

Condensers are a critical, integral part of all continuous polystyrene processes. The amount of unreacted styrene recovered for reuse in the process can vary greatly, as condenser operating parameters vary from one plant to another. Lowering the coolant operating temperature will lower VOC emissions, all other things being equal.

Other than the VOC reduction achieved by the process condensers, most plants do not use VOC control devices. A plant having controls, however, can significantly reduce the level of VOC emissions. One company, for example, uses an organic scrubber to reduce VOC air emissions. Another uses a condenser downstream from the primary process condensers to control VOCs.

6.6.3.3 Expandable Polystyrene[1-2,10-11]

The suspension process is a batch polymerization process that may be used to produce crystal, impact, or expandable polystyrene beads. An expandable polystyrene (EPS) bead typically consists of high molecular weight crystal grade polystyrene (to produce the proper structure when the beads are expanded) with 5 to 8 percent being a low-boiling-point aliphatic hydrocarbon blowing agent dissolved in the polymer bead. The blowing agent typically is pentane or isopentane although others, such as esters, alcohols, and aldehydes, can be used. When used to produce an EPS bead, the suspension process can be adapted in one of two ways for the impregnation of the bead with the blowing agent. One method is to add the blowing agent to a reactor after polymerization, and the other is to add the blowing agent to the monomer before polymerization. The former method, called the "post-impregnation" suspension process, is more common than the latter, referred to as the "in-situ" suspension process. Both processes are described below.

EPS beads generally are processed in one of three ways, (1) gravity- or air-fed into closed molds, then heated to expand up to 50 times their original volume; (2) pre-expanded by heating and then molding in a separate processing operation; and (3) extruded into sheets. EPS beads are used to produce a number of foamed polystyrene materials. Extruded foam sheets are formed into egg cartons, meat and poultry trays, and fast food containers. In the building/construction industry, EPS board is used extensively as a low-temperature insulator.

6.6.3.3.1 Process Description[1,10-12] -

Post-impregnation Suspension Process -

This process is essentially a two-part process using two process lines in series. In the first process line, raw styrene monomer is polymerized and a finished polystyrene bead is produced. The second process line takes the finished bead from the first line, impregnates the bead with a blowing agent, and produces a finished EPS bead. Figure 6.6.3-3 is a schematic representation of this process.

In the first line, styrene monomer, water, initiator, and suspending agents form the basic charge to the suspension reactor (1). The styrene-to-water ratio varies with the type of polystyrene required. A typical ratio is about one-quarter to one-half monomer to water volume. Initiators are commonly used because the reaction temperature is usually too low for adequate thermal initiation of polymerization. Suspending agents are usually protective colloids and insoluble inorganic salts. Protective colloids are added to increase the viscosity of the continuous water phase, and insoluble inorganic salts such as magnesium carbonate ($MgCO_3$) are added to prevent coalescence of the drops upon collision.

In the reactor, the styrene is suspended, through use of mechanical agitation and suspending agents, in the form of droplets throughout the water phase. Droplet size may range from about 0.1 to 1.0 mm. The reactor is heated to start the polymerization, which takes place within the droplets. An inert gas, such as nitrogen, is frequently used as a blanketing agent in order to maintain a positive pressure at all times during the cycle to prevent air leaks. Once polymerization starts, temperature control is typically maintained through a water-cooled jacket around the reactor and is facilitated by the added heat capacity of the water in the reactor. The size of the product bead depends on both the strength of agitation and the nature of the monomer and suspending system. Between 20 and 70 percent conversion, agitation becomes extremely critical. If agitation weakens or stops between these limits, excessive agglomeration of the polymer particles may occur, followed by a runaway reaction. Polymerization typically occurs within several hours, the actual time varying largely with the temperature and with the amount and type of initiator(s) used. Residual styrene concentrations at the end of a run are frequently as low as 0.1 percent.

Once the reaction has been completed (essentially 100 percent conversion), the polystyrene-water slurry is normally pumped from the reactor to a hold tank (2), which has an agitator to maintain dispersion of the polymer particles. Hold tanks have at least three functions: (1) the polymer-water slurry is cooled to below the heat distortion temperature of the polymer (generally 50 to 60°C [122 to 140°F]); (2) chemicals are added to promote solubilization of the suspension agents; and (3) the tank serves as a storage tank until the slurry can be centrifuged. From the hold tanks, the polymer-water slurry is fed to a centrifuge (3) where the water and solids are separated. The solids are then washed with water, and the wash water is separated from the solids and is discarded. The polymer product beads, which may retain between 1 and 5 percent water, are sent to dryers (4). From the dryers, they may be sent to a classifier (5) to separate the beads according to size, and then to storage bins or tanks (6). Product beads do not always meet criteria for further processing into expandable beads, and "off-spec" beads may be processed and sold as crystal (or possibly impact) polystyrene.

In the second line, the product bead (from the storage bins of the first line), water, blowing agent (7), and any desired additives are added to an impregnation reactor (8). The beads are impregnated with the blowing agent through utilization of temperature and pressure. Upon

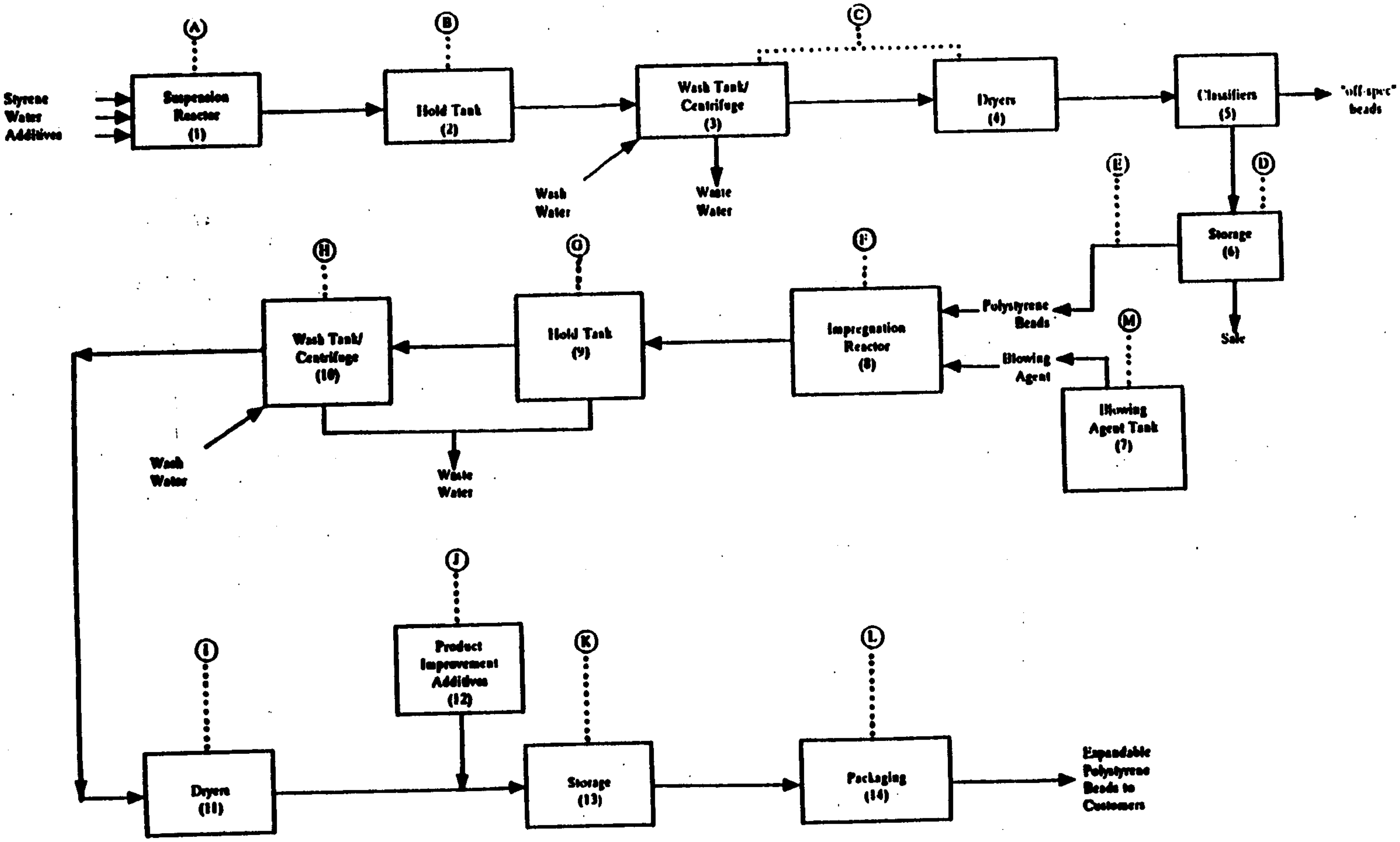


Figure 6.6.3-3. Simplified flow diagram of the expandable polystyrene post-impregnation suspension process.

completion of the impregnation process, the bead-water slurry is transferred to a hold tank (9) where acid may be added and part of the water is drained as waste water. From the hold tanks, the slurry is washed and dewatered in centrifuges (10) and then dried in low-temperature dryers (11). In some instances, additives (12) may be applied to the EPS bead to improve process characteristics. From the dryers, the EPS bead may undergo sizing, if not already done, before being transferred to storage silos (13) or directly to packaging (14) for shipment to the customer.

In-situ Suspension Process -

The in-situ suspension process is shown schematically in Figure 6.6.3-4. The major difference between this process and the post-impregnation suspension process is that polymerization and impregnation takes place at the same time in a single reactor. The reaction mixture from the mix tank (1), composed of styrene monomer, water, polymerization catalysts, and additives, are charged to a reactor (2) to which a blowing agent is added. The styrene monomer is polymerized at elevated temperatures and pressure in the presence of the blowing agent, so that 5 to 7 percent of the blowing agent is entrapped in the polymerized bead. After polymerization and impregnation have taken place, the EPS bead-water slurry follows essentially the same steps as in the post-impregnation suspension process. These steps are repeated in Figure 6.6.3-4.

6.6.3.3.2 Emissions And Controls[10,12-16] -

Emission rates have been determined from information on three plants using the post-impregnation suspension process. VOC emissions from this type of facility are generally uncontrolled. Two of these plants gave fairly extensive information and, of these, one reported an overall uncontrolled VOC emission rate of 9.8 g/kg of product. For the other, an overall uncontrolled VOC emission rate of 7.7 g/kg is indicated, by back-calculating two emission streams controlled by condensers.

The information on emission rates for individual streams varied greatly from plant to plant. For example, one plant reported a VOC emission rate for the suspension reactor of 0.027 g/kg of product, while another reported a rate of 1.9 g/kg of product. This inconsistency in emission rates may be because of differences in process reactors, operating temperatures, and/or reaction times, but sufficient data to determine this are not available. Therefore, individual stream emission rates for the post-impregnation process are not given here.

Particulate emissions (emissions of fines from dryers, storage, and pneumatic transfer of the polymer) usually are controlled by either cyclones alone or cyclones followed by baghouses. Overall, controlled particulate emissions are relatively small, approximately 0.18 g particulate/kg of product or less. Control efficiencies of 99 percent were indicated and, thus, uncontrolled particulate emissions might be around 18 g particulate/kg of product.

Table 6.6.3-3 summarizes uncontrolled VOC emissions factors for the in-situ process, based on a study of a single plant. An uncontrolled emission rate of about 5.4 gVOC/kg of product is estimated for this suspension EPS process. Most emission streams are uncontrolled at this plant. However, reactor emissions are vented to the boiler as primary fuel, and some of the dryer emissions are vented to the boiler as supplementary fuel, thereby resulting in some VOC control.

The blowing agent, which continually diffuses out of the bead both in manufacturing and during storage, constitutes almost all VOCs emitted from both processes. A small amount of styrene is emitted from the suspension reactors in the post-impregnation process and from the mix tanks and reactors in the in-situ process.

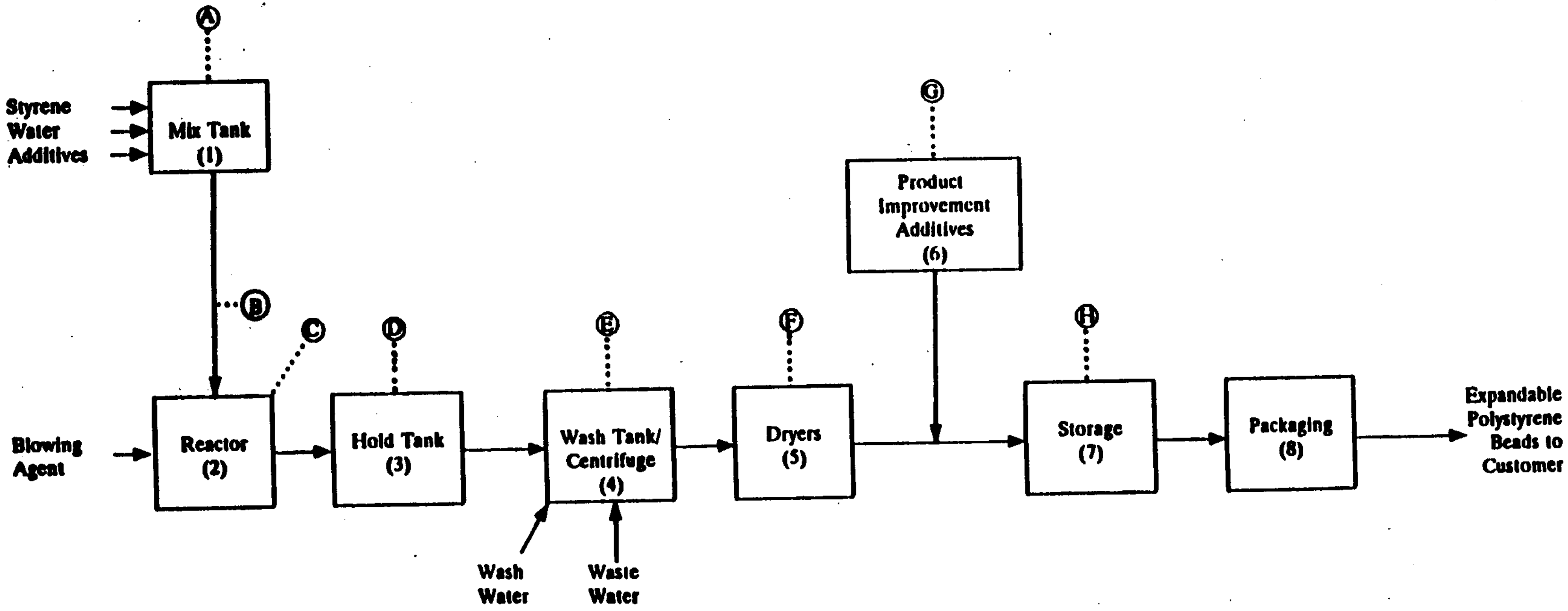


Figure 6.6.3-4. Simplified flow diagram of the expandable polystyrene in-situ suspension process.

Table 6.6.3-3 (Metric Units). EMISSION FACTORS FOR IN-SITU PROCESS EXPANDABLE POLYSTYRENE[a]

EMISSION FACTOR RATING: C

Stream Identification	Emission Stream	Nonmethane VOC	References
A	Mix tank vents	0.13	16
B	Regranulator hoppers	negligible	16
C	Reactor vents	1.09[b]	17
D	Holding tank vents	0.053	16
E	Wash tank vents	0.023	16
F	Dryer vents	2.77[b]	16
G	Product improvement vents	0.008	16
H	Storage vents and conveying losses	1.3	16
Total Plant		5.37[c]	

[a] Stream identification refers to Figure 6.6.3-4. Units are grams VOC per kilogram of product.

[b] Reference 16. All reactor vents and some dryer vents are controlled in a boiler. Rates are before control.

[c] At plant where all reactor vents and some dryer vents are controlled in a boiler (and assuming 99% reduction), an overall emission rate of 3.75 is estimated.

Because of the diffusing of the blowing agent, the EPS bead is unstable for long periods of time. Figure 6.6.3-5 shows the loss of blowing agent over time when beads are stored under standard conditions. This diffusion means that the stock of beads must be rotated. An up-to-date analysis of the blowing agent content of the bead (measured as percent volatiles at 100°C [212°F]) also needs to be maintained, because the blowing agent content determines processing characteristics, ultimate density, and economics. Expandable beads should be stored below 32°C (90°F) and in full containers (to reduce gas volume space).

Since pentane, a typical blowing agent, forms explosive mixtures, precautions must be taken whenever it is used. For example, after storage containers are opened, a time lag of 10 minutes is suggested to allow fumes or pentane vapors to dissipate out of the containers. Care must be taken to prevent static electricity and sparks from igniting the blowing agent vapors.

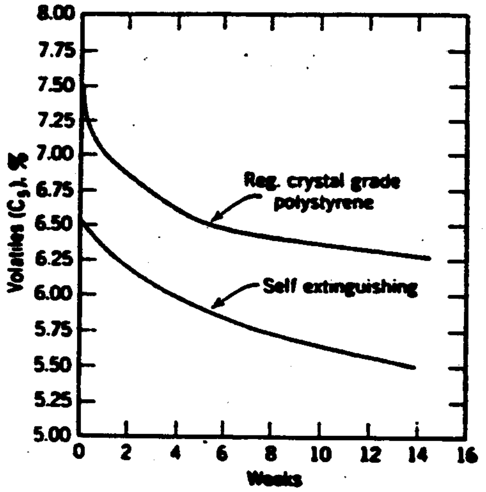


Figure 6.6.3-5. EPS beads stored in fiber drum at 21 - 24°C (70 - 75°F).

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14. Written communication from B. F. Rivers, American Hoechst Corporation, Leominster, MA, to K. Meardon, Pacific Environmental Services, Inc., Durham, NC, July 20, 1983.

15. Written communication from T. M. Nairn, Cosden Oil And Chemical Company, Big Spring, TX, to J. R. Farmer, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 30, 1983.

16. Written communication from A. D. Gillen, BASF Wyandotte Corporation, Parsippany, NJ, to J. R. Farmer, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 18, 1983.

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6.6.4 Polypropylene

6.6.4.1 Process Description[1]

The manufacture of most resins or plastics begins with the polymerization or linking of the basic compound (monomer), usually a gas or liquid, into high molecular weight noncrystalline solids. The manufacture of the basic monomer is not considered part of the plastics industry and is usually accomplished at a chemical or petroleum plant.

The manufacture of most plastics involves an enclosed reaction or polymerization step, a drying step, and a final treating and forming step. These plastics are polymerized or otherwise combined in completely enclosed stainless steel or glass-lined vessels. Treatment of the resin after polymerization varies with the proposed use. Resins for moldings are dried and crushed or ground into molding powder. Resins such as the alkyd to be used for protective coatings are usually transferred to an agitated thinning tank, where they are thinned with some type of solvent and then stored in large steel tanks equipped with water-cooled condensers to prevent loss of solvent to the atmosphere. Still other resins are stored in latex form as they come from the kettle.

6.6.4.2 Emissions And Controls[1]

The major sources of air contamination in plastics manufacturing are the raw materials or monomers, solvents, or other volatile liquids emitted during the reaction; sublimed solids such as phthalic anhydride emitted in alkyd production, and solvents lost during storage and handling of thinned resins. Emission factors for the manufacture of polypropylene are shown in Table 6.6.4-1.

Table 6.6.4-1 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR PLASTICS MANUFACTURING[a]

EMISSION FACTOR RATING: E

Type of Plastic	Particulate		Gases	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Polypropylene	1.5	3	0.35[b]	0.7[b]

[a] References 2-3.

[b] As propylene.

Much of the control equipment used in this industry is a basic part of the system serving to recover a reactant or product. These controls include floating roof tanks or vapor recovery systems on volatile material, storage units, vapor recovery systems (adsorption or condensers), purge lines venting to a flare system, and vacuum exhaust line recovery systems.

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3. Communication between Resources Research, Inc., Reston, VA, and State Department of Health, Baltimore, MD, November 1969.

6.7 Printing Ink

6.7.1 Process Description[1]

There are 4 major classes of printing ink: letterpress and lithographic inks, commonly called oil or paste inks; and flexographic and rotogravure inks, which are referred to as solvent inks. These inks vary considerably in physical appearance, composition, method of application, and drying mechanism. Flexographic and rotogravure inks have many elements in common with the paste inks but differ in that they are of very low viscosity, and they almost always dry by evaporation of highly volatile solvents.[2]

There are 3 general processes in the manufacture of printing inks: (1) cooking the vehicle and adding dyes, (2) grinding of a pigment into the vehicle using a roller mill, and (3) replacing water in the wet pigment pulp by an ink vehicle (commonly known as the flushing process).[3] The ink "varnish" or vehicle is generally cooked in large kettles at 200 to 600°F (93 to 315°C) for an average of 8 to 12 hours in much the same way that regular varnish is made. Mixing of the pigment and vehicle is done in dough mixers or in large agitated tanks. Grinding is most often carried out in 3-roller or 5-roller horizontal or vertical mills.

6.7.2 Emissions And Controls[1,4]

Varnish or vehicle preparation by heating is by far the largest source of ink manufacturing emissions. Cooling the varnish components — resins, drying oils, petroleum oils, and solvents — produces odorous emissions. At about 350°F (175°C) the products begin to decompose, resulting in the emission of decomposition products from the cooking vessel. Emissions continue throughout the cooking process with the maximum rate of emissions occurring just after the maximum temperature has been reached. Emissions from the cooking phase can be reduced by more than 90 percent with the use of scrubbers or condensers followed by afterburners.[4-5]

Compounds emitted from the cooking of oleoresinous varnish (resin plus varnish) include water vapor, fatty acids, glycerine, acrolein, phenols, aldehydes, ketones, terpene oils, terpenes, and carbon dioxide. Emissions of thinning solvents used in flexographic and rotogravure inks may also occur.

The quantity, composition, and rate of emissions from ink manufacturing depend upon the cooking temperature and time, the ingredients, the method of introducing additives, the degree of stirring, and the extent of air or inert gas blowing. Particulate emissions resulting from the addition of pigments to the vehicle are affected by the type of pigment and its particle size. Emission factors for the manufacture of printing ink are presented in Table 6.7-1.

Table 6.7-1 (Metric And English Units). EMISSION FACTORS FOR PRINTING INK MANUFACTURING[a]

EMISSION FACTOR RATING: E

Type of Process	Nonmethane Volatile Organic Compounds[b]		Particulates	
	kg/Mg of Product	lb/ton of Product	kg/Mg of Pigment	lb/ton of Pigment
Vehicle cooking				
General	60	120	NA	NA
Oils	20	40	NA	NA
Oleoresinous	75	150	NA	NA
Alkyds	80	160	NA	NA
Pigment mixing	NA	NA	1	2

[a] Based on data from Section 6.4, Paint and Varnish. NA = not applicable.

[b] The nonmethane VOC emissions are a mix of volatilized vehicle components, cooking decomposition products, and ink solvent.

References For Section 6.7

1. *Air Pollutant Emission Factors*, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.
2. R. N. Shreve, *Chemical Process Industries*, 3rd Ed., New York, McGraw Hill Book Co., 1967.
3. L. M. Larsen, *Industrial Printing Inks*, New York, Reinhold Publishing Company, 1962.
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6.8 Soap And Detergents

6.8.1 General

6.8.1.1 Soap Manufacturing[1,3,6] -

The term "soap" refers to a particular type of detergent in which the water-solubilized group is carboxylate and the positive ion is usually sodium or potassium. The largest soap market is bar soap used for personal bathing. Synthetic detergents replaced soap powders for home laundering in the late 1940s, because the carboxylate ions of the soap react with the calcium and magnesium ions in the natural hard water to form insoluble materials called lime soap. Some commercial laundries that have soft water continue to use soap powders. Metallic soaps are alkali-earth or heavy-metal long-chain carboxylates that are insoluble in water but soluble in nonaqueous solvents. They are used as additives in lubricating oils, greases, rust inhibitors, and jellied fuels.

6.8.1.2 Detergent Manufacturing[1,3,6,8] -

The term "synthetic detergent products" applies broadly to cleaning and laundering compounds containing surface-active (surfactant) compounds along with other ingredients. Heavy-duty powders and liquids for home and commercial laundry detergent comprise 60 to 65 percent of the U. S. soap and detergent market and were estimated at 2.6 megagrams (Mg) (2.86 million tons) in 1990.

Until the early 1970s, almost all laundry detergents sold in the U. S. were heavy-duty powders. Liquid detergents were introduced that utilized sodium citrate and sodium silicate. The liquids offered superior performance and solubility at a slightly increased cost. Heavy-duty liquids now account for 40 percent of the laundry detergents sold in the U. S., up from 15 percent in 1978. As a result, 50 percent of the spray drying facilities for laundry granule production have closed since 1970. Some current trends, including the introduction of superconcentrated powder detergents, will probably lead to an increase in spray drying operations at some facilities. Manufacturers are also developing more biodegradable surfactants from natural oils.

6.8.2 Process Descriptions

6.8.2.1 Soap [1,3,6] -

From American colonial days to the early 1940s, soap was manufactured by an alkaline hydrolysis reaction called saponification. Soap was made in huge kettles into which fats, oils, and caustic soda were piped and heated to a brisk boil. After cooling for several days, salt was added, causing the mixture to separate into two layers with the "neat" soap on top and spent lye and water on the bottom. The soap was pumped to a closed mixing tank called a crutcher where builders, perfumes, and other ingredients were added. Builders are alkaline compounds that improve the cleaning performance of the soap. Finally, the soap was rolled into flakes, cast or milled into bars, or spray-dried into soap powder.

An important modern process (post 1940s) for making soap is the direct hydrolysis of fats by water at high temperatures. This permits fractionation of the fatty acids, which are neutralized to soap in a continuous process as shown in Figure 6.8-1. Advantages for this process include close control of the soap concentration, the preparation of soaps of certain chain lengths for specific purposes, and easy recovery of glycerin, a byproduct. After the soap is recovered, it is pumped to the crutcher and treated the same as the product from the kettle process.

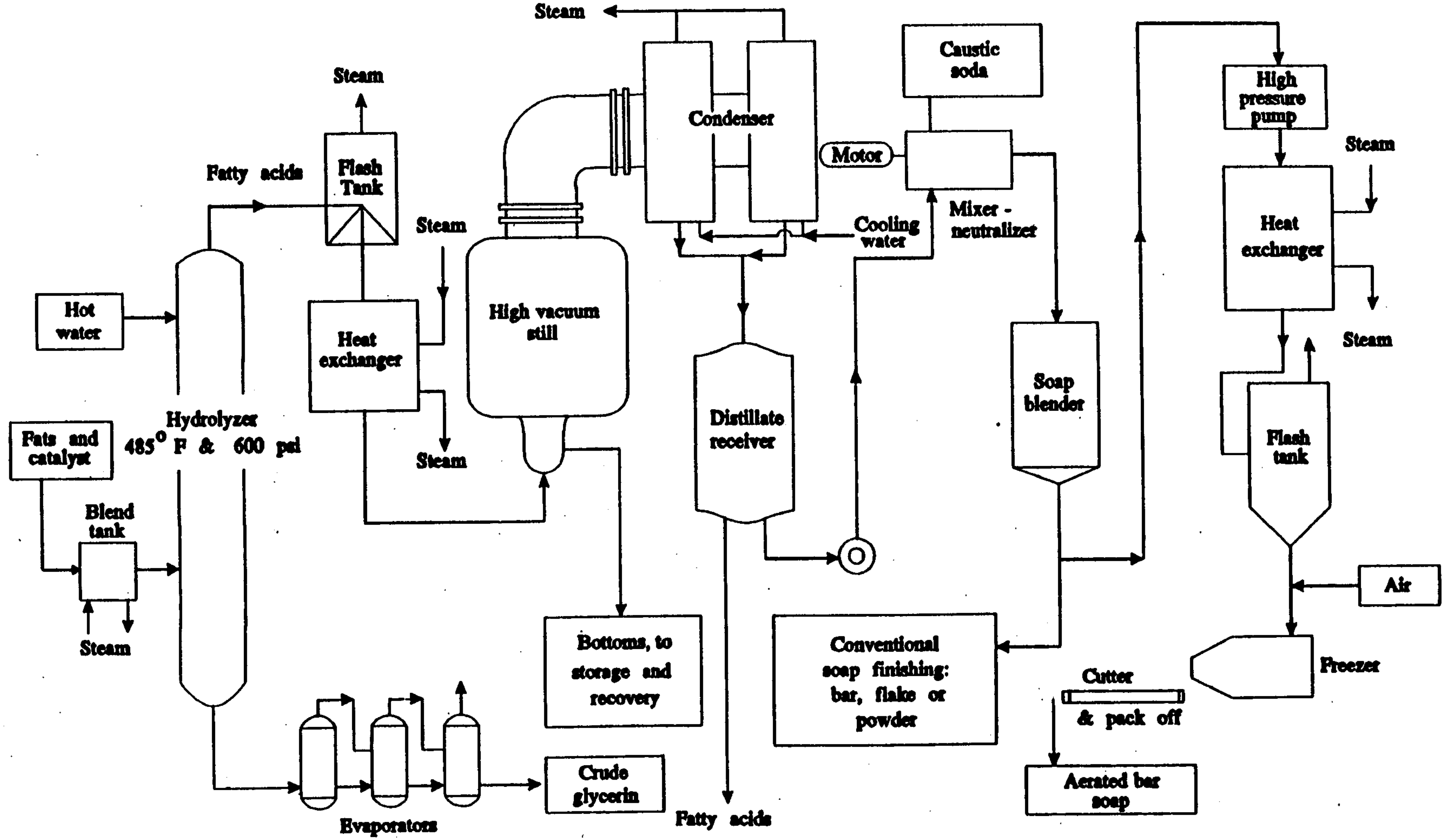


Figure 6.8-1. Continuous process for fatty acids and soaps.

6.8.2.2 Detergent[1,3,6,8] -

The manufacture of spray-dried detergent has 3 main processing steps: (1) slurry preparation, (2) spray drying, and (3) granule handling. The 3 major components of detergent are surfactants (to remove dirt and other unwanted materials), builders (to treat the water to improve surfactant performance), and additives to improve cleaning performance. Additives may include bleaches, bleach activators, antistatic agents, fabric softeners, optical brighteners, antiredeposition agents, and fillers.

The formulation of slurry for detergent granules requires the intimate mixing of various liquid, powdered, and granulated materials. Detergent slurry is produced by blending liquid surfactant with powdered and liquid materials (builders and other additives) in a closed mixing tank called a soap crutcher. Premixing of various minor ingredients is performed in a variety of equipment prior to charging to the crutcher or final mixer. Figure 6.8-2 illustrates the various operations. Liquid surfactant used in making the detergent slurry is produced by the sulfonation of either a linear alkylate or a fatty acid, which is then neutralized with a caustic solution containing sodium hydroxide (NaOH). The blended slurry is held in a surge vessel for continuous pumping to a spray dryer. The slurry is atomized by spraying through nozzles rather than by centrifugal action. The slurry is sprayed at pressures of 4.100 to 6.900 kilopascals (kPa) (600 to 1000 pounds per square inch [psi]) in single-fluid nozzles and at pressures of 340 to 690 kPa (50 to 100 psi) in 2-fluid nozzles. Steam or air is used as the atomizing fluid in the 2-fluid nozzles. The slurry is sprayed at high pressure into a vertical drying tower having a stream of hot air of from 315 to 400°C (600 to 750°F). All spray drying equipment designed for detergent granule production incorporates the following components: spray drying tower, air heating and supply system, slurry atomizing and pumping equipment, product cooling equipment, and conveying equipment. Most towers designed for detergent production are countercurrent, with slurry introduced at the top and heated air introduced at the bottom. The towers are cylindrical with cone bottoms and range in size from 4 to 7 meters (m) (12 to 24 feet [ft]) in diameter and 12 to 38 m (40 to 125 ft) in height. The detergent granules are conveyed mechanically or by air from the tower to a mixer to incorporate additional dry or liquid ingredients, and finally to packaging and storage.

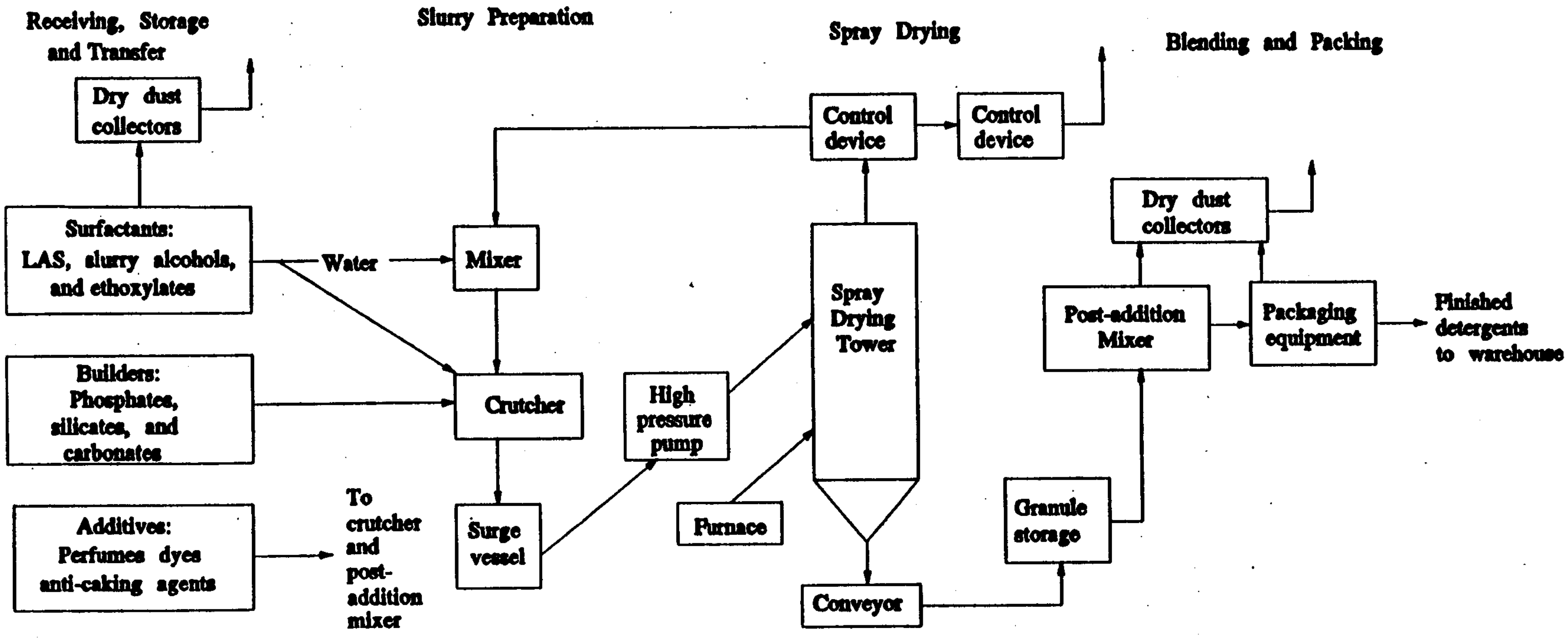
6.8.3 Emissions And Controls

6.8.3.1 Soap[1,3,6] -

The main atmospheric pollution problem in soap manufacturing is odor. The storage and handling of liquid ingredients (including sulfonic acids and salts) and sulfates are some of the sources of this odor. Vent lines, vacuum exhausts, raw material and product storage, and waste streams are all potential odor sources. Control of these odors may be achieved by scrubbing exhaust fumes and, if necessary, incinerating the remaining volatile organic compounds (VOC). Odors emanating from the spray dryer may be controlled by scrubbing with an acid solution. Blending, mixing, drying, packaging, and other physical operations may all involve dust emissions. The production of soap powder by spray drying is the single largest source of dust in the manufacture of synthetic detergents. Dust emissions from other finishing operations can be controlled by dry filters such as baghouses. The large sizes of the particulate from synthetic detergent drying means that high-efficiency cyclones installed in series can achieve satisfactory control. Currently, no emission factors are available for soap manufacturing. No information on hazardous air pollutants (HAP), VOCs, ozone depleters, or heavy metal emissions information were found for soap manufacturing.

6.8.3.2 Detergent[1,3-4,6,8] -

The exhaust air from detergent spray drying towers contains 2 types of air contaminants: (1) fine detergent particles and (2) organics vaporized in the higher temperature zones of the tower. Emission factors for particulates from spray drying operations are shown in Table 6.8-1. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton) of product.



LAS = linear alkyl sulfonate

Figure 6.8-2. Manufacture of spray-dried detergents.

Table 6.8-1 (Metric And English Units). PARTICULATE EMISSION FACTORS FOR DETERGENT SPRAY DRYING[a]

EMISSION FACTOR RATING: E[b]

Control Device	Efficiency (%)	Particulate	
		kg/Mg of Product	lb/ton of Product
Uncontrolled (SCC 3-01-009-01)	NA	45	90
Cyclone	85	7	14
Cyclone with:			
Spray chamber	92	3.5	7
Packed scrubber	95	2.5	5
Venturi scrubber	97	1.5	3
Wet scrubber	99	0.544	1.09
Wet scrubber/ESP	99.9	0.023	0.046
Packed bed/ESP	99[c]	0.47	0.94
Fabric filter	99	0.54	1.1

[a] Some type of primary collector, such as a cyclone, is considered integral to a spray drying system. NA = not applicable. ESP = electrostatic precipitator. SCC = Source Classification Code.

[b] Emission factors are estimations and are not supported by current test data.

[c] Emission factor has been calculated from a single source test. An efficiency of 99% has been estimated.

Dust emissions are generated at scale hoppers, mixers, and crutchers during the batching and mixing of fine dry ingredients to form slurry. Conveying, mixing, and packaging of detergent granules can also cause dust emissions. Pneumatic conveying of fine materials causes dust emissions when conveying air is separated from bulk solids. For this process, fabric filters are generally used, not only to reduce or to eliminate dust emissions, but also to recover raw materials. The dust emissions principally consist of detergent compounds, although some of the particles are uncombined phosphates, sulfates, and other mineral compounds.

Dry cyclones and cyclonic impingement scrubbers are the primary collection equipment employed to capture the detergent dust in the spray dryer exhaust for return to processing. Dry cyclones are used in parallel or in series to collect this particulate matter (PM) and recycle it back to the crutcher. The dry cyclone separators can remove 90 percent or more by weight of the detergent product fines from the exhaust air. Cyclonic impinged scrubbers are used in parallel to collect the particulate from a scrubbing slurry and to recycle it to the crutcher.

Secondary collection equipment is used to collect fine particulates that escape from primary devices. For example, cyclonic impingement scrubbers are often followed by mist eliminators, and dry cyclones are followed by fabric filters or scrubber/electrostatic precipitator units. Several types of scrubbers can be used following the cyclone collectors. Venturi scrubbers have been used but are being replaced with packed bed scrubbers. Packed bed scrubbers are usually followed by wet-pipe-type electrostatic precipitators built immediately above the packed bed in the same vessel. Fabric filters have been used after cyclones but have limited applicability, especially on efficient spray dryers, due to condensing water vapor and organic aerosols binding the fabric filter.

In addition to particulate emissions, volatile organics may be emitted when the slurry contains organic materials with low vapor pressures. The VOCs originate primarily from the surfactants included in the slurry. The amount vaporized depends on many variables such as tower temperature and the volatility of organics used in the slurry. These vaporized organic materials condense in the tower exhaust airstream into droplets or particles. Paraffin alcohols and amides in the exhaust stream can result in a highly visible plume that persists after the condensed water vapor plume has dissipated.

Opacity and the organic emissions are influenced by granule temperature and moisture at the end of drying, temperature profiles in the dryer, and formulation of the slurry. A method for controlling visible emissions would be to remove offending organic compounds (i. e., by substitution) from the slurry. Otherwise, tower production rate may be reduced thereby reducing air inlet temperatures and exhaust temperatures. Lowering production rate will also reduce organic emissions.

Some of the HAPs and VOCs identified from the VOC/PM Speciate Database Management System (SPECIATE) are: hexane, methyl alcohol, 1,1,1-trichloroethane, perchloroethylene, benzene, and toluene. Lead was identified from SPECIATE data as the only heavy metal constituent. No numerical data are presented for lead, HAP, or VOC emissions due to the lack of sufficient supporting documentation.

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6.9 Synthetic Fibers

6.9.1 General[1-3]

There are 2 types of synthetic fiber products, the semisynthetics, or cellulosics (viscose rayon and cellulose acetate), and the true synthetics, or noncellulosics (polyester, nylon, acrylic and modacrylic, and polyolefin). These 6 fiber types compose over 99 percent of the total production of manmade fibers in the U. S.

6.9.2 Process Description[2-6]

Semisynthetics are formed from natural polymeric materials such as cellulose. True synthetics are products of the polymerization of smaller chemical units into long-chain molecular polymers. Fibers are formed by forcing a viscous fluid or solution of the polymer through the small orifices of a spinnerette (see Figure 6.9-1) and immediately solidifying or precipitating the resulting filaments. This prepared polymer may also be used in the manufacture of other nonfiber products such as the enormous number of extruded plastic and synthetic rubber products.

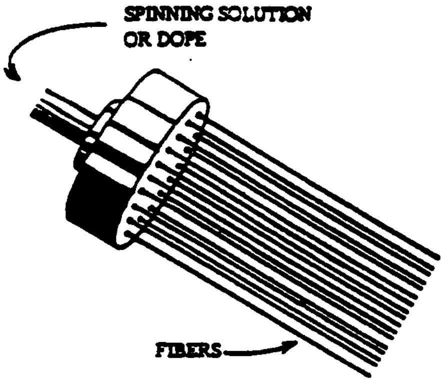

Figure 6.9-1. Spinnerette.

Synthetic fibers (both semisynthetic and true synthetic) are produced typically by 2 easily distinguishable methods, melt spinning and solvent spinning. Melt spinning processes use heat to melt the fiber polymer to a viscosity suitable for extrusion through the spinnerette. Solvent spinning processes use large amounts of organic solvents, which usually are recovered for economic reasons, to dissolve the fiber polymer into a fluid polymer solution suitable for extrusion through a spinnerette. The major solvent spinning operations are dry spinning and wet spinning. A third method, reaction spinning, is also used, but to a much lesser extent. Reaction spinning processes involve the formation of filaments from prepolymers and monomers that are further polymerized and cross-linked after the filament is formed.

Figure 6.9-2 is a general process diagram for synthetic fiber production using the major types of fiber spinning procedures. The spinning process used for a particular polymer is determined by the polymer's melting point, melt stability, and solubility in organic and/or inorganic (salt) solvents. (The polymerization of the fiber polymer is typically carried out at the same facility that produces the fiber.) Table 6.9-1 lists the different types of spinning methods with the fiber types produced by each method. After the fiber is spun, it may undergo one or more different processing treatments to meet the required physical or handling properties. Such processing treatments include drawing, lubrication, crimping, heat setting, cutting, and twisting. The finished fiber product may be classified as tow, staple, or continuous filament yarn.

Table 6.9-1. TYPES OF SPINNING METHODS AND FIBER TYPES PRODUCED

Spinning Method	Fiber Type
Melt spinning	Polyester Nylon 6 Nylon 66 Polyolefin
Solvent spinning	
Dry solvent spinning	Cellulose acetate Cellulose triacetate Acrylic Modacrylic Vinyon Spandex
Wet solvent spinning	Acrylic Modacrylic
Reaction spinning	Spandex Rayon (viscose process)

6.9.2.1 Melt Spinning -

Melt spinning uses heat to melt the polymer to a viscosity suitable for extrusion. This type of spinning is used for polymers that are not decomposed or degraded by the temperatures necessary for extrusion. Polymer chips may be melted by a number of methods. The trend is toward melting and immediate extrusion of the polymer chips in an electrically heated screw extruder. Alternatively, the molten polymer is processed in an inert gas atmosphere, usually nitrogen, and is metered through a precisely machined gear pump to a filter assembly consisting of a series of metal gauges interspersed in layers of graded sand. The molten polymer is extruded at high pressure and constant rate through a spinnerette into a relatively cooler air stream that solidifies the filaments. Lubricants and finishing oils are applied to the fibers in the spin cell. At the base of the spin cell, a thread guide converges the individual filaments to produce a continuous filament yarn, or a spun yarn, that typically is composed of between 15 and 100 filaments. Once formed, the filament yarn either is immediately wound onto bobbins or is further treated for certain desired characteristics or end use.

Since melt spinning does not require the use of solvents, VOC emissions are significantly lower than those from dry and wet solvent spinning processes. Lubricants and oils are sometimes added during the spinning of the fibers to provide certain properties necessary for subsequent operations such as lubrication and static suppression. These lubricants and oils vaporize, condense,

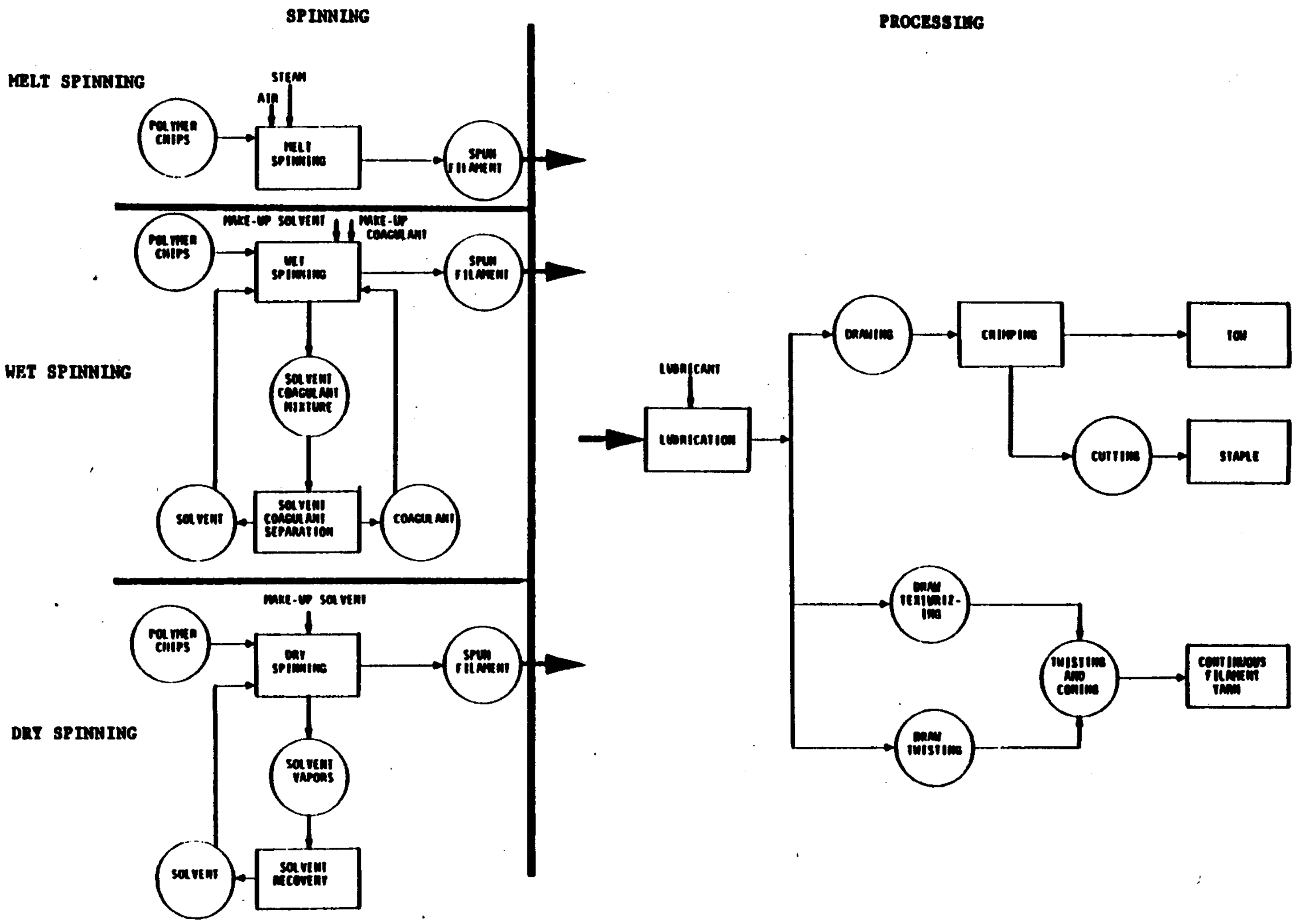

Figure 6.9-2. General process diagram for melt, wet, and dry spun synthetic fibers.

and then coalesce as aerosols primarily from the spinning operation, although certain post-spinning operations may also give rise to these aerosol emissions. Treatments include drawing, lubrication, crimping, heat setting, cutting, and twisting.

6.9.2.2. Dry Solvent Spinning -

The dry spinning process begins by dissolving the polymer in an organic solvent. This solution is blended with additives and is filtered to produce a viscous polymer solution, referred to as "dope", for spinning. The polymer solution is then extruded through a spinnerette as filaments into a zone of heated gas or vapor. The solvent evaporates into the gas stream and leaves solidified filaments, which are further treated using one or more of the processes described in the general process description section. (See Figure 6.9-3.) This type of spinning is used for easily dissolved polymers such as cellulose acetate, acrylics, and modacrylics.

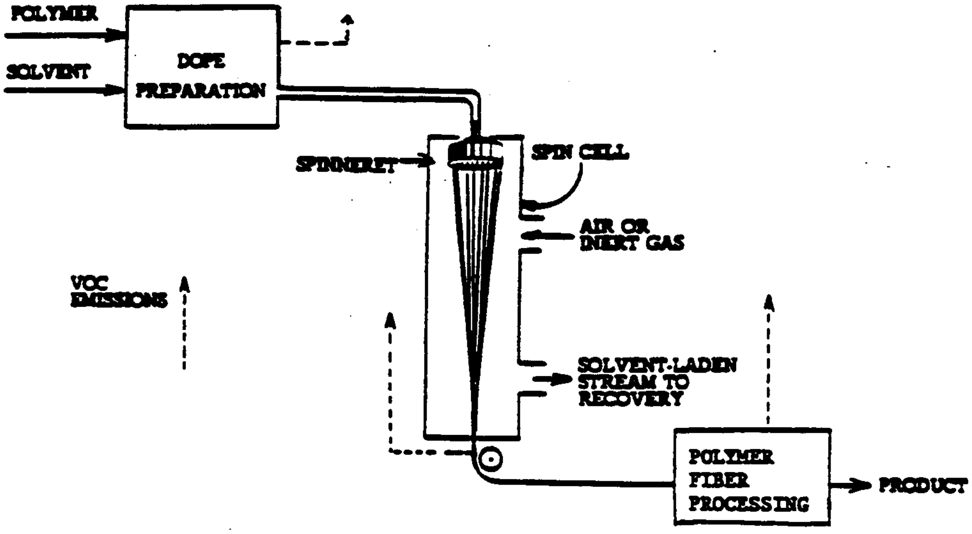

Figure 6.9-3. Dry spinning.

Dry spinning is the fiber formation process potentially emitting the largest amounts of VOCs per pound of fiber produced. Air pollutant emissions include volatilized residual monomer, organic solvents, additives, and other organic compounds used in fiber processing. Unrecovered solvent constitutes the major substance. The largest amounts of unrecovered solvent are emitted from the fiber spinning step and drying the fiber. Other emission sources include dope preparation (dissolving the polymer, blending the spinning solution, and filtering the dope), fiber processing (drawing, washing, and crimping), and solvent recovery.

6.9.2.3 Wet Solvent Spinning -

Wet spinning also uses solvent to dissolve the polymer to prepare the spinning dope. The process begins by dissolving polymer chips in a suitable organic solvent, such as dimethylformamide (DMF), dimethylacetamide (DMAc), or acetone, as in dry spinning; or in a weak inorganic acid, such as zinc chloride or aqueous sodium thiocyanate. In wet spinning, the spinning solution is extruded through spinnerettes into a precipitation bath that contains a coagulant (or precipitant) such as aqueous

DMAc or water. Precipitation or coagulation occurs by diffusion of the solvent out of the thread and by diffusion of the coagulant into the thread. Wet spun filaments also undergo one or more of the additional treatment processes described earlier, as depicted in Figure 6.9-4.

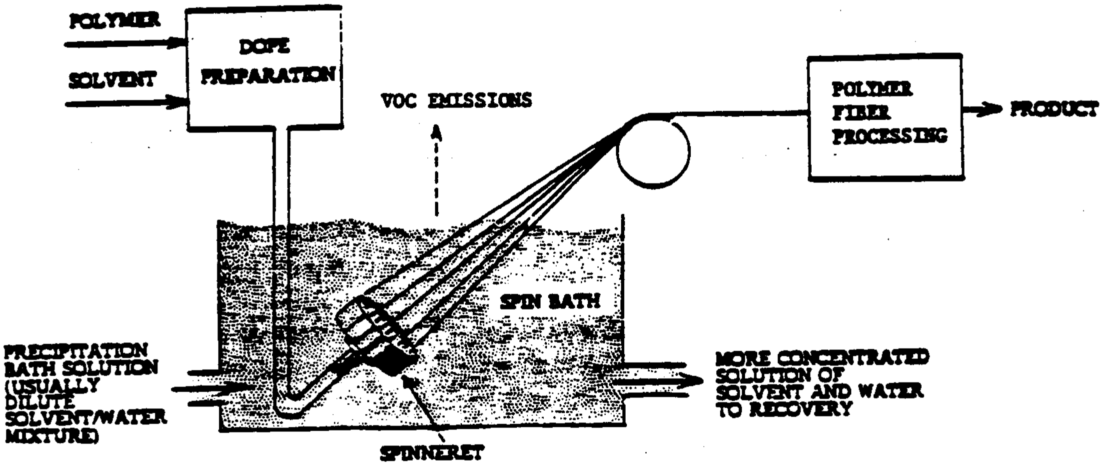

Figure 6.9-4. Wet spinning.

Air pollution emission points in the wet spinning organic solvent process are similar to those of dry spinning. Wet spinning processes that use solutions of acids or salts to dissolve the polymer chips emit no solvent VOC, only unreacted monomer, and are, therefore, relatively clean from an air pollution standpoint. For those that require solvent, emissions occur as solvent evaporates from the spinning bath and from the fiber in post-spinning operations.

6.9.2.4 Reaction Spinning -

As in the wet and dry spinning processes, the reaction spinning process begins with the preparation of a viscous spinning solution, which is prepared by dissolving a low molecular weight polymer, such as polyester for the production of spandex fibers, in a suitable solvent and a reactant, such as di-isocyanate. The spinning solution is then forced through spinnerettes into a solution containing a diamine, similarly to wet spinning, or is combined with the third reactant and then dry spun. The primary distinguishable characteristic of reaction spinning processes is that the final cross-linking between the polymer molecule chains in the filament occurs after the fibers have been spun. Post-spinning steps typically include drying and lubrication. Emissions from the wet and dry reaction spinning processes are similar to those of solvent wet and dry spinning, respectively.

6.9.3 Emissions And Controls

For each pound of fiber produced with the organic solvent spinning processes, a pound of polymer is dissolved in about 3 pounds of solvent. Because of the economic value of the large amounts of solvent used, capture and recovery of these solvents are an integral portion of the solvent spinning processes. At present, 94 to 98 percent of the solvents used in these fiber formation processes is recovered. In both dry and wet spinning processes, capture systems with subsequent solvent recovery are applied most frequently to the fiber spinning operation alone, because the emission stream from the spinning operation contains the highest concentration of solvent and, emission stream from the spinning operation contains the highest concentration of solvent and, therefore, possesses the greatest potential for efficient and economic solvent recovery. Recovery systems used include gas adsorption, gas absorption, condensation, and distillation and are specific to a particular fiber type or spinning method. For example, distillation is typical in wet spinning processes to recover solvent from the spinning bath, drawing, and washing (see Figure 6.9-8), while condensers or scrubbers are typical in dry spinning processes for recovering solvent from the spin cell (see Figure 6.9-6 and Figure 6.9-9). The recovery systems themselves are also a source of emissions from the spinning processes.

The majority of VOC emissions from pre-spinning (dope preparation, for example) and post-spinning (washing, drawing, crimping, etc.) operations typically are not recovered for reuse. In many instances, emissions from these operations are captured by hoods or complete enclosures to prevent worker exposure to solvent vapors and unreacted monomer. Although already captured, the quantities of solvent released from these operations are typically much smaller than those released during the spinning operation. The relatively high air flow rates required in order to reduce solvent and monomer concentrations around the process line to acceptable health and safety limits make recovery economically unattractive. Solvent recovery, therefore, is usually not attempted.

Table 6.9-2 presents emission factors from production of the most widely known semisynthetic and true synthetic fibers. These emission factors address emissions only from the spinning and post-spinning operations and the associated recovery or control systems. Emissions from the polymerization of the fiber polymer and from the preparation of the fiber polymer for spinning are not included in these emission factors. While significant emissions occur in the polymerization and related processes, these emissions are discussed in Sections 6.6, "Plastics", and 6.10, "Synthetic Rubber".

Examination of VOC pollutant emissions from the synthetic fibers industry has recently concentrated on those fiber production processes that use an organic solvent to dissolve the polymer for extrusion or that use an organic solvent in some other way during the filament forming step. Such processes, while representing only about 20 percent of total industry production, do generate about 94 percent of total industry VOC emissions. Particulate emissions from fiber plants are relatively low, at least an order of magnitude lower than the solvent VOC emissions.

6.9.4 Semisynthetics

6.9.4.1 Rayon Fiber Process Description[5,7-10] -

In the United States, most rayon is made by the viscose process. Rayon fibers are made using cellulose (dissolved wood pulp), sodium hydroxide, carbon disulfide, and sulfuric acid. As shown in Figure 6.9-5, the series of chemical reactions in the viscose process used to make rayon consists of the following stages:

1. Wood cellulose and a concentrated solution of sodium hydroxide react to form soda cellulose.

2. The soda cellulose reacts with carbon disulfide to form sodium cellulose xanthate.

3. The sodium cellulose xanthate is dissolved in a dilute solution of sodium hydroxide to give a viscose solution.

Table 6.9-2 (English Units). EMISSION FACTORS FOR SYNTHETIC FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: C

Type Of Fiber	Nonmethane Volatile Organics	Particulate	References
Rayon, viscose process	0	—[c]	7-8,10,35-36
Cellulose acetate, filter tow	112[d]	—[c]	11,37
Cellulose acetate and triacetate, filament yarn	199[d,e]	—[c]	11,38
Polyester, melt spun			41-42
Staple	0.6[f,g]	252[h,j]	
Yarn[k]	0.05[f,g]	0.03[g,j]	
Acrylic, dry spun			21,43-44
Uncontrolled	40	—[c]	
Controlled	32[m]	—[c]	
Modacrylic, dry spun	125[g,h]	—[c]	45
Acrylic and modacrylic, wet spun	6.75[p]	—[c]	19,46
Acrylic, inorganic wet spun			47-48
Homopolymer	20.7[g,q]	—[c]	
Copolymer	2.75[g,r]	—[c]	
Nylon 6, melt spun			25,49
Staple	3.93[g]	0.01[g]	
Yarn	0.45[s]	—[c]	
Nylon 66, melt spun			26
Uncontrolled	2.13[f,t]	0.5[u]	
Controlled	0.31[f,v]	0.1[u]	
Polyolefin, melt spun	5[g]	0.01[g]	5,25,28,49
Spandex, dry spun	4.23[m]	—[c]	32
Spandex, reaction spun	138[x]	—[c]	50-51
Vinyon, dry spun	150[m]	—[c]	52

[a] Factors are pounds of emissions per 1000 pounds (lb) of fiber spun including waste fiber.

[b] Uncontrolled carbon disulfide (CS_2) emissions are 251 lb CS_2/1000 lb fiber spun; uncontrolled hydrogen sulfide (H_2S) emissions are 50.4 lb H_2S/1000 lb fiber spun. If recovery of CS_2 from the "hot dip" stage takes place, CS_2 emissions are reduced by about 16%.

[c] Particulate emissions from the spinning solution preparation area and later stages through the finished product are essentially nil.

Table 6.9-2 (cont.).

[d] After recovery from the spin cells and dryers. Use of more extensive recovery systems can reduce emissions by 40% or more.

[e] Use of methyl chloride and methanol as the solvent, rather than acetone, in production of triacetate can double emissions.

[f] Emitted in aerosol form.

[g] Uncontrolled.

[h] After control on extrusion parts cleaning operations.

[j] Mostly particulate, with some aerosols.

[k] Factors for high intrinsic viscosity industrial and tire yarn production are 0.18 lb VOC and 3.85 lb particulate.

[m] After recovery from spin cells.

[n] About 18 lb is from dope preparation, and about 107 lb is from spinning/post-spinning operations.

[p] After solvent recovery from the spinning, washing, and drawing stages. This factor includes acrylonitrile emissions. An emission factor of 87 lb/1000 lb fiber has been reported.

[q] Average emission factor; range is from 13.9 to 27.7 lb.

[r] Average emission factor; range is from 2.04 to 16.4 lb.

[s] After recovery of emissions from the spin cells. Without recovery, emission factor would be 1.39 lb.

[t] Average of plants producing yarn from batch and continuous polymerization processes. Range is from abut 0.5 to 4.9 lb. Add 0.1 lb to the average factor for plants producing tow or staple. Continuous polymerization processes average emission rates approximately 170%. Batch polymerization processes average emission rates approximately 80%.

[u] For plants with spinning equipment cleaning operations.

[v] After control of spin cells in plants with batch and continuous polymerization processes producing yarn. Range is from 0.1 to 0.6 lb. Add 0.02 lb to the average controlled factor for producing tow or staple. Double the average controlled emission factor for plants using continuous polymerization only; subtract 0.01 lb for plants using batch polymerization only.

[w] After control of spinning equipment cleaning operation.

[x] After recovery by carbon adsorption from spin cells and post-spinning operations. Average collection efficiency 83%. Collection efficiency of carbon adsorber decreases over 18 months from 95% to 63%.

4. The solution is ripened or aged to complete the reaction.

5. The viscose solution is extruded through spinnerettes into dilute sulfuric acid, which regenerates the cellulose in the form of continuous filaments.

Emissions And Controls -

Air pollutant emissions from viscose rayon fiber production are mainly carbon disulfide (CS_2), hydrogen sulfide (H_2S), and small amounts of particulate matter. Most CS_2 and H_2S emissions occur during the spinning and post-spinning processing operations. Emission controls are not used extensively in the rayon fiber industry. A countercurrent scrubber (condenser) is used in at least one instance to recover CS_2 vapors from the sulfuric acid bath alone. The emissions from this operation are high enough in concentration and low enough in volume to make such recovery both technically and economically feasible. The scrubber recovers nearly all of the CS_2 and H_2S that enters it, reducing overall CS_2 and H_2S emissions from the process line by about 14 percent. While carbon adsorption systems are capable of CS_2 emission reductions of up to 95 percent, attempts to use carbon adsorbers have had serious problems.

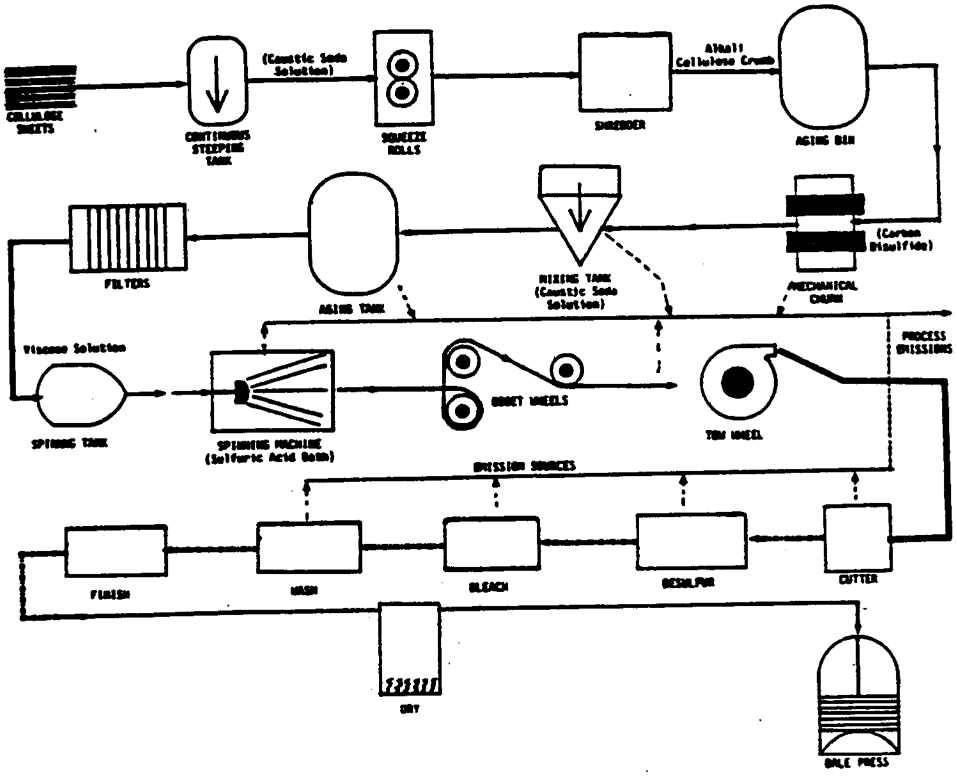

Figure 6.9-5. Rayon viscose process.

6.9.4.2. Cellulose Acetate And Triacetate Fiber Process Description[5,11-14] -

All cellulose acetate and triacetate fibers are produced by dry spinning. These fibers are used for either cigarette filter tow or filament yarn. Figure 6.9-6 shows the typical process for the production of cigarette filter tow. Dried cellulose acetate polymer flakes are dissolved in a solvent, acetone and/or a chlorinated hydrocarbon in a closed mixer. The spinning solution (dope) is filtered, as it is with other fibers. The dope is forced through spinnerettes to form cellulose acetate filaments, from which the solvent rapidly evaporates as the filaments pass down a spin cell or column. After the filaments emerge from the spin cell, there is a residual solvent content that continues to evaporate more slowly until equilibrium is attained. The filaments then undergo several post-spinning operations before they are cut and baled.

In the production of filament yarn, the same basic process steps are carried out as for filter tow, up through and including the actual spinning of the fiber. Unlike filter tow filaments, however, filaments used for filament yarn do not undergo the series of post-spinning operations shown in Figure 6.9-6, but rather are wound immediately onto bobbins as they emerge from the spin cells. In some instances, a slight twist is given to the filaments to meet product specifications. In another area, the wound filament yarn is subsequently removed from the bobbins and wrapped on beams or cones (referred to as "beaming") for shipment.

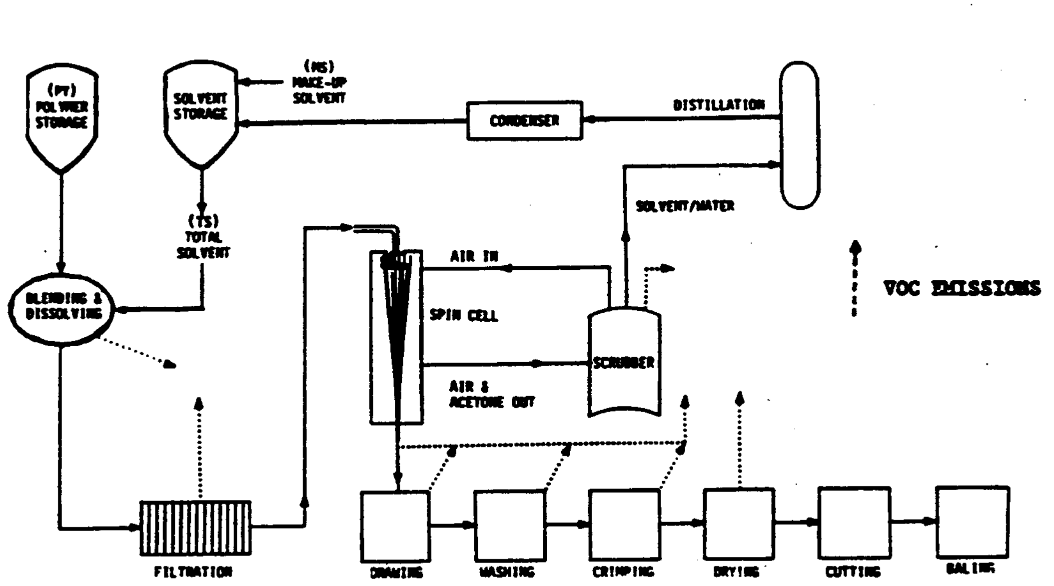

Figure 6.9-6. Cellulose acetate and triacetate filter tow.

Emissions And Controls -

Air pollutant emissions from cellulose acetate fiber production include solvents, additives, and other organic compounds used in fiber processing. Acetone, methyl ethyl ketone, and methanol are the only solvents currently used in commercial production of cellulose acetate and triacetate fibers.

In the production of all cellulose acetate fibers, i. e., tow, staple, or filament yarn, solvent emissions occur during dissolving of the acetate flakes, blending and filtering of the dope, spinning of the fiber, processing of the fiber after spinning, and the solvent recovery process. The largest emissions of solvent occur during spinning and processing of the fiber. Filament yarns are typically not dried as thoroughly in the spinning cell as are tow or staple yarns. Consequently, they contain larger amounts of residual solvent, which evaporates into the spinning room air where the filaments are wound and into the room air where the wound yarn is subsequently transferred to beams. This residual solvent continues to evaporate for several days until an equilibrium is attained. The largest emissions occur during the spinning of the fiber and the evaporation of the residual solvent from the wound and beamed filaments. Both processes also emit lubricants (various vegetable and mineral oils) applied to the fiber after spinning and before winding, particularly from the dryers in the cigarette filter tow process.

VOC control techniques are primarily carbon adsorbers and scrubbers. They are used to control and recover solvent emissions from process gas streams from the spin cells in both the production of cigarette filter tow and filament yarn. Carbon adsorbers also are used to control and recover solvent emissions from the dryers used in the production of cigarette filter tow. The solvent recovery efficiencies of these recovery systems range from 92 to 95 percent. Fugitive emissions from other post-spinning operations, even though they are a major source, are generally not controlled. In at least one instance however, an air management system is being used in which the air from the dope preparation and beaming areas is combined at carefully controlled rates with the spinning room air that is used to provide the quench air for the spin cell. A fixed amount of spinning room air is then combined with the process gas stream from the spin cell and this mix is vented to the recovery system.

6.9.5 True Synthetic Fibers

6.9.5.1 Polyester Fiber Process Description[5,11,15-17] -

Polyethylene terephthalate (PET) polymer is produced from ethylene glycol and either dimethyl terephthalate (DMT) or terephthalic acid (TPA). Polyester filament yarn and staple are manufactured either by direct melt spinning of molten PET from the polymerization equipment or by spinning reheated polymer chips. Polyester fiber spinning is done almost exclusively with extruders, which feed the molten polymer under pressure through the spinnerettes. Filament solidification is induced by blowing the filaments with cold air at the top of the spin cell. The filaments are then led down the spin cell through a fiber finishing application, from which they are gathered into tow, hauled off, and coiled into spinning cans. The post-spinning processes, steps 14 through 24 in Figure 6.9-7, usually take up more time and space and may be located far from the spinning machines. Depending on the desired product, post-spinning operations vary but may include lubrication, drawing, crimping, heat setting, and stapling.

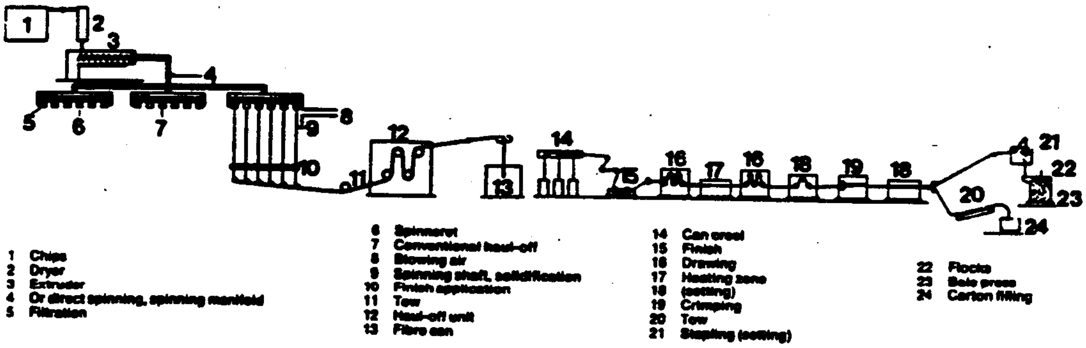

Figure 6.9-7. Polyester production.

Emissions And Controls -

Air pollutant emissions from polyester fiber production include polymer dust from drying operations, volatilized residual monomer, fiber lubricants (in the form of fume or oil smoke), and the burned polymer and combustion products from cleaning the spinning equipment. Relative to the solvent spinning processes, the melt spinning of polyester fibers does not generate significant amounts of volatilized monomer or polymer, so emission control measures typically are not used in the spinning area. Finish oils that are applied in polyester fiber spinning operations are usually recovered and recirculated. When applied, finish oils are vaporized in the spin cell to some extent and, in some instances, are vented to either demisters, which remove some of the oils, or catalytic incinerators, which oxidize significant quantities of volatile hydrocarbons. Small amounts of finish oils are vaporized in the post-spinning process. Vapors from hot draw operations are typically controlled by devices such as electrostatic precipitators. Emissions from most other steps are not controlled.

6.9.5.2 Acrylic And Modacrylic Fiber Process Description[5,18-24,53] -

Acrylic and modacrylic fibers are based on acrylonitrile monomer, which is derived from propylene and ammonia. Acrylics are defined as those fibers that are composed of at least 85 percent acrylonitrile. Modacrylics are defined as those fibers that are composed of between 35 and 85 percent acrylonitrile. The remaining composition of the fiber typically includes at least one of the following: methyl methacrylate, methyl acrylate, vinyl acetate, vinyl chloride, or vinylidene chloride.

Polyacrylonitrile fiber polymers are produced by the industry using 2 methods, suspension polymerization and solution polymerization. Either batch or continuous reaction modes may be employed.

As shown in Figure 6.9-8 and Figure 6.9-9, the polymer is dissolved in a suitable solvent, such as dimethylformamide or dimethylacetamide. Additives and delusterants are added, and the solution is usually filtered in plate and frame presses. The solution is then pumped through a manifold to the spinnerettes (usually a bank of 30 to 50 per machine). At this point in the process, either wet or dry spinning may be used to form the acrylic fibers. The spinnerettes are in a spinning bath for wet spun fiber or at the top of an enclosed column for dry spinning. The wet spun filaments are pulled from the bath on takeup wheels, then washed to remove more solvent. After washing, the filaments are gathered into a tow band, stretched to improve strength, dried, crimped, heat set, and then cut into staple. The dry spun filaments are gathered into a tow band, stretched, dried, crimped, and cut into staple.

Emissions And Controls -

Air pollutant emissions from the production of acrylic and modacrylic fibers include emissions of acrylonitrile (volatilized residual monomer), solvents, additives, and other organics used in fiber processing. As shown in Figure 6.9-8 and Figure 6.9-9, both the wet and the dry spinning processes have many emission points. The major emission areas for the wet spin fiber process are the spinning and washing steps. The major emission areas from dry spinning of acrylic and modacrylic fibers are the spinning and post-spinning areas, up through and including drying. Solvent recovery in dry-spinning of modacrylic fibers is also a major emission point.

The most cost-effective method for reducing solvent VOC emissions from both wet and dry spinning processes is a solvent recovery system. In wet spinning processes, distillation is used to recover and recycle solvent from the solvent/water stream that circulates through the spinning, washing, and drawing operations. In dry spinning processes, control techniques include scrubbers, condensers, and carbon adsorption. Scrubbers and condensers are used to recover solvent emissions from the spinning cells and the dryers. Carbon adsorption is used to recover solvent emissions from storage tank vents and from mixing and filtering operations. Distillation columns are also used in dry spinning processes to recover solvent from the condenser, scrubber, and wash water (from the washing operation).

6.9.5.3 Nylon Fiber 6 And 66 Process Description[5,17,24-27] -

Nylon 6 polymer is produced from caprolactam. Caprolactam is derived most commonly from cyclohexanone, which in turn comes from either phenol or cyclohexane. About 70 percent of all nylon 6 polymer is produced by continuous polymerization. Nylon 66 polymer is made from adipic acid and hexamethylene diamine, which react to form hexamethylene diamonium adipate (AH salt). The salt is then washed in a methyl alcohol bath. Polymerization then takes place under heat and pressure in a batch process. The fiber spinning and processing procedures are the same as described earlier in the description of melt spinning. The nylon production process is shown in Figure 6.9-10.

Emissions And Controls -

The major air pollutant emissions from production of nylon 6 fibers are volatilized monomer (caprolactam) and oil vapors or mists. Caprolactam emissions may occur at the spinning step because the polymerization reaction is reversible and exothermic, and the heat of extrusion causes the polymer to revert partially to the monomer form. A monomer recovery system is used on caprolactam volatilized at the spinnerette during nylon 6 fiber formation. Monomer recovery systems are not used in nylon 66 (polyhexamethylene adipamide) spinning operations because nylon 66 does not contain a significant amount of residual monomer. Emissions, though small, are in some instances controlled by catalytic incinerators. The finish oils, plasticizers, and lubricants applied to both nylon 6 and 66

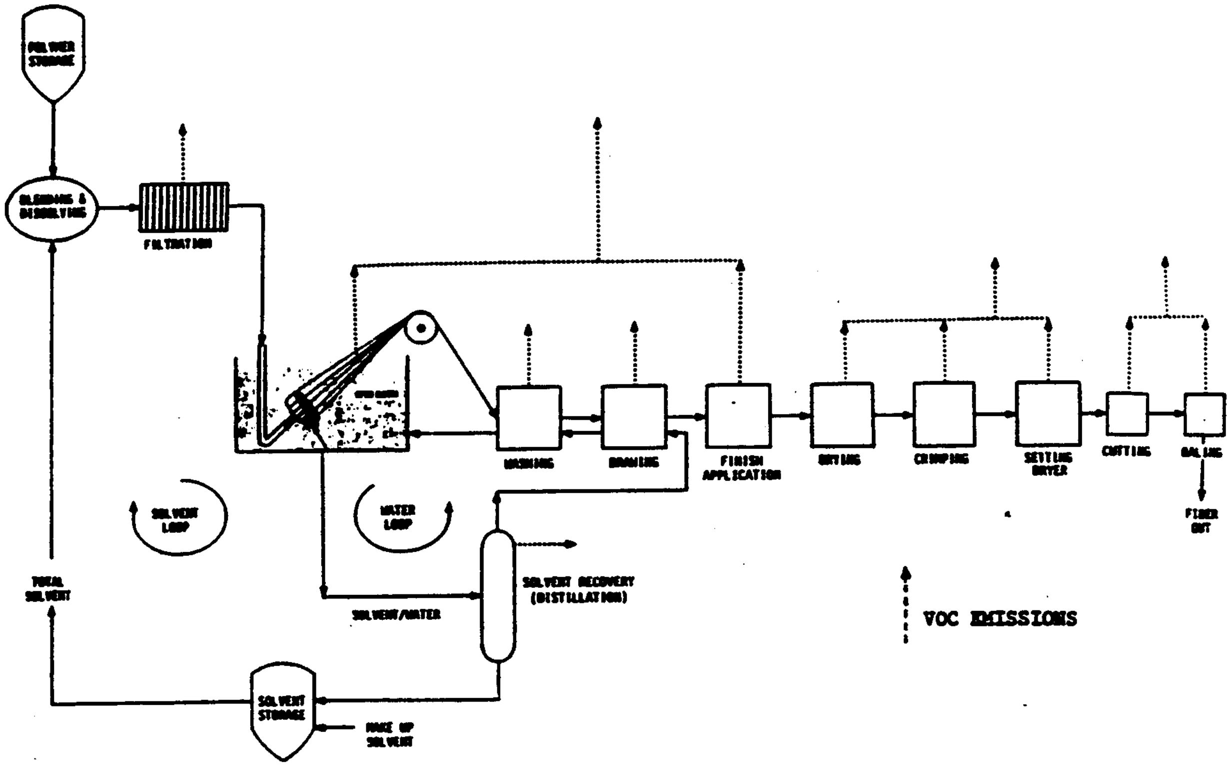

Figure 6.9-8. Acrylic fiber wet spinning.

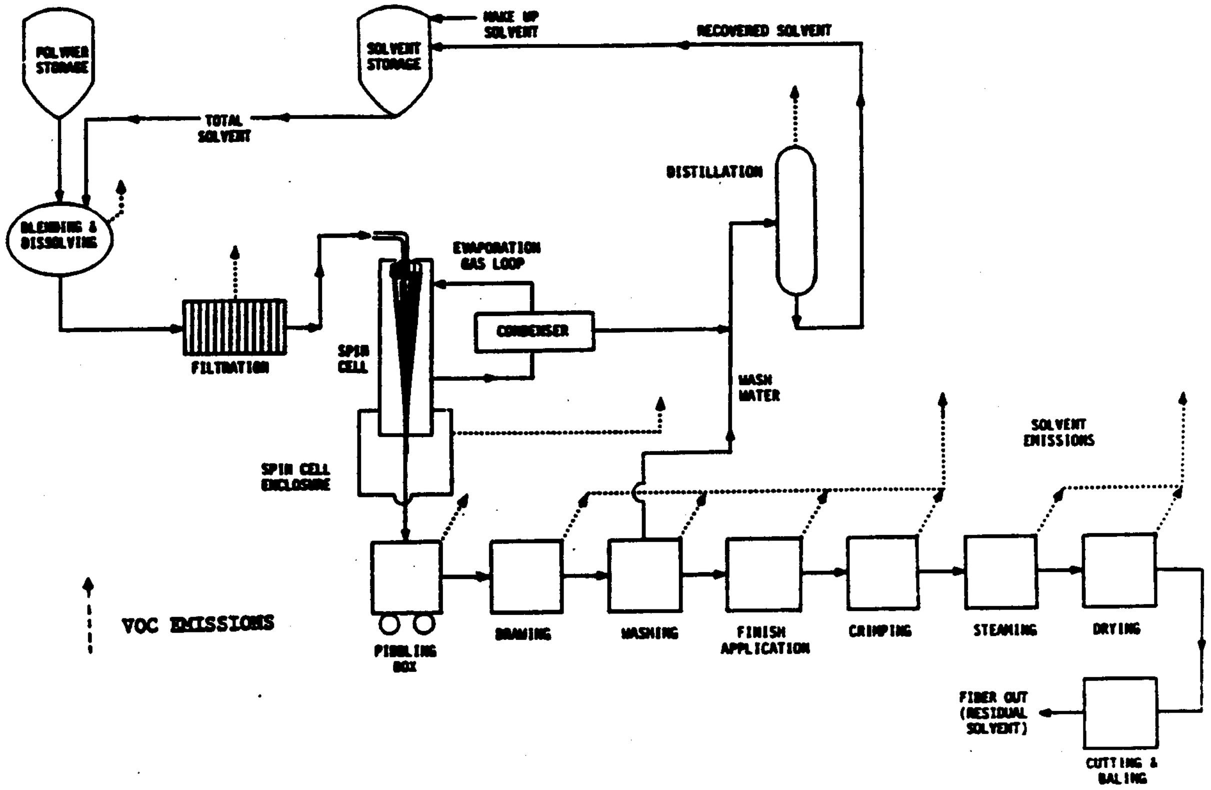

Figure 6.9-9. Acrylic fiber dry spinning.

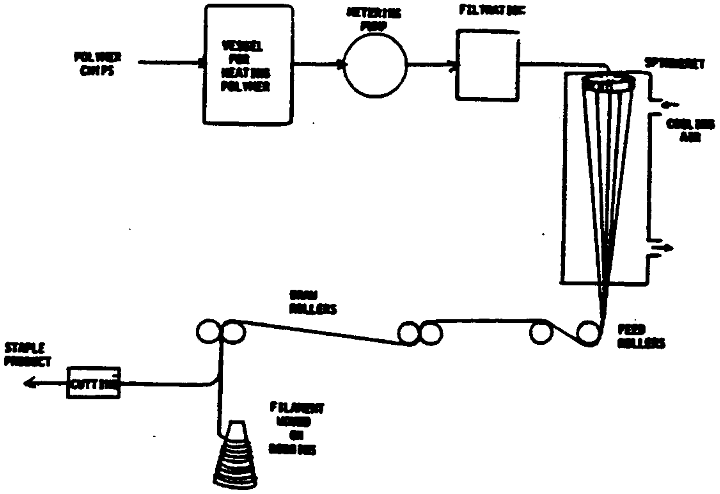

Figure 6.9-10. Nylon production.

fibers during the spinning process are vaporized during post-spinning processes and, in some instances such as the hot drawing of nylon 6, are vented to fabric filters, scrubbers and/or electrostatic precipitators.

6.9.5.4 Polyolefin Fiber Process Description[2,5,28-30] -

Polyolefin fibers are molecularly oriented extrusions of highly crystalline olefinic polymers, predominantly polypropylene. Melt spinning of polypropylene is the method of choice because the high degree of polymerization makes wet spinning or dissolving of the polymer difficult. The fiber spinning and processing procedures are generally the same as described earlier for melt spinning. Polypropylene is also manufactured by the split film process in which it is extruded as a film and then stretched and split into flat filaments, or narrow tapes, that are twisted or wound into a fiber. Some fibers are manufactured as a combination of nylon and polyolefin polymers being melted together in a ratio of about 20 percent nylon 6 and 80 percent polyolefin such as polypropylene, and being spun from this melt. Polypropylene is processed more like nylon 6 than nylon 66 because of the lower melting point of 203°C (397°F) for nylon 6 versus 263°C (505°F) for nylon 66. The polyolefin fiber production process is shown in Figure 6.9-11.

Emissions And Controls -

Limited information is available on emissions from the actual spinning or processing of polyolefin fibers. The available data quantify and describe the emissions from the extruder/pelletizer stage, the last stage of polymer manufacture, and from just before the melting of the polymer for spinning. VOC content of the dried polymer after extruding and pelletizing was found to be as much as 0.5 weight percent. Assuming the content is as high as 0.5 percent and that all this VOC is lost in the extrusion and processing of the fiber (melting, spinning, drawing, winding, etc.), there would be 5 pounds of VOC emissions per 1,000 pounds of polyolefin fiber. The VOCs in the dried polymer are hexane, propane, and methanol, and the approximate proportions are 1.6 pounds of hexane, 1.6 pounds of propane, and 1.8 pounds of methanol.

During processing, lubricant and finish oils are added to the fiber, and some of these additives are driven off in the form of aerosols during processing. No specific information has been obtained

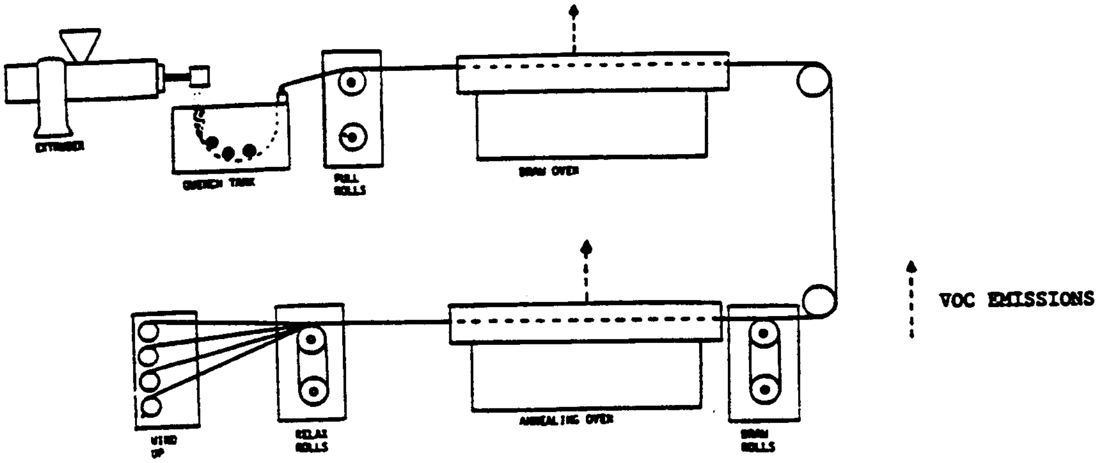

Figure 6.9-11. Polyolefin fiber production.

to describe the oil aerosol emissions for polyolefin processing, but certain assumptions may be made to provide reasonably accurate values. Because polyolefins are melt spun similarly to other melt spun fibers (nylon 6, nylon 66, polyester, etc.), a fiber similar to the polyolefins would exhibit similar emissions. Processing temperatures are similar for polyolefins and nylon 6. Thus, aerosol emission values for nylon 6 can be assumed valid for polyolefins.

6.9.5.5 Spandex Fiber Manufacturing Process Description[5,31-33] -

Spandex is a generic name for a polyurethane fiber in which the fiber-forming substance is a long chain of synthetic polymer comprised of at least 85 percent of a segmented polyurethane. In between the urethane groups, there are long chains that may be polyglycols, polyesters, or polyamides. Being spun from a polyurethane (a rubber-like material), spandex fibers are elastomeric, that is, they stretch. Spandex fibers are used in such stretch fabrics as belts, foundation garments, surgical stockings, and stocking tops.

Spandex is produced by 2 different processes in the United States. One process is similar in some respects to that used for acetate textile yarn, in that the fiber is dry spun, immediately wound onto takeup bobbins, and then twisted or processed in other ways. This process is referred to as dry spinning. The other process, which uses reaction spinning, is substantially different from any other fiber forming process used by domestic synthetic fiber producers.

6.9.5.6 Spandex Dry Spun Process Description -

This manufacturing process, which is illustrated in Figure 6.9-12, is characterized by use of solution polymerization and dry spinning with an organic solvent. Tetrahydrofuran is the principal raw material. The compound's molecular ring structure is opened, and the resulting straight chain compound is polymerized to give a low molecular weight polymer. This polymer is then treated with an excess of a di-isocyanate. The reactant, with any unreacted di-isocyanate, is next reacted with some diamine, with monoamine added as a stabilizer. This final polymerization stage is carried out in dimethylformamide solution, and then the spandex is dry spun from this solution. Immediately after spinning, spandex yarn is wound onto a bobbin as continuous filament yarn. This yarn is later transferred to large spools for shipment or for further processing in another part of the plant.

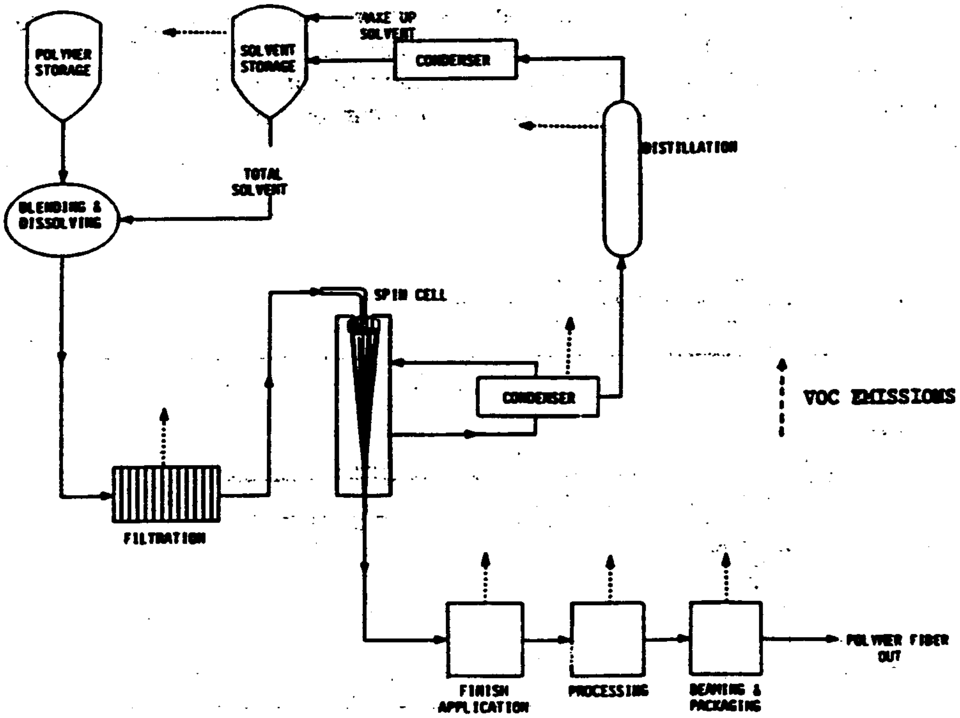

Figure 6.9-12. Spandex dry spinning.

Emissions And Controls -

The major emissions from the spandex dry spinning process are volatilized solvent losses, which occur at a number of points of production. Solvent emissions occur during filtering of the spin dope, spinning of the fiber, treatment of the fiber after spinning, and the solvent recovery process. The emission points from this process are also shown in Figure 6.9-12.

Total emissions from spandex fiber dry spinning are considerably lower than from other dry spinning processes. It appears that the single most influencing factor that accounts for the lower emissions is that, because of nature of the polymeric material and/or spinning conditions, the amount of residual solvent in the fiber as it leaves the spin cell is considerably lower than other dry spun fibers. This situation may be because of the lower solvent/polymer ratio that is used in spandex dry spinning. Less solvent is used for each unit of fiber produced relative to other fibers. A condensation system is used to recover solvent emissions from the spin cell exhaust gas. Recovery of solvent emissions from this process is as high as 99 percent. Since the residual solvent in the fiber leaving the spin cell is much lower than for other fiber types, the potential for economic capture and recovery is also much lower. Therefore, these post-spinning emissions, which are small, are not controlled.

6.9.5.7 Spandex Reaction Spun Process Description -

In the reaction spun process, a polyol (typically polyester) is reacted with an excess of di-isocynate to form the urethane prepolymer, which is pumped through spinnerettes at a constant rate into a bath of dilute solution of ethylenediamine in toluene. The ethylenediamine reacts with isocyanate end groups on the resin to form long-chain cross-linked polyurethane elastomeric fiber. The final cross-linking reaction takes place after the fiber has been spun. The fiber is transported from the bath to an oven, where solvent is evaporated. After drying, the fiber is lubricated and is wound on tubes for shipment.

Emissions And Controls -

Essentially all air that enters the spinning room is drawn into the hooding that surrounds the process equipment and then leads to a carbon adsorption system (see Figure 6.9-13). The oven is also vented to the carbon adsorber. The gas streams from the spinning room and oven are combined and cooled in a heat exchanger before they enter the activated carbon bed.

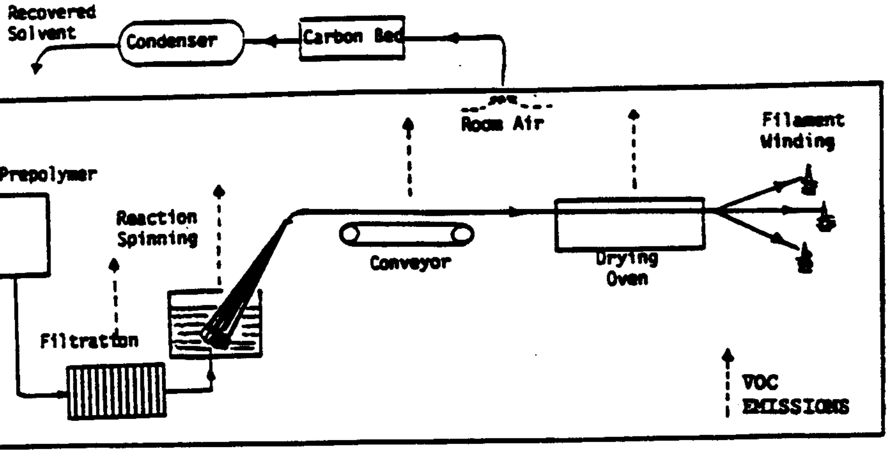

Figure 6.9-13. Spandex reaction spinning.

6.9.5.8 Vinyon Fiber Process Description[5,34] -

Vinyon is a copolymer of vinyl chloride (88 percent) and vinyl acetate (12 percent). The polymer is dissolved in a ketone (acetone or methyl ethyl ketone) to make a 23 weight percent spinning solution. After filtering, the solution is extruded as filaments into warm air to evaporate the solvent and to allow its recovery and reuse. The spinning process is similar to that of cellulose acetate. After spinning, the filaments are stretched to achieve molecular orientation to impart strength.

Emissions And Controls -

Emissions occur at steps similar to those of cellulose acetate, at dope preparation and spinning, and as fugitive emissions from the spun fiber during processes such as winding and stretching. The major source of VOCs is the spinning step, where the warm air stream evaporates the solvent. This air/solvent stream is sent to either a scrubber or carbon adsorber for solvent recovery. Emissions may also occur at the exhausts from these control devices.

6.9.5.9 Other Fibers -

There are synthetic fibers manufactured on a small volume scale relative to the commodity fibers. Because of the wide variety of these fiber manufacturing processes, specific products and processes are not discussed. Table 6.9-3 lists some of these fibers and the respective producers.

Table 6.9-3. OTHER SYNTHETIC FIBERS AND THEIR MAKERS

Fiber	Manufacturer
Nomex (aramid)	DuPont
Kevlar (aramid)	DuPont
PBI (polybenzimidazole)	Celanese
Kynol (novoloid)	Carborundum
Teflon	DuPont

GLOSSARY

Crimping:	A process in which waves and angles are set into fibers, such as acrylic fiber filaments, to help simulate properties of natural fibers.
Coagulant:	A substance, either a salt or an acid, used to precipitate polymer solids out of emulsions or latexes.
Continuous filament yarn:	Very long fibers that have been converged to form a multifiber yarn, typically consisting of 15 to 100 filaments.
Cutting:	Refers to the conversion of tow to staple fiber.
Delusterant:	Fiber finishing additives (typically clays or barium sulfate) used to dull the surfaces of the fibers.
Dope:	The polymer, either in molten form or dissolved in solvent, that is spun into fiber.
Drawing:	The stretching of the filaments in order to increase the fiber's strength; also makes the fiber more supple and unshrinkable (that is, the stretch is irreversible). The degree of stretching varies with the yarn being spun.
Filament:	The solidified polymer that has emerged from a single hole or orifice in a spinnerette.
Filament yarn:	See continuous filament yarn.
Heat setting:	The dimensional stabilization of the fibers with heat so that the fibers are completely undisturbed by subsequent treatments such as washing or dry cleaning at a lower temperature. To illustrate, heat setting allows a pleat to be retained in the fabric while helping prevent undesirable creases later in the life of the fabric.
Lubrication:	The application of oils or similar substances to the fibers in order, for example, to facilitate subsequent handling of the fibers and to provide static suppression.

Spinnerette:	A spinnerette is used in the production of all man-made fiber whereby liquid is forced through holes. Filaments emerging from the holes are hardened and solidified. The process of extrusion and hardening is called spinning.
Spun yarn:	Yarn made from staple fibers that have been twisted or spun together into a continuous strand.
Staple:	Lengths of fiber made by cutting man-made fiber tow into short (1- to 6-inch) and usually uniform lengths, which are subsequently twisted into spun yarn.
Tow:	A collection of many (often thousands) parallel, continuous filaments, without twist, that are grouped together in a rope-like form having a diameter of about one-quarter inch.
Twisting:	Giving the filaments in a yarn a very slight twist that prevents the fibers from sliding over each other when pulled, thus increasing the strength of the yarn.

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6.10 Synthetic Rubber

6.10.1 Emulsion Styrene-Butadiene Copolymers

6.10.1.1 General -

Two types of polymerization reaction are used to produce styrene-butadiene copolymers, the emulsion type and the solution type. This section addresses volatile organic compound (VOC) emissions from the manufacture of copolymers of styrene and butadiene made by emulsion polymerization processes. The emulsion products can be sold in either a granular solid form, known as crumb, or in a liquid form, known as latex.

Copolymers of styrene and butadiene can be made with properties ranging from those of a rubbery material to those of a very resilient plastic. Copolymers containing less than 45 weight percent styrene are known as styrene-butadiene rubber (SBR). As the styrene content is increased over 45 weight percent, the product becomes increasingly more plastic.

6.10.1.2 Emulsion Crumb Process -

As shown in Figure 6.10-1, fresh styrene and butadiene are piped separately to the manufacturing plant from the storage area. Polymerization of styrene and butadiene proceeds continuously through a train of reactors, with a residence time in each reactor of approximately 1 hour. The reaction product formed in the emulsion phase of the reaction mixture is a milky white emulsion called latex. The overall polymerization reaction ordinarily is not carried out beyond a 60 percent conversion of monomers to polymer, because the reaction rate falls off considerably beyond this point and product quality begins to deteriorate.

Because recovery of the unreacted monomers and their subsequent purification are essential to economical operation, unreacted butadiene and styrene from the emulsion crumb polymerization process normally are recovered. The latex emulsion is introduced to flash tanks where, using vacuum flashing, the unreacted butadiene is removed. The butadiene is then compressed, condensed, and pumped back to the tank farm storage area for subsequent reuse. The condenser tail gases and noncondensables pass through a butadiene adsorber/desorber unit, where more butadiene is recovered. Some noncondensables and VOC vapors pass to the atmosphere or, at some plants, to a flare system. The latex stream from the butadiene recovery area is then sent to the styrene recovery process, usually taking place in perforated plate steam stripping columns. From the styrene stripper, the latex is stored in blend tanks.

From this point in the manufacturing process, latex is processed continuously. The latex is pumped from the blend tanks to coagulation vessels, where dilute sulfuric acid (H_2SO_4 of pH 4 to 4.5) and sodium chloride solution are added. The acid and brine mixture causes the emulsion to break, releasing the styrene-butadiene copolymer as crumb product. The coagulation vessels are open to the atmosphere.

Leaving the coagulation process, the crumb and brine acid slurry is separated by screens into solid and liquid. The crumb product is processed in rotary presses that squeeze out most of the entrained water. The liquid (brine/acid) from the screening area and the rotary presses is cycled to the coagulation area for reuse.

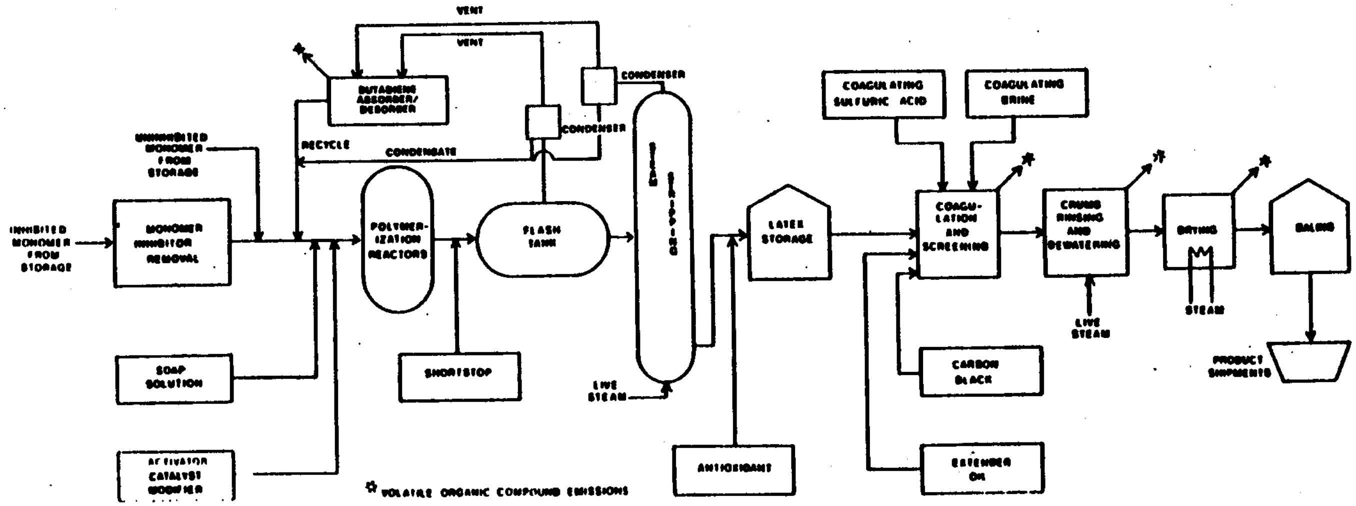


Figure 6.10-1. Typical process for crumb production by emulsion polymerization.

The partially dried crumb is then processed in a continuous belt dryer that blows hot air at approximately 93°C (200°F) across the crumb to complete the drying of the product. Some plants have installed single-pass dryers, where space permits, but most plants still use the triple-pass dryers, which were installed as original equipment in the 1940s. The dried product is baled and weighed before shipment.

6.10.1.3 Emulsion Latex Process -

Emulsion polymerization can also be used to produce latex products. These latex products have a wider range of properties and uses than do the crumb products, but the plants are usually much smaller. Latex production, shown in Figure 6.10-2, follows the same basic processing steps as emulsion crumb polymerization, with the exception of final product processing.

As in emulsion crumb polymerization, the monomers are piped to the processing plant from the storage area. The polymerization reaction is taken to near completion (98 to 99 percent conversion), and the recovery of unreacted monomers is therefore uneconomical. Process economy is directed towards maximum conversion of the monomers in one process trip.

Because most emulsion latex polymerization is done in a batch process, the number of reactors used for latex production is usually smaller than for crumb production. The latex is sent to a blowdown tank where, under vacuum, any unreacted butadiene and some unreacted styrene are removed from the latex. If the unreacted styrene content of the latex has not been reduced sufficiently to meet product specifications in the blowdown step, the latex is introduced to a series of steam stripping steps to reduce the content further. Any steam and styrene vapor from these stripping steps is taken overhead and is sent to a water-cooled condenser. Any uncondensables leaving the condenser are vented to the atmosphere.

After discharge from the blowdown tank or the styrene stripper, the latex is stored in process tanks. Stripped latex is passed through a series of screen filters to remove unwanted solids and is stored in blending tanks, where antioxidants are added and mixed. Finally, latex is pumped from the blending tanks to be packaged into drums or to be bulk loaded into railcars or tank trucks.

6.10.2 Emissions And Controls

Emission factors for emulsion styrene-butadiene copolymer production processes are presented in Table 6.10-1.

In the emulsion crumb process, uncontrolled noncondensed tail gases (VOCs) pass through a butadiene absorber control device, which is 90 percent efficient, to the atmosphere or, in some plants, to a flare stack.

No controls are presently employed for the blend tank and/or coagulation tank areas, on either crumb or latex facilities. Emissions from dryers in the crumb process and the monomer removal part of the latex process do not employ control devices.

Individual plant emissions may vary from the average values listed in Table 6.10-1 with facility age, size, and plant modification factors.

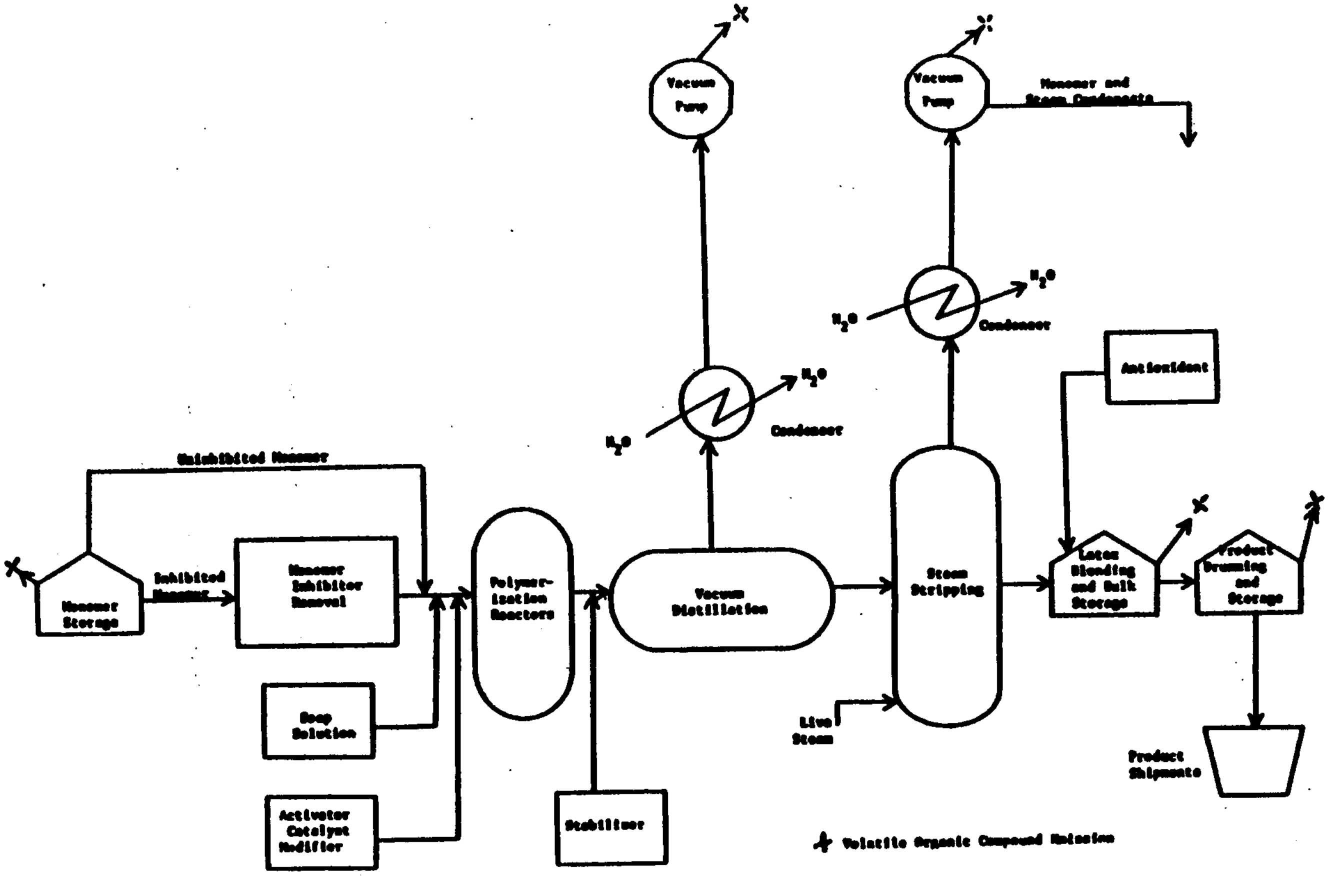


Figure 6.10-2. Typical process for latex production by emulsion polymerization.

Table 6.10-1 (Metric And English Units). EMISSION FACTORS FOR EMULSION STYRENE-BUTADIENE COPOLYMER PRODUCTION[a]

EMISSION FACTOR RATING: B

Process	Volatile Organic Emissions[b]	
	g/kg	lb/ton
Emulsion Crumb		
Monomer recovery, uncontrolled[c]	2.6	5.2
Absorber vent	0.26	0.52
Blend/coagulation tank, uncontrolled[d]	0.42	0.84
Dryers[e]	2.51	5.02
Emulsion Latex		
Monomer removal condenser vent[f]	8.45	16.9
Blend tanks, uncontrolled[f]	0.1	0.2

[a] Nonmethane VOC, mainly styrene and butadiene. For emulsion crumb and emulsion latex processes only. Factors for related equipment and operations (storage, fugitives, boilers, etc.) are presented in other sections of AP-42.

[b] Expressed as units per unit of copolymer produced.

[c] Average of 3 industry-supplied stack tests.

[d] Average of 1 industry stack test and 2 industry-supplied emission estimates.

[e] No controls available. Average of 3 industry-supplied stack tests and 1 industry estimate.

[f] EPA estimates from industry supplied data, confirmed by industry.

References For Section 6.10

1. *Control Techniques Guideline* (Draft), EPA Contract No. 68-02-3168, GCA, Inc., Chapel Hill, NC, April 1981.

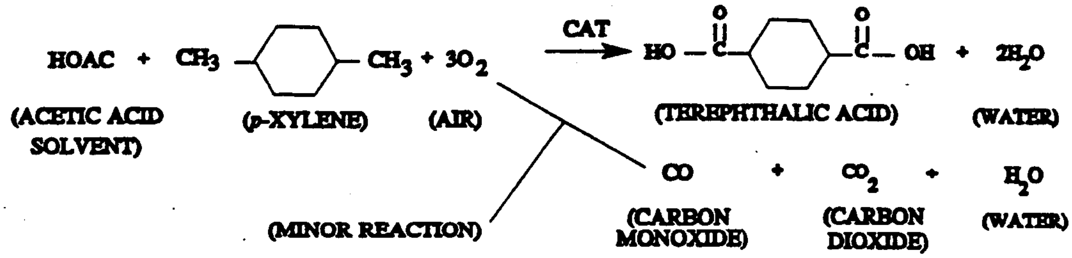
2. *Emulsion Styrene-Butadiene Copolymers: Background Document*, EPA Contract No. 68-02-3063, TRW Inc., Research Triangle Park, NC, May 1981.

3. Confidential written communication from C. Fabian, U. S. Environmental Protection Agency, Research Triangle Park, NC, to Styrene-Butadiene Rubber File (76/15B), July 16, 1981.

6.11 Terephthalic Acid

6.11.1 Process Description[1]

Terephthalic acid (TPA) is made by air oxidation of *p*-xylene and requires purification for use in polyester fiber manufacture. A typical continuous process for the manufacture of crude terephthalic acid (C-TPA) is shown in Figure 6.11-1. The oxidation and product recovery portion essentially consists of the Mid-Century oxidation process, whereas the recovery and recycle of acetic acid and recovery of methyl acetate are essentially as practiced by dimethyl terephthalate (DMT) technology. The purpose of the DMT process is to convert the terephthalic acid contained in C-TPA to a form that will permit its separation from impurities. C-TPA is extremely insoluble in both water and most common organic solvents. Additionally, it does not melt, it sublimes. Some products of partial oxidation of *p*-xylene, such as *p*-toluic acid and *p*-formyl benzoic acid, appear as impurities in TPA. Methyl acetate is also formed in significant amounts in the reaction.



6.11.1.1 C-TPA Production -

Oxidation Of *p*-Xylene -

p-Xylene (stream 1 of Figure 6.11-1), fresh acetic acid (2), a catalyst system such as manganese or cobalt acetate and sodium bromide (3), and recovered acetic acid are combined into the liquid feed entering the reactor (5). Air (6), compressed to a reaction pressure of about 2000 kPa (290 psi), is fed to the reactor. The temperature of the exothermic reaction is maintained at about 200°C (392°F) by controlling the pressure at which the reaction mixture is permitted to boil and form the vapor stream leaving the reactor (7).

Inert gases, excess oxygen, CO, CO_2, and volatile organic compounds (VOC) (8) leave the gas/liquid separator and are sent to the high-pressure absorber. This stream is scrubbed with water under pressure, resulting in a gas stream (9) of reduced VOC content. Part of the discharge from the high-pressure absorber is dried and is used as a source of inert gas (IG), and the remainder is passed through a pressure control valve and a noise silencer before being discharged to the atmosphere through process vent A. The underflow (23) from the absorber is sent to the azeotrope still for recovery of acetic acid.

Crystallization And Separation -

The reactor liquid containing TPA (10) flows to a series of crystallizers, where the pressure is relieved and the liquid is cooled by the vaporization and return of condensed VOC and water. The partially oxidized impurities are more soluble in acetic acid and tend to remain in solution, while TPA crystallizes from the liquor. The inert gas that was dissolved and entrained in the liquid under pressure is released when the pressure is relieved and is subsequently vented to the atmosphere along

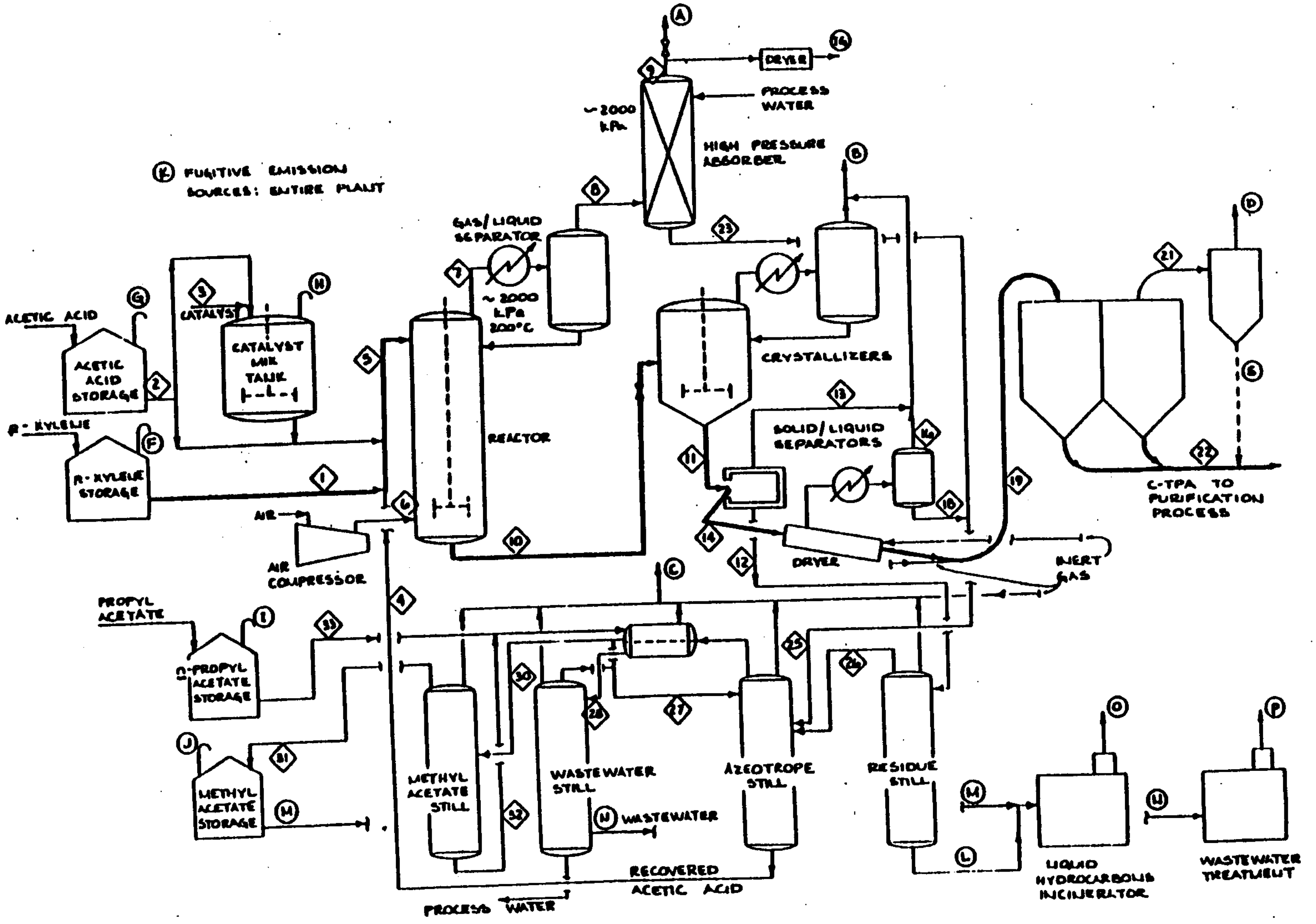


Figure 6.11-1. Crude terephthalic acid process.

with the contained VOC (B). The slurry (11) from the crystallizers is sent to solid/liquid separators, where the TPA is recovered as a wet cake (14). The mother liquor (12) from the solid/liquid separators is sent to the distillation section, while the vent gas (13) is discharged to the atmosphere (B).

Drying, Handling And Storage -

The wet cake (14) from solid/liquid separation is sent to dryers, where with the use of heat and IG, the moisture, predominately acetic acid, is removed leaving the product, C-TPA, as dry free-flowing crystals (19). IG is used to convey the product (19) to storage silos. The transporting gas (21) is vented from the silos to bag dust collectors to reduce its particulate loading, then is discharged to the atmosphere (D). The solids (S) from the bag filter can be forwarded to purification or can be incinerated.

Hot VOC-laden IG from the drying operation is cooled to condense and recover VOC (18). The cooled IG (16) is vented to the atmosphere (B), and the condensate (stream 18) is sent to the azeotrope still for recovery of acetic acid.

Distillation And Recovery -

The mother liquor (12) from solid/liquid separation flows to the residue still, where acetic acid, methyl acetate, and water are recovered overhead (26) and product residues are discarded. The overhead (26) is sent to the azeotrope still where dry acetic acid is obtained by using *n*-propyl acetate as the water-removing agent.

The aqueous phase (28) contains saturation amounts of *n*-propyl acetate and methyl acetate, which are stripped from the aqueous matter in the waste water still. Part of the bottoms product is used as process water in absorption, and the remainder (N) is sent to waste water treatment. A purge stream of the organic phase (30) goes to the methyl acetate still, where methyl acetate and saturation amounts of water are recovered as an overhead product (31) and are disposed of as a fuel (M). *n*-Propyl acetate, obtained as the bottoms product (32), is returned to the azeotrope still. Process losses of *n*-propyl acetate are made up from storage (33). A small amount of inert gas, which is used for blanketing and instrument purging, is emitted to the atmosphere through vent C.

6.11.1.2 C-TPA Purification -

The purification portion of the Mid-Century oxidation process involves the hydrogenation of C-TPA over a palladium-containing catalyst at about 232°C (450°F). High-purity TPA is recrystallized from a high-pressure water solution of the hydrogenated material.

The Olin-Mathieson manufacturing process is similar to the Mid-Century process except the former uses 95 percent oxygen, rather than air, as the oxidizing agent. The final purification step consists essentially of a continuous sublimation and condensation procedure. The C-TPA is combined with small quantities of hydrogen and a solid catalyst, dispersed in steam, and transported to a furnace. There the C-TPA is vaporized and certain of the contained impurities are catalytically destroyed. Catalyst and nonvolatile impurities are removed in a series of filters, after which the pure TPA is condensed and transported to storage silos.

6.11.2 Emissions And Controls[1-3]

A general characterization of the atmospheric emissions from the production of C-TPA is difficult because of the variety of processes. Emissions vary considerably, both qualitatively and quantitatively. The Mid-Century oxidation process appears to be one of the lowest polluters, and its predicted preeminence will suppress future emissions totals.

The reactor gas at vent A normally contains nitrogen (from air oxidation); unreacted oxygen; unreacted *p*-xylene; acetic acid (reaction solvent); carbon monoxide, carbon dioxide, and methyl acetate from oxidation of *p*-xylene and acetic acid not recovered by the high-pressure absorber; and water. The quantity of VOC emitted at vent A can vary with absorber pressure and the temperature of exiting vent gases. During crystallization of TPA and separation of crystallized solids from the solvent (by centrifuge or filters), noncondensable gases carrying VOC are released. These vented gases and the C-TPA dryer vent gas are combined and released to the atmosphere at vent B. Different methods used in this process can affect the amounts of noncondensable gases and accompanying VOCs emitted from this vent.

Gases released from the distillation section at vent C are the small amount of gases dissolved in the feed stream to distillation; the IG used in inert blanketing, instrument purging pressure control; and the VOC vapors carried by the noncondensable gases. The quantity of this discharge is usually small.

The gas vented from the bag filters on the product storage tanks (silos) (D) is dry, reaction-generated IG containing the VOC not absorbed in the high-pressure absorber. The vented gas stream contains a small quantity of TPA particulate that is not removed by the bag filters.

Performance of carbon adsorption control technology for a VOC gas stream similar to the reactor vent gas (A) and product transfer vent gas (D) has been demonstrated, but CO emissions will not be reduced. An alternative to the carbon adsorption system is a thermal oxidizer that provides reduction of both CO and VOC.

Emission sources and factors for the C-TPA process are presented in Table 6.11-1.

Table 6.11-1 (Metric Units). UNCONTROLLED EMISSION FACTORS FOR CRUDE TEREPHTHALIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: C

Emission Source	Stream Designation (Figure 6.11-1)	Emissions (g/kg)	
		Nonmethane VOC[b,c]	CO[c]
Reactor vent	A	15	17
Crystallization, separation, drying vent	B	1.9	NA
Distillation and recovery vent	C	1.1	NA
Product transfer vent[d]	D	1.8	2

[a] Factors are expressed as g of pollutant/kg of product produced. NA = not applicable.

[b] Reference 1. VOC gas stream consists of methyl acetate, *p*-xylene, and acetic acid. No methane was found.

[c] Reference 1. Typically, thermal oxidation results in >99% reduction of VOC and CO. Carbon adsorption gives a 97% reduction of VOC only (Reference 1).

[d] Stream contains 0.7 g of TPA particulates/kg. VOC and CO emissions originated in reactor offgas (IG) used for transfer.

References For Section 6.11

1. S. W. Dylewski, *Organic Chemical Manufacturing, Volume 7: Selected Processes*, EPA-450/3-80-028b, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1981.

2. D. F. Durocher, *et al.*, *Screening Study To Determine Need For Standards Of Performance For New Sources Of Dimethyl Terephthalate And Terephthalic Acid Manufacturing*, EPA Contract No. 68-02-1316, Radian Corporation, Austin, TX, July 1976.

3. J. W. Pervier, *et al.*, *Survey Reports On Atmospheric Emissions From The Petrochemical Industry, Volume II*, EPA-450/3-73-005b, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1974.

6.12 Lead Alkyl

6.12.1 Process Description[1]

Two alkyl lead compounds, tetraethyl lead (TEL) and tetramethyl lead (TML), are used as antiknock gasoline additives. Over 75 percent of the 1973 additive production was TEL, more than 90 percent of which was made by alkylation of sodium/lead alloy.

Lead alkyl is produced in autoclaves by the reaction of sodium/lead alloy with an excess of either ethyl (for TEL) or methyl (for TML) chloride in the presence of an acetone catalyst. The reaction mass is distilled to separate the product, which is then purified, filtered, and mixed with chloride/bromide additives. Residue is sluiced to a sludge pit, from which the bottoms are sent to an indirect steam dryer, and the dried sludge is fed to a reverberatory furnace to recover lead.

Gasoline additives are also manufactured by the electrolytic process, in which a solution of ethyl (or methyl) magnesium chloride and ethyl (or methyl) chloride is electrolyzed, with lead metal as the anode.

6.12.2 Emissions And Controls[1]

Lead emissions from the sodium/lead alloy process consist of particulate lead oxide from the recovery furnace (and, to a lesser extent, from the melting furnace and alloy reactor), alkyl lead vapor from process vents, and fugitive emissions from the sludge pit. Lead emission factors for the manufacture of lead alkyl appear in Table 6.12-1. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton).

Emissions from the lead recovery furnace are controlled by fabric filters or wet scrubbers. Vapor streams rich in lead alkyl can either be incinerated and passed through a fabric filter or be scrubbed with water prior to incinerating. Control efficiencies are presented in Table 6.12-2.

Emissions from electrolytic process vents are controlled by using an elevated flare and a liquid incinerator, while a scrubber with toluene as the scrubbing medium controls emissions from the blending and tank car loading/unloading systems.

Table 6.12-1 (Metric And English Units). LEAD ALKYL MANUFACTURE LEAD EMISSION FACTORS[a]

EMISSION FACTOR RATING: B

Process	Lead	
	kg/Mg	lb/ton
Electrolytic[b]	0.5	1.0
Sodium/lead alloy		
Recovery furnace[c]	28	55
Process vents, TEL[d]	2	4
Process vents, TML[d]	75	150
Sludge pits[d]	0.6	1.2

[a] No information on other emissions from lead alkyl manufacturing is available. Emission factors are expressed as weight per unit weight of product.

[b] References 1-3.

[c] References 1-2,4.

[d] Reference 1.

Table 6.12-2. LEAD ALKYL MANUFACTURE CONTROL EFFICIENCIES[a]

Process	Control	Percent Reduction
Sodium/lead alloy	Fabric filter	99+
	Low energy wet scrubber	80 - 85
	High energy wet scrubber	95 - 99

[a] Reference 1.

References For Section 6.12

1. *Background Information In Support Of The Development Of Performance Standards For The Lead Additive Industry*, EPA Contract No. 68-02-2085, PEDCo-Environmental Specialists, Inc., Cincinnati, OH, January 1976.

2. *Control Techniques For Lead Air Emissions*, EPA-450/2-77-012, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1977.

3. W. E. Davis, *Emissions Study Of Industrial Sources Of Lead Air Pollutants, 1970*, EPA Contract No. 68-02-0271, U. E. Davis and Associates, Leawood, KS, April 1973.

4. R. P. Betz, *et al.*, *Economics Of Lead Removal In Selected Industries*, EPA Contract No. 68-02-0611, Batelle Columbus Laboratories, Columbus, OH, August 1973.

6.13 Pharmaceuticals Production

6.13.1 Process Description

Thousands of individual products are categorized as pharmaceuticals. These products usually are produced in modest quantities in relatively small plants using batch processes. A typical pharmaceutical plant will use the same equipment to make several different products at different times. Rarely is equipment dedicated to the manufacture of a single product.

Organic chemicals are used as raw materials and as solvents, and some chemicals such as ethanol, acetone, isopropanol, and acetic anhydride are used in both ways. Solvents are almost always recovered and used many times.

In a typical batch process, solid reactants and solvent are charged to a reactor where they are held (and usually heated) until the desired product is formed. The solvent is distilled off, and the crude residue may be treated several times with additional solvents to purify it. The purified material is separated from the remaining solvent by centrifuge and finally is dried to remove the last traces of solvent. As a rule, solvent recovery is practiced for each step in the process where it is convenient and cost effective to do so. Some operations involve very small solvent losses, and the vapors are vented to the atmosphere through a fume hood. Generally, all operations are carried out inside buildings, so some vapors may be exhausted through the building ventilation system.

Certain pharmaceuticals — especially antibiotics — are produced by fermentation processes. In these instances, the reactor contains an aqueous nutrient mixture with living organisms such as fungi or bacteria. The crude antibiotic is recovered by solvent extraction and is purified by essentially the same methods described above for chemically synthesized pharmaceutical. Similarly, other pharmaceuticals are produced by extraction from natural plant or animal sources. The production of insulin from hog or beef pancreas is an example. The processes are not greatly different from those used to isolate antibiotics from fermentation broths.

6.13.2 Emissions And Controls

Emissions consist almost entirely of organic solvents that escape from dryers, reactors, distillation systems, storage tanks, and other operations. These emissions are exclusively nonmethane organic compounds. Emissions of other pollutants are negligible (except for particulates in unusual circumstances) and are not treated here. It is not practical to attempt to evaluate emissions from individual steps in the production process or to associate emissions with individual pieces of equipment because of the great variety of batch operations that may be carried out at a single production plant. It is more reasonable to obtain data on total solvent purchases by a plant and to assume that these represent replacements for solvents lost by evaporation. Estimates can be refined by subtracting the materials that do not enter the air because of being incinerated or incorporated into the pharmaceutical product by chemical reaction.

If plant-specific information is not available, industrywide data may be used instead. Table 6.13-1 lists annual purchases of solvents by U. S. pharmaceutical manufacturers and shows the ultimate disposition of each solvent. Disposal methods vary so widely with the type of solvent that it is not possible to recommend average factors for air emissions from generalized solvents. Specific information for individual solvents must be used. Emissions can be estimated by obtaining

Table 6.13-1. SOLVENT PURCHASES AND ULTIMATE DISPOSITION BY PHARMACEUTICAL MANUFACTURERS[a]

Solvent	Annual Purchase (megagrams)	Ultimate Disposition (%)					Liquid Density lb/gal @ 68°F
		Air Emissions	Sewer	Incineration	Solid Waste or Contract Haul	Product	
Acetic Acid	930	1	82	—	—	17	8.7
Acetic Anhydride	1,265	1	57	—	—	42	9.0
Acetone	12,040	14	22	38	7	19	6.6
Acetonitrile	35	83	17	—	—	—	6.6
Amyl Acetate	285	42	58	—	—	—	7.3
Amyl Alcohol	1,430	99	—	—	—	1	6.8
Benzene	1,010	29	37	16	8	10	7.3
Blendan (AMOCO)	530	—	—	—	—	100	NA
Butanol	320	24	8	1	36	31	6.8
Carbon Tetrachloride	1,850	11	7	82	—	—	13.3
Chloroform	500	57	5	—	38	—	12.5
Cyclohexylamine	3,930	—	—	—	—	100	7.2
o-Dichlorobenzene	60	2	98	—	—	—	10.9
Diethylamine	50	94	6	—	—	—	5.9
Diethyl Carbonate	30	4	71	—	—	25	8.1
Dimethyl Acetamide	95	7	—	—	93	—	7.9
Dimethyl Formamide	1,630	71	3	20	6	—	7.9

Table 6.13-1 (cont.).

Solvent	Annual Purchase (megagrams)	Ultimate Disposition (%)					Liquid Density lb/gal @ 68°F
		Air Emissions	Sewer	Incineration	Solid Waste or Contract Haul	Product	
Dimethylsulfoxide	750	1	28	71	—	—	11.1
1,4-Dioxane	43	5	—	—	95	—	8.6
Ethanol	13,230	10	6	7	1	76	6.6
Ethyl Acetate	2,380	30	47	20	3	—	7.5
Ethyl Bromide	45	—	100	—	—	—	12.1
Ethylene Glycol	60	—	100	—	—	—	9.3
Ethyl Ether	280	85	4	—	11	—	6.0
Formaldehyde	30	19	77	—	—	4	—[b]
Formamide	440	—	67	—	26	7	9.5
Freons	7,150	0.1	—	—	—	99.9	—[c]
Hexane	530	17	—	15	68	—	5.5
Isobutyraldehyde	85	50	50	—	—	—	6.6
Isopropanol	3,850	14	17	17	7	45	6.6
Isopropyl Acetate	480	28	11	61	—	—	7.3
Isopropyl Ether	25	50	50	—	—	—	6.0
Methanol	7,960	31	45	14	6	4	6.6
Methyl Cellosolve	195	47	53	—	—	—	8.7

Table 6.13-1 (cont.).

Solvent	Annual Purchase (megagrams)	Ultimate Disposition (%)					Liquid Density lb/gal @ 68°F
		Air Emissions	Sewer	Incineration	Solid Waste or Contract Haul	Product	
Methylene Chloride	10,000	53	5	20	22	—	11.1
Methyl Ethyl Ketone	260	65	12	23	—	—	6.7
Methyl Formate	415	—	74	—	12	14	8.2
Methyl Isobutyl Ketone	260	80	—	—	—	20	6.7
Polyethylene Glycol 600	3	—	—	—	—	100	9.5
Pyridine	3	—	100	—	—	—	8.2
Skelly Solvent B (hexanes)	1,410	29	2	69	—	—	5.6
Tetrahydrofuran	4	—	—	100	—	—	7.4
Toluene	6,010	31	14	26	29	—	7.2
Trichloroethane	135	100	—	—	—	—	11.3
Xylene	3,090	6	19	70	5	—	7.2

[a] These data were reported by 26 member companies of the Pharmaceutical Manufacturers Association, accounting for 53% of pharmaceutical sales in 1975.

[b] Sold as aqueous solutions containing 37% to 50% formaldehyde by weight.

[c] Some Freons are gases, and others are liquids weighing 12-14 lb/gal.

plant-specific data on purchases of individual solvents and computing the quantity of each solvent that evaporates into the air, either from information in Table 6.13-1 or from information obtained for the specific plant under consideration. If solvent volumes are given, rather than weights, liquid densities in Table 6.13-1 can be used to compute weights.

Table 6.13-1 gives for each plant the percentage of each solvent that is evaporated into the air and the percentage that is flushed into the sewer. Ultimately, much of the volatile material from the sewer will evaporate and will reach the air somewhere other than the pharmaceutical plant. Thus, for certain applications it may be appropriate to include both the air emissions and the sewer disposal in an emissions inventory that covers a broad geographic area.

Since solvents are expensive and must be recovered and reused for economic reasons, solvent emissions are controlled as part of the normal operating procedures in a pharmaceutical industry. In addition, most manufacturing is carried out inside buildings, where solvent losses must be minimized to protect the health of the workers. Water- or brine-cooled condensers are the most common control devices, with carbon adsorbers in occasional use. With each of these methods, solvent can be recovered. Where the main objective is not solvent reuse but is the control of an odorous or toxic vapor, scrubbers or incinerators are used. These control systems are usually designed to remove a specific chemical vapor and will be used only when a batch of the corresponding drug is being produced. Usually, solvents are not recovered from scrubbers and reused and, of course, no solvent recovery is possible from an incinerator.

It is difficult to make a quantitative estimate of the efficiency of each control method because it depends on the process being controlled, and pharmaceutical manufacture involves hundreds of different processes. Incinerators, carbon adsorbers, and scrubbers have been reported to remove greater than 90 percent of the organics in the control equipment inlet stream. Condensers are limited in that they can only reduce the concentration in the gas stream to saturation at the condenser temperature, but not below that level. Lowering the temperature will, of course, lower the concentration at saturation, but it is not possible to operate at a temperature below the freezing point of one of the components of the gas stream.

Reference For Section 6.13

1. *Control Of Volatile Organic Emissions From Manufacture Of Synthesized Pharmaceutical Products*, EPA-450/2-78-029, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1978.

6.14 Maleic Anhydride

6.14.1 General[1]

The dominant end use of maleic anhydride (MA) is in the production of unsaturated polyester resins. These laminating resins, which have high structural strength and good dielectric properties, have a variety of applications in automobile bodies, building panels, molded boats, chemical storage tanks, lightweight pipe, machinery housings, furniture, radar domes, luggage, and bathtubs. Other end products are fumaric acid, agricultural chemicals, alkyd resins, lubricants, copolymers, plastics, succinic acid, surface active agents, and more. In the United States, one plant uses only n-butane and another uses n-butane for 20 percent of its feedstock, but the primary raw material used in the production of MA is benzene. The MA industry is converting old benzene plants and building new plants to use n-butane. MA also is a byproduct of the production of phthalic anhydride. It is a solid at room temperature but is a liquid or gas during production. It is a strong irritant to skin, eyes, and mucous membranes of the upper respiratory system.

The model MA plant, as described in this section, has a benzene-to-MA conversion rate of 94.5 percent, has a capacity of 22,700 megagrams (Mg) (25,000 tons) of MA produced per year, and runs 8000 hours per year.

Because of a lack of data on the n-butane process, this discussion covers only the benzene oxidation process.

6.14.2 Process Description[2]

Maleic anhydride is produced by the controlled air oxidation of benzene, illustrated by the following chemical reaction:

$$2\ C_6H_6 \quad + \quad 9\ O_2 \quad \xrightarrow[MoO_3]{V_2O_5} \quad 2\ C_4H_2O_3 \quad + \quad H_2O \quad + \quad 4\ CO_2$$

Benzene	Oxygen	Catalyst ——>	Maleic anhydride	Water	Carbon dioxide

Vaporized benzene and air are mixed and heated before entering the tubular reactor. Inside the reactor, the benzene/air mixture is reacted in the presence of a catalyst that contains approximately 70 percent vanadium pentoxide (V_2O_5), with usually 25 to 30 percent molybdenum trioxide (MoO_3), forming a vapor of MA, water, and carbon dioxide. The vapor, which may also contain oxygen, nitrogen, carbon monoxide, benzene, maleic acid, formaldehyde, formic acid, and other compounds from side reactions, leaves the reactor and is cooled and partially condensed so that about 40 percent of the MA is recovered in a crude liquid state. The effluent is then passed through a separator that directs the liquid to storage and the remaining vapor to the product recovery absorber. The absorber contacts the vapor with water, producing a liquid of about 40 percent maleic acid. The 40 percent mixture is converted to MA, usually by azeotropic distillation with xylene. Some processes may use a double-effect vacuum evaporator at this point. The effluent then flows to the xylene stripping column where the xylene is extracted. This MA is then combined in storage with that from the separator. The molten product is aged to allow color-forming impurities to polymerize.

These are then removed in a fractionation column, leaving the finished product. Figure 6.14-1 represents a typical process.

MA product is usually stored in liquid form, although it is sometimes flaked and pelletized into briquets and bagged.

6.14.3 Emissions And Controls[2]

Nearly all emissions from MA production are from the main process vent of the product recovery absorber, the largest vent in the process. The predominant pollutant is unreacted benzene, ranging from 3 to 10 percent of the total benzene feed. The composition of uncontrolled emissions from the product recovery absorber is presented in Table 6.14-1. The refining vacuum system vent, the only other exit for process emissions, produces 0.28 kilograms (kg) (0.62 pounds [lb]) per hour of MA and xylene.

Table 6.14-1 (Metric And English Units). COMPOSITION OF UNCONTROLLED EMISSIONS FROM PRODUCT RECOVERY ABSORBER[a]

Component	Wt.%	kg/Mg	lb/ton
Nitrogen	73.37	21,406.0	42,812.0
Oxygen	16.67	4,863.0	9,726.0
Water	4.00	1,167.0	2,334.0
Carbon dioxide	3.33	972.0	1,944.0
Carbon monoxide	2.33	680.0	1,360.0
Benzene	0.33	67.0	134.0
Formaldehyde	0.05	14.4	28.8
Maleic acid	0.01	2.8	5.6
Formic acid	0.01	2.8	5.6
Total		29,175.0	58,350.0

[a] Reference 2.

Fugitive emissions of benzene, xylene, MA, and maleic acid also arise from the storage (see Chapter 7) and handling (see Section 5.1.3) of benzene, xylene, and MA. Dust from the briquetting operations can contain MA, but no data are available on the quantity of such emissions.

Potential sources of secondary emissions are spent reactor catalyst, excess water from the dehydration column, vacuum system water, and fractionation column residues. The small amount of residual organics in the spent catalyst after washing has low vapor pressure and produces a small percentage of total emissions. Xylene is the principal organic contaminant in the excess water from the dehydration column and in the vacuum system water. The residues from the fractionation column are relatively heavy organics, with a molecular weight greater than 116, and they produce a small percentage of total emissions.

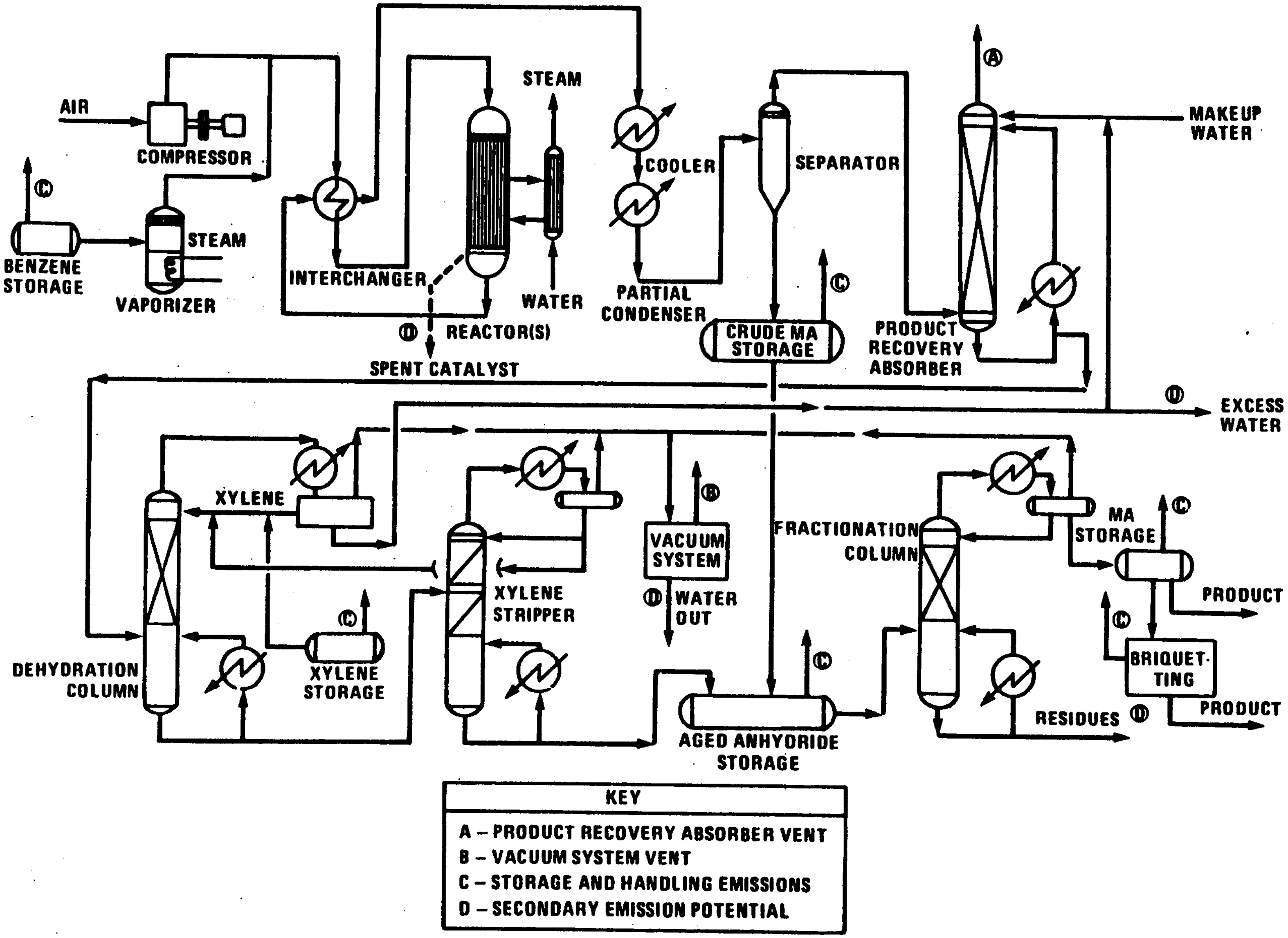


Figure 6.14-1. Process flow diagram for uncontrolled model plant.

Benzene oxidation process emissions can be controlled at the main vent by means of carbon adsorption, thermal incineration, or catalytic incineration. Benzene emissions can be eliminated by conversion to the n-butane process. Catalytic incineration and conversion from the benzene process to the n-butane process are not discussed for lack of data. The vent from the refining vacuum system is combined with that of the main process as a control for refining vacuum system emissions. A carbon adsorption system or an incineration system can be designed and operated at a 99.5 percent removal efficiency for benzene and volatile organic compounds with the operating parameters given in Appendix R of Reference 2.

Fugitive emissions from pumps and valves may be controlled by an appropriate leak detection system and maintenance program. No control devices are presently being used for secondary emissions. Table 6.14-2 presents emission factors for MA production.

Table 6.14-2 (Metric And English Units). EMISSION FACTORS FOR MALEIC ANHYDRIDE PRODUCTION[a]

EMISSION FACTOR RATING: C

Source	Nonmethane VOC[b]		Benzene	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Product vents (recovery absorber and refining vacuum system combined vent)				
Uncontrolled	87	174	67.0	134.0
With carbon adsorption[c]	0.34	0.68	0.34	0.68
With incineration	0.43	0.86	0.34	0.68
Storage and handling emissions[d]	—[d]	—[d]	—[d]	—[d]
Fugitive emissions[e]	—[e]	—[e]	—[e]	—[e]
Secondary emissions[f]	ND	ND	ND	ND

[a] No data are available for catalytic incineration or for plants producing MA from n-butane. ND = no data.

[b] VOC also includes the benzene. For recovery absorber and refining vacuum, VOC can be MA and xylene; for storage and handling, MA, xylene and dust from briquetting operations; for secondary emissions, residual organics from spent catalyst, excess water from dehydration column, vacuum system water, and fractionation column residues. VOC contains no methane.

[c] Before exhaust gas stream goes into carbon adsorber, it is scrubbed with caustic to remove organic acids and water soluble organics. Benzene is the only likely VOC remaining.

[d] See Chapter 7.

[e] See Section 5.1.3.

[f] Secondary emission sources are excess water from dehydration column, vacuum system water, and organics from fractionation column. No data are available on the quantity of these emissions.

References For Section 6.14

1. B. Dmuchovsky and J. E. Franz, "Maleic Anhydride", *Kirk-Othmer Encyclopedia of Chemical Technology, Volume 12*, John Wiley and Sons, Inc., New York, NY, 1967, pp. 819-837.

2. J. F. Lawson, *Emission Control Options For The Synthetic Organic Chemicals Manufacturing Industry: Maleic Anhydride Product Report*, EPA Contract No. 68-02-2577, Hydroscience, Inc., Knoxville, TN, March 1978.

6.15 Methanol

[Work In Progress]

6.16 Acetone And Phenol

[Work In Progress]

6.17 Propylene

[Work In Progress]

6.18 Benzene, Toluene, And Xylenes

[Work In Progress]

6.19 Butadiene

[Work In Progress]

6.20 Cumene

[Work In Progress]

6.21 Ethanol

[Work In Progress]

6.22 Ethyl Benzene

[Work In Progress]

6.23 Ethylene

[Work In Progress]

6.24 Ethylene Dichloride And Vinyl Chloride

[Work In Progress]

6.25 Ethylene Glycol

[Work In Progress]

6.26 Ethylene Oxide

[Work In Progress]

6.27 Formaldehyde

[Work In Progress]

6.28 Glycerine

[Work In Progress]

6.29 Isopropyl Alcohol

[Work In Progress]

7. LIQUID STORAGE TANKS

This chapter presents models for estimating air emissions from organic liquid storage tanks. It also contains detailed descriptions of typical varieties of such tanks, including horizontal, vertical, and underground fixed roof tanks, and internal and external floating roof tanks.

The emission estimation equations presented herein have been developed by the American Petroleum Institute (API), which retains the legal right to these equations. API has granted EPA permission for the nonexclusive, noncommercial distribution of this material to governmental and regulatory agencies. However, API reserves its rights regarding all commercial duplication and distribution of its material. Hence, the material presented is available for public use, but it cannot be sold without written permission from both the American Petroleum Institute and the U. S. Environmental Protection Agency.

The major pollutant of concern is volatile organic compounds. There also may be speciated organic compounds that may be toxic or hazardous.

7.1 Organic Liquid Storage Tanks

7.1.1 Process Description$^{1-2}$

Storage vessels containing organic liquids can be found in many industries, including (1) petroleum producing and refining, (2) petrochemical and chemical manufacturing, (3) bulk storage and transfer operations, and (4) other industries consuming or producing organic liquids. Organic liquids in the petroleum industry, usually called petroleum liquids, generally are mixtures of hydrocarbons having dissimilar true vapor pressures (for example, gasoline and crude oil). Organic liquids in the chemical industry, usually called volatile organic liquids, are composed of pure chemicals or mixtures of chemicals with similar true vapor pressures (for example, benzene or a mixture of isopropyl and butyl alcohols).

Five basic tank designs are used for organic liquid storage vessels: fixed roof (vertical and horizontal), external floating roof, internal floating roof, variable vapor space, and pressure (low and high). A brief description of each tank is provided below. Loss mechanisms associated with each type of tank are provided in Part 7.1.2, below.

The emission estimating equations presented herein were developed by the American Petroleum Institute (API). API retains the copyright to these equations. API has granted permission for the nonexclusive, noncommercial distribution of this material to governmental and regulatory agencies. However, API reserves its rights regarding all commercial duplication and distribution of its material. Therefore, the material presented in Part 7.1 is available for public use, but the material cannot be sold without written permission from the American Petroleum Institute and the U. S. Environmental Protection Agency.

7.1.1.1 Fixed Roof Tanks -

A typical vertical fixed roof tank is shown in Figure 7.1-1. This type of tank consists of a cylindrical steel shell with a permanently affixed roof, which may vary in design from cone- or dome-shaped to flat.

Fixed roof tanks are either freely vented or equipped with a pressure/vacuum vent. The latter allows them to operate at a slight internal pressure or vacuum to prevent the release of vapors during very small changes in temperature, pressure, or liquid level. Of current tank designs, the fixed roof tank is the least expensive to construct and is generally considered the minimum acceptable equipment for storing organic liquids.

Horizontal fixed roof tanks are constructed for both above-ground and underground service, and are usually constructed of steel, steel with a fiberglass overlay, or fiberglass-reinforced polyester. Horizontal tanks are generally small storage tanks with capacities of less than 40,000 gallons. Horizontal tanks are constructed such that the length of the tank is not greater than 6 times the diameter to ensure structural integrity. Horizontal tanks are usually equipped with pressure-vacuum vents, gauge hatches and sample wells, and manholes to provide access to these tanks. In addition, underground tanks are cathodically protected to prevent corrosion of the tank shell. Cathodic protection is accomplished by placing sacrificial anodes in the tank that are connected to an impressed current system or by using galvanic anodes in the tank.

The potential emission sources for above-ground horizontal tanks are the same as those for vertical fixed roof tanks. Emissions from underground storage tanks are associated mainly with changes in the liquid level in the tank. Losses due to changes in temperature or barometric pressure are minimal for underground tanks because the surrounding earth limits the diurnal temperature change, and changes in the barometric pressure result in only small losses.

7.1.1.2 External Floating Roof Tanks -

A typical external floating roof tank consists of an open-topped cylindrical steel shell equipped with a roof that floats on the surface of the stored liquid. Floating roof tanks that are currently in use are constructed of welded steel plate and are of 2 general types: pontoon or double-deck. Pontoon-type and double-deck-type external floating roofs are shown in Figure 7.1-2 and Figure 7.1-3, respectively. With all types of external floating roof tanks, the roof rises and falls with the liquid level in the tank. External floating roof tanks are equipped with a seal system, which is attached to the roof perimeter and contacts the tank wall. The purpose of the floating roof and seal system is to reduce evaporative loss of the stored liquid. Some annular space remains between the seal system and the tank wall. The seal system slides against the tank wall as the roof is raised and lowered. The floating roof is also equipped with roof fittings that penetrate the floating roof and serve operational functions. The external floating roof design is such that evaporative losses from the stored liquid are limited to losses from the seal system and roof fittings (standing storage loss) and any exposed liquid on the tank walls (withdrawal loss).

7.1.1.3 Internal Floating Roof Tanks -

An internal floating roof tank has both a permanent fixed roof and a floating deck inside. The terms "deck" and "floating roof" can be used interchangeably in reference to the structure floating on the liquid inside the tank. There are 2 basic types of internal floating roof tanks: tanks in which the fixed roof is supported by vertical columns within the tank, and tanks with a self-supporting fixed roof and no internal support columns. Fixed roof tanks that have been retrofitted to use a floating deck are typically of the first type. External floating roof tanks that have been converted to internal floating roof tanks typically have a self-supporting roof. Newly constructed internal floating roof tanks may be of either type. The deck in internal floating roof tanks rises and falls with the liquid level and either floats directly on the liquid surface (contact deck) or rests on pontoons several inches above the liquid surface (noncontact deck). The majority of aluminum internal floating roofs currently in service are noncontact decks. Typical contact deck and noncontact deck internal floating roof tanks are shown in Figure 7.1-4.

Contact decks can be (1) aluminum sandwich panels that are bolted together, with a honeycomb aluminum core floating in contact with the liquid; (2) pan steel decks floating in contact with the liquid, with or without pontoons; and (3) resin-coated, fiberglass-reinforced polyester (FRP) buoyant panels floating in contact with the liquid. The majority of internal contact floating roofs currently in service are aluminum sandwich panel-type or pan steel-type. The FRP roofs are less common. The panels of pan steel decks are usually welded together.

Typical noncontact decks have an aluminum deck and an aluminum grid framework supported above the liquid surface by tubular aluminum pontoons or some other buoyant structure. The noncontact decks usually have bolted deck seams. Installing a floating roof or deck minimizes evaporative losses of the stored liquid. As with the external floating roof tanks, both contact and noncontact decks incorporate rim seals and deck fittings for the same purposes previously described for external floating roof tanks. Evaporation losses from decks may come from deck fittings, nonwelded deck seams, and the annular space between the deck and tank wall. In addition, these tanks are freely vented by circulation vents at the top of the fixed roof. The vents minimize the possibility of organic vapor accumulation in concentrations approaching the flammable range. An internal floating roof tank not freely vented is considered a pressure tank. Emission estimation methods for such tanks are not provided in AP-42.

7.1.1.4 Variable Vapor Space Tanks -

Variable vapor space tanks are equipped with expandable vapor reservoirs to accommodate vapor volume fluctuations attributable to temperature and barometric pressure changes. Although variable vapor space tanks are sometimes used independently, they are normally connected to the vapor spaces of 1 or more fixed roof tanks. The 2 most common types of variable vapor space tanks are lifter roof tanks and flexible diaphragm tanks.

Lifter roof tanks have a telescoping roof that fits loosely around the outside of the main tank wall. The space between the roof and the wall is closed by either a wet seal, which is a trough filled with liquid, or a dry seal, which uses a flexible coated fabric.

Flexible diaphragm tanks use flexible membranes to provide expandable volume. They may be either separate gasholder units or integral units mounted atop fixed roof tanks.

Variable vapor space tank losses occur during tank filling when vapor is displaced by liquid. Loss of vapor occurs only when the tank's vapor storage capacity is exceeded.

7.1.1.5 Pressure Tanks -

Two classes of pressure tanks are in general use: low pressure (2.5 to 15 psig) and high pressure (higher than 15 psig). Pressure tanks generally are used for storing organic liquids and gases with high vapor pressures and are found in many sizes and shapes, depending on the operating pressure of the tank. Pressure tanks are equipped with a pressure/vacuum vent that is set to prevent venting loss from boiling and breathing loss from daily temperature or barometric pressure changes. High-pressure storage tanks can be operated so that virtually no evaporative or working losses occur. In low-pressure tanks, working losses can occur with atmospheric venting of the tank during filling operations. No appropriate correlations are available to estimate vapor losses from pressure tanks.

7.1.2 Emission Mechanisms And Control

Emissions from organic liquids in storage occur because of evaporative loss of the liquid during its storage and as a result of changes in the liquid level. The emission sources vary with tank design, as does the relative contribution of each type of emission source. Emissions from fixed roof tanks are a result of evaporative losses during storage and are known as breathing losses (or standing storage losses), and evaporative losses during filling and emptying operations are known as working losses. External and internal floating roof tanks are emission sources because of evaporative losses that occur during standing storage and withdrawal of liquid from the tank. Standing storage losses are a result of evaporative losses through rim seals, deck fittings, and/or deck seams. The loss mechanisms for fixed roof and external and internal floating roof tanks are described in more detail in this part. Variable vapor space tanks are also emission sources because of evaporative losses that result during filling operations. The loss mechanism for variable vapor space tanks is also described in this part. Emissions occur from pressure tanks, as well. However, loss mechanisms from these sources are not described in this part.

7.1.2.1 Fixed Roof Tanks -

The 2 significant types of emissions from fixed roof tanks are storage and working losses. Storage loss is the expulsion of vapor from a tank through vapor expansion and contraction, which are the result of changes in temperature and barometric pressure. This loss occurs without any liquid level change in the tank.

The combined loss from filling and emptying is called working loss. Evaporation during filling operations is a result of an increase in the liquid level in the tank. As the liquid level increases, the pressure inside the tank exceeds the relief pressure and vapors are expelled from the tank. Evaporative loss during emptying occurs when air drawn into the tank during liquid removal becomes saturated with organic vapor and expands, thus exceeding the capacity of the vapor space.

Fixed roof tank emissions vary as a function of vessel capacity, vapor pressure of the stored liquid, utilization rate of the tank, and atmospheric conditions at the tank location.

Several methods are used to control emissions from fixed roof tanks. Emissions from fixed roof tanks can be controlled by installing an internal floating roof and seals to minimize evaporation of the product being stored. The control efficiency of this method ranges from 60 to 99 percent, depending on the type of roof and seals installed and on the type of organic liquid stored.

Vapor balancing is another means of emission control. Vapor balancing is probably most common in the filling of tanks at gasoline stations. As the storage tank is filled, the vapors expelled from the storage tank are directed to the emptying gasoline tanker truck. The truck then transports the vapors to a centralized station where a vapor recovery or control system is used to control emissions. Vapor balancing can have control efficiencies as high as 90 to 98 percent if the vapors are subjected to vapor recovery or control. If the truck vents the vapor to the atmosphere instead of to a recovery or control system, no control is achieved.

Vapor recovery systems collect emissions from storage vessels and convert them to liquid product. Several vapor recovery procedures may be used, including vapor/liquid absorption, vapor compression, vapor cooling, vapor/solid adsorption, or a combination of these. The overall control efficiencies of vapor recovery systems are as high as 90 to 98 percent, depending on the methods used, the design of the unit, the composition of vapors recovered, and the mechanical condition of the system.

In a typical thermal oxidation system, the air/vapor mixture is injected through a burner manifold into the combustion area of an incinerator. Control efficiencies for this system can range from 96 to 99 percent.

7.1.2.2 External Floating Roof Tanks[2-3,5] -

Total emissions from external floating roof tanks are the sum of withdrawal losses and standing storage losses. Withdrawal losses occur as the liquid level, and thus the floating roof, is lowered. Some liquid remains attached to the tank surface and is exposed to the atmosphere. Evaporative losses will occur until the tank is filled and the exposed surface (with the liquid) is again covered. Standing storage losses from external floating roof tanks include rim seal and roof fitting losses. Rim seal losses can occur through many complex mechanisms, but the majority of rim seal vapor losses have been found to be wind-induced. Other potential standing storage loss mechanisms include breathing losses as a result of temperature and pressure changes. Also, standing storage losses can occur through permeation of the seal material with vapor or via a wicking effect of the liquid. Testing has indicated that breathing, solubility, and wicking loss mechanisms are small in comparison to the wind-induced loss. Also, permeation of the seal material generally does not occur if the correct seal fabric is used. The rim seal loss factors incorporate all types of losses.

The roof fitting losses can be explained by the same mechanisms as the rim seal loss mechanisms. However, the relative contribution of each is not known. The roof fitting losses identified in this section account for the combined effect of all of the mechanisms.

A rim seal system is used to allow the floating roof to travel within the tank as the liquid level changes. The seal system also helps to fill the annular space between the rim and the tank shell and therefore minimize evaporative losses from this area. A rim seal system may consist of just a primary seal, or a primary seal and a secondary seal, which is mounted above the primary seal. Examples of primary and secondary seal configurations are shown in Figure 7.1-5, Figure-7.1-6, and Figure 7.1-7. 3 basic types of primary seals are used on external floating roofs: mechanical (metallic) shoe, resilient filled (nonmetallic), and flexible wiper. The resilient seal can be mounted to eliminate the vapor space between the seal and liquid surface (liquid mounted) or to allow a vapor space between the seal and liquid surface (vapor mounted). A primary seal serves as a vapor conservation device by closing the annular space between the edge of the floating roof and the tank wall. Some primary seals are protected by a metallic weather shield. Additional evaporative loss may be controlled by a secondary seal. Secondary seals can be either flexible wiper seals or resilient filled seals. Two configurations of secondary seals are currently available: shoe mounted and rim mounted. Although there are other seal systems, the systems described here include the majority in use today.

Roof fitting loss emissions from external floating roof tanks result from penetrations in the roof by deck fittings, the most common of which are described below. Roof fittings are also shown in Figure 7.1-8 and Figure 7.1-9. Some of the fittings are typical of both external and internal floating roof tanks.

1. <u>Access hatch</u>. An access hatch is an opening in the deck with a peripheral vertical well that is large enough to provide passage for workers and materials through the deck for construction or servicing. Attached to the opening is a removable cover that may be bolted and/or gasketed to reduce evaporative loss. On internal floating roof tanks with noncontact decks, the well should extend down into the liquid to seal off the vapor space below the noncontact deck. A typical access hatch is shown in Figure 7.1-8a.

2. <u>Gauge-float well</u>. A gauge-float is used to indicate the level of liquid within the tank. The float rests on the liquid surface and is housed inside a well that is closed by a cover. The cover may be bolted and/or gasketed to reduce evaporation loss. As with other similar deck penetrations, the well extends down into the liquid on noncontact decks in internal floating roof tanks. A typical gauge-float well is shown in Figure 7.1-8b.

3. <u>Gauge-hatch/sample well</u>. A gauge-hatch/sample well consists of a pipe sleeve equipped with a self-closing gasketed cover (to reduce evaporative losses) and allows hand-gauging or sampling of the stored liquid. The gauge-hatch/sample well is usually located beneath the gauger's platform, which is mounted on top of the tank shell. A cord may be attached to the self-closing gasketed cover so that the cover can be opened from the platform. A typical gauge-hatch/sample well is shown in Figure 7.1-8c.

4. <u>Rim vents</u>. Rim vents are usually used only on tanks equipped with a mechanical-shoe primary seal. A typical rim vent is shown in Figure 7.1-8d. The vent is used to release any excess pressure or vacuum that is present in the vapor space bounded by the primary-seal shoe and the floating roof rim, and the primary-seal fabric and the liquid level. Rim vents usually consist of weighted pallets that rest on a gasketed cover.

5. <u>Roof drains</u>. Currently 2 types of roof drains are in use (closed and open roof drains) to remove rainwater from the floating roof surface. Closed roof drains carry rainwater from the surface of the roof through a flexible hose or some other type of piping system that runs through the stored

liquid prior to exiting the tank. The rainwater does not come in contact with the liquid, so no evaporative losses result.

Open roof drains can be either flush or overflow drains and are used only on double-deck external floating roofs. Both types consist of a pipe that extends below the roof to allow the rainwater to drain into the stored liquid. The liquid from the tank enters the pipe, so evaporative losses can result from the tank opening. Flush drains are flush with the roof surface. Overflow drains are elevated above the roof surface. A typical overflow roof drain is shown in Figure 7.1-9a. Overflow drains are used to limit the maximum amount of rainwater that can accumulate on the floating roof, providing emergency drainage of rainwater if necessary. Overflow drains are usually used in conjunction with a closed drain system to carry rainwater outside the tank.

6. Roof leg. To prevent damage to fittings underneath the deck and to allow for tank cleaning or repair, supports are provided to hold the deck at a predetermined distance off the tank bottom. These supports consist of adjustable or fixed legs attached to the floating deck or hangers suspended from the fixed roof. For adjustable legs or hangers, the load-carrying element passes through a well or sleeve into the deck. With noncontact decks, the well should extend into the liquid. Evaporative losses may occur in the annulus between the roof leg and its sleeve. A typical roof leg is shown in Figure 7.1-9b.

7. Unslotted guidepole wells. A guidepole well is an antirotational device that is fixed to the top and bottom of the tank, passing through the floating roof. The guidepole is used to prevent adverse movement of the roof and thus damage to roof fittings and the rim seal system. A typical guidepole well is shown in Figure 7.1-9c.

8. Slotted guidepole/sample wells. The function of the slotted guidepole/sample well is similar to the unslotted guidepole well but also has additional features. A typical slotted guidepole well is shown in Figure 7.1-9d. As shown in this figure, the guidepole is slotted to allow stored liquid to enter. The liquid entering the guidepole is well mixed, having the same composition as the remainder of the stored liquid, and is at the same liquid level as the liquid in the tank. Representative samples can therefore be collected from the slotted guidepole. The opening at the top of the guidepole and along the exposed sides is typically the emission source. However, evaporative loss from the top of the guidepole can be reduced by placing a float inside the guidepole.

9. Vacuum breaker. A vacuum breaker equalizes the pressure of the vapor space across the deck as the deck is either being landed on or floated off its legs. A typical vacuum breaker is shown in Figure 7.1-9e. As depicted in this figure, the vacuum breaker consists of a well with a cover. Attached to the underside of the cover is a guided leg long enough to contact the tank bottom as the floating deck approaches. When in contact with the tank bottom, the guided leg mechanically opens the breaker by lifting the cover off the well; otherwise, the cover closes the well. The closure may be gasketed or ungasketed. Because the purpose of the vacuum breaker is to allow the free exchange of air and/or vapor, the well does not extend appreciably below the deck.

7.1.2.3 Internal Floating Roof Tanks[4-5] -

Total emissions from internal floating roof tanks are the sum of withdrawal losses and standing storage losses. Withdrawal losses occur in the same manner as in external floating roof tanks: as the floating roof lowers, some liquid remains attached to the tank surface and evaporates. Also, in internal floating roof tanks that have a column-supported fixed roof, some liquid clings to the columns. Standing storage losses from internal floating roof tanks include rim seal, deck fitting, and deck seam losses. The loss mechanisms described in Part 7.1.2.2 for external floating roof rim seal and roof fitting losses also apply to internal floating roofs. However, unlike external floating roof tanks in which wind is the predominant factor affecting rim seal loss, no dominant wind loss mechanism has been identified for internal floating roof tank rim seal losses. Deck seams in internal floating roof tanks are a source of emissions to the extent that these seams may not be completely vapor tight. The loss mechanisms described in Part 7.1.2.2 for external floating roof tank rim seals and roof fittings can describe internal floating roof deck seam losses. As with internal floating roof rim seal and roof fittings, the relative importance of each of the loss mechanisms is not known. It should be noted that welded internal floating roofs do not have deck seam losses.

Internal floating roofs typically incorporate 1 of 2 types of flexible, product-resistant seals: resilient foam-filled seals, or wiper seals. Similar to those used on external floating roofs, each of these seals closes the annular vapor space between the edge of the floating roof and the tank shell to reduce evaporative losses. They are designed to compensate for small irregularities in the tank shell and allow the roof to move freely up and down in the tank without binding.

A resilient foam-filled seal used on an internal floating roof is similar in design to that described in Part 7.1.2.2 for external floating roofs. Two types of resilient foam-filled seals for internal floating roofs are shown in Figure 7.1-10a and Figure 7.1-10b. These seals can be mounted either in contact with the liquid surface (liquid-mounted) or several centimeters above the liquid surface (vapor-mounted).

Resilient foam-filled seals work because of the expansion and contraction of a resilient material to maintain contact with the tank shell while accommodating varying annular rim space widths. These seals consist of a core of open-cell foam encapsulated in a coated fabric. The elasticity of the foam core pushes the fabric into contact with the tank shell. The seals are attached to a mounting on the deck perimeter and are continuous around the roof circumference. Polyurethane-coated nylon fabric and polyurethane foam are commonly used materials. For emission control, it is important that the mounting and radial seal joints be vapor-tight and that the seal be in substantial contact with the tank shell.

Wiper seals are commonly used as primary seals for internal floating roof tanks. This type of seal is depicted in Figure 7.1-10c. New tanks with wiper seals may have dual wipers, 1 mounted above the other.

Wiper seals generally consist of a continuous annular blade of flexible material fastened to a mounting bracket on the deck perimeter that spans the annular rim space and contacts the tank shell. The mounting is such that the blade is flexed, and its elasticity provides a sealing pressure against the tank shell. Such seals are vapor-mounted; a vapor space exists between the liquid stock and the bottom of the seal. For emission control, it is important that the mounting be vapor-tight, that the seal be continuous around the circumference of the roof, and that the blade be in substantial contact with the tank shell.

Two types of materials are commonly used to make the wipers. One type consists of a cellular, elastomeric material tapered in cross section with the thicker portion at the mounting. Buna-N rubber is a commonly used material. All radial joints in the blade are joined.

A second type of wiper seal construction uses a foam core wrapped with a coated fabric. Polyurethane on nylon fabric and polyurethane foam are common materials. The core provides the flexibility and support, while the fabric provides the vapor barrier and wear surface.

Secondary seals may be used to provide some additional evaporative loss control over that achieved by the primary seal. The secondary seal is mounted to an extended vertical rim plate, above the primary seal, as shown in Figure 7.1-11. Secondary seals can be either a resilient foam-filled seal or an elastomeric wiper seal, as previously described. For a given roof design, using a secondary seal further limits the operating capacity of a tank due to the need to keep the seal from interfering with the fixed-roof rafters when the tank is filled.

Numerous deck fittings penetrate or are attached to an internal floating roof. These fittings accommodate structural support members or allow for operational functions. The fittings can be a source of evaporative loss in that they require penetrations in the deck. Other accessories are used that do not penetrate the deck and are not, therefore, sources of evaporative loss. The most common fittings relevant to controlling vapor losses are described in the following paragraphs.

The access hatches, guidepole wells, roof legs, vacuum breakers, and automatic gauge-float wells for internal floating roofs are similar fittings to those already described for external floating roofs. Other fittings used on internal floating roof tanks include column wells, ladder wells, and stub drains.

1. Column wells. The most common fixed-roof designs are normally supported from inside the tank by means of vertical columns, which necessarily penetrate an internal floating deck. (Some fixed roofs are entirely self-supporting and, therefore, have no support columns.) Column wells are similar to unslotted guidepole wells on external floating roofs. Columns are made of pipe with circular cross sections or of structural shapes with irregular cross sections (built-up). The number of columns varies with tank diameter from a minimum of 1 to over 50 for very large tanks.

The columns pass through deck openings via peripheral vertical wells. With noncontact decks, the well should extend down into the liquid stock. Generally, a closure device exists between the top of the well and the column. Several proprietary designs exist for this closure, including sliding covers and fabric sleeves, which must accommodate the movements of the deck relative to the column as the liquid level changes. A sliding cover rests on the upper rim of the column well (which is normally fixed to the roof) and bridges the gap or space between the column well and the column. The cover, which has a cutout, or opening, around the column slides vertically relative to the column as the roof raises and lowers. At the same time, the cover slides horizontally relative to the rim of the well, which is fixed to the roof. A gasket around the rim of the well reduces emissions from this fitting. A flexible fabric sleeve seal between the rim of the well and the column (with a cutout or opening, to allow vertical motion of the seal relative to the columns) similarly accommodates limited horizontal motion of the roof relative to the column. A third design combines the advantages of the flexible fabric sleeve seal with a well that excludes all but a small portion of the liquid surface from direct exchange with the vapor space above the floating roof.

2. Ladder wells. Some tanks are equipped with internal ladders that extend from a manhole in the fixed roof to the tank bottom. The deck opening through which the ladder passes is constructed with similar design details and considerations to deck openings for column wells, as previously discussed.

3. Stub drains. Bolted internal floating roof decks are typically equipped with stub drains to allow any stored product that may be on the deck surface to drain back to the underside of the deck. The drains are attached so that they are flush with the upper deck. Stub drains are approximately 1 inch in diameter and extend down into the product on noncontact decks.

7.1.3 Emission Estimation Procedures

The following section presents the emission estimation procedures for fixed roof, external floating roof, and internal floating roof tanks. These procedures are valid for all petroleum liquids, pure volatile organic liquids, and chemical mixtures with similar true vapor pressures. It is important to note that in all the emission estimation procedures, the physical properties of the vapor do not include the noncondensables (e. g., air) in the gas, but only refer to the condensable components of the stored liquid. To aid in the emission estimation procedures, a list of variables with their corresponding definitions was developed and is presented in Table 7.1-1.

The factors presented in AP-42 are those that are currently available and have been reviewed and approved by the Agency. As storage tank equipment vendors design new floating decks and equipment, new emission factors may be developed based on that equipment. If the new emission factors are reviewed and approved, the emission factors will be added to AP-42 during the next update.

The emission estimation procedures outlined in this chapter have been used as the basis for the development of a software program to estimate emissions from storage tanks. The software program entitled *TANKS* is available through the CHIEF bulletin board system maintained by the Agency.

7.1.3.1 Total Losses From Fixed Roof Tanks[4,6-12] -

The following equations, provided to estimate standing storage and working loss emissions, apply to tanks with vertical cylindrical shells and fixed roofs. These tanks must be substantially liquid- and vapor-tight and must operate approximately at atmospheric pressure. Total losses from fixed roof tanks are equal to the sum of the standing storage loss and working loss:

$$L_T = L_S + L_W \qquad (1\text{-}1)$$

where:

L_T = total losses, lb/yr

L_S = standing storage losses, lb/yr

L_W = working losses, lb/yr

<u>Standing Storage Loss</u> -

Fixed roof tank breathing or standing storage losses can be estimated from:

$$L_S = 365\ V_V W_V K_E K_S \qquad (1\text{-}2)$$

where:

L_S = standing storage loss, lb/yr

V_V = vapor space volume, ft^3

W_V = vapor density, lb/ft^3

K_E = vapor space expansion factor, dimensionless

K_S = vented vapor saturation factor, dimensionless

365 = constant, days/year

Tank Vapor Space Volume, V_V -

The tank vapor space volume is calculated using the following equation:

$$V_V = \frac{\pi}{4} D^2 H_{VO} \qquad (1\text{-}3)$$

where:

V_V = vapor space volume, ft^3

D = tank diameter, ft; see Note 1 for horizontal tanks

H_{VO} = vapor space outage, ft

The vapor space outage, H_{VO}, is the height of a cylinder of tank diameter, D, whose volume is equivalent to the vapor space volume of a fixed roof tank, including the volume under the cone or dome roof. The vapor space outage, H_{VO}, is estimated from:

$$H_{VO} = H_S - H_L + H_{RO} \qquad (1\text{-}4)$$

where:

H_{VO} = vapor space outage, ft

H_S = tank shell height, ft

H_L = liquid height, ft

H_{RO} = roof outage, ft; see Note 2 for a cone roof or Note 3 for a dome roof

Notes:

1. The emission estimating equations presented above were developed for vertical fixed roof tanks. If a user needs to estimate emissions from a horizontal fixed roof tank, some of the tank parameters can be modified before using the vertical tank emission estimating equations. First, by assuming that the tank is one-half filled, the surface area of the liquid in the tank is approximately equal to the length of the tank times the diameter of the tank. Next, assume that this area represents a circle, i. e., that the liquid is an upright cylinder. Therefore, the effective diameter, D_E, is then equal to:

$$D_E = \sqrt{\frac{LD}{0}.785} \qquad (1\text{-}5)$$

where:

D_E = effective tank diameter, ft

L = length of tank, ft

D = actual diameter of tank, ft

One-half of the actual diameter of the horizontal tank should be used as the vapor space outage, H_{VO}. This method yields only a very approximate value for emissions from horizontal storage tanks. For underground horizontal tanks, assume that no breathing or standing storage losses occur ($L_S = 0$) because the insulating nature of the earth limits the diurnal temperature change. No modifications to the working loss equation are necessary for either above-ground or underground horizontal tanks.

2. For a cone roof, the roof outage, H_{RO}, is calculated as follows:

$$H_{RO} = 1/3\ H_R \tag{1-6}$$

where:

H_{RO} = roof outage (or shell height equivalent to the volume contained under the roof), ft

H_R = tank roof height, ft

The tank roof height, H_R, is equal to $S_R\ R_S$

where:

S_R = tank cone roof slope, ft/ft (if unknown, a standard value of 0.0625 ft/ft is used)

R_S = tank shell radius, ft

3. For a dome roof, the roof outage, H_{RO}, is calculated as follows:

$$H_{RO} = H_R \left[1/2 + 1/6 \left[\frac{H_R}{R_S} \right]^2 \right] \tag{1-7}$$

where:

H_{RO} = roof outage, ft

H_R = tank roof height, ft

R_S = tank shell radius, ft

The tank roof height, H_R, is calculated:

$$H_R = R_R - (R_R^2 - R_S^2)^{0.5} \tag{1-8}$$

where:

H_R = tank roof height, ft

R_R = tank dome roof radius, ft

R_S = tank shell radius, ft

The value of R_R usually ranges from 0.8D - 1.2D. If R_R is unknown, the tank diameter is used in its place. If the tank diameter is used as the value for R_R, Equations 1-7 and 1-8 reduce to $H_R = 0.268\ R_S$ and $H_{RO} = 0.137\ R_S$.

Vapor Density, W_V -
The density of vapor is calculated using the following equation:

$$W_V = \frac{M_V P_{VA}}{R T_{LA}} \qquad (1\text{-}9)$$

where:

W_V = vapor density, lb/ft^3

M_V = vapor molecular weight, lb/lb-mole; see Note 1

R = the ideal gas constant, 10.731 psia • ft^3/lb-mole • °R

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2

T_{LA} = daily average liquid surface temperature, °R; see Note 3

Notes:

1. The molecular weight of the vapor, M_V, can be determined from Tables 7.1-2 and 7.1-3 for selected petroleum liquids and volatile organic liquids, respectively, or by analyzing vapor samples. Where mixtures of organic liquids are stored in a tank, M_v can be calculated from the liquid composition. The molecular weight of the vapor, M_v, is equal to the sum of the molecular weight, M_i, multiplied by the vapor mole fraction, y_i, for each component. The vapor mole fraction is equal to the partial pressure of component i divided by the total vapor pressure. The partial pressure of component i is equal to the true vapor pressure of component i (P) multiplied by the liquid mole fraction, (x_i). Therefore,

$$M_V = \Sigma M_i y_i = \Sigma M_i \left[\frac{Px_i}{P_{VA}} \right] \qquad (1\text{-}10)$$

where P_{VA}, total vapor pressure of the stored liquid, by Raoult's law, is:

$$P_{VA} = \Sigma P x_i \qquad (1\text{-}11)$$

For more detailed information, please refer to Part 7.1.4.

2. True vapor pressure is the equilibrium partial pressure exerted by a volatile organic liquid, as defined by ASTM-D 2879 or as obtained from standard reference texts. Reid vapor pressure is the absolute vapor pressure of volatile crude oil and volatile nonviscous petroleum liquids, except liquified petroleum gases, as determined by ASTM-D-323. True vapor pressures for organic liquids can be determined from Table 7.1-3. True vapor pressure can be determined for crude oils using Figure 7.1-12a and Figure 7.1-12b. For refined stocks (gasolines and naphthas), Table 7.1-2 or Figure 7.1-13a and Figure 7.1-13b can be used. In order to use Figure 7.1-12a, Figure 7.1-12b, Figure 7.1-13a, or Figure 7.1-13b, the stored liquid surface temperature, T_{LA}, must be determined in degrees Fahrenheit. See Note 3 to determine T_{LA}.

Alternatively, true vapor pressure for selected petroleum liquid stocks, at the stored liquid surface temperature, can be determined using the following equation:

$$P_{VA} = \exp\,[A - (B/T_{LA})] \qquad (1\text{-}12a)$$

where:

exp = exponential function

A = constant in the vapor pressure equation, dimensionless

B = constant in the vapor pressure equation, °R

T_{LA} = daily average liquid surface temperature, °R

P_{VA} = true vapor pressure, psia

For selected petroleum liquid stocks, physical property data are presented in Table 7.1-2. For refined petroleum stocks, the constants A and B can be calculated from the equations presented in Figure 7.1-14 and the distillation slopes presented in Table 7.1-4. For crude oil stocks, the constants A and B can be calculated from the equations presented in Figure 7.1-15. Note that in Equation 1-12a, T_{LA} is determined in degrees Rankine instead of degrees Fahrenheit.

The true vapor pressure of organic liquids at the stored liquid temperature can be estimated by Antoine's equation:

$$\log P_{VA} = A - \frac{B}{T_{LA} + C} \qquad (1\text{-}12b)$$

where:

A = constant in vapor pressure equation

B = constant in vapor pressure equation

C = constant in vapor pressure equation

T_{LA} = daily average liquid surface temperature, °C

P_{VA} = vapor pressure at average liquid surface temperature, mm Hg

For organic liquids, the values for the constants A, B, and C are listed in Table 7.1-5. Note that in Equation 1-12b, T_{LA} is determined in degrees Celsius instead of degrees Rankine. Also, in Equation 1-12b, P_{VA} is determined in mm Hg rather than psia (760 mm Hg = 14.7 psia).

3. If the daily average liquid surface temperature, T_{LA}, is unknown, it is calculated using the following equation:

$$T_{LA} = 0.44T_{AA} + 0.56T_B + 0.0079\ \alpha I \tag{1-13}$$

where:

T_{LA} = daily average liquid surface temperature, °R

T_{AA} = daily average ambient temperature, °R; see Note 4

T_B = liquid bulk temperature, °R; see Note 5

α = tank paint solar absorptance, dimensionless; see Table 7.1-7

I = daily total solar insolation factor, Btu/ft^2•day; see Table 7.1-6

If T_{LA} is used to calculate P_{VA} from Figures 7.1-12a through 7.1-13b, T_{LA} must be converted from degrees Rankine to degrees Fahrenheit (°F = °R - 460). If T_{LA} is used to calculate P_{VA} from Equation 1-12b, T_{LA} must be converted from degrees Rankine to degrees Celsius [°C = (°R - 492)/1.8]. Equation 1-13 should not be used to estimate liquid surface temperature from insulated tanks. In the case of insulated tanks, the average liquid surface temperature should be based on liquid surface temperature measurements from the tank.

4. The daily average ambient temperature, T_{AA}, is calculated using the following equation:

$$T_{AA} = (T_{AX} + T_{AN})/2 \tag{1-14}$$

where:

T_{AA} = daily average ambient temperature, °R

T_{AX} = daily maximum ambient temperature, °R

T_{AN} = daily minimum ambient temperature, °R

Table 7.1-6 gives values of T_{AX} and T_{AN} for selected U.S. cities.

5. The liquid bulk temperature, T_B, is calculated using the following equation:

$$T_B = T_{AA} + 6\alpha - 1 \tag{1-15}$$

where:

T_B = liquid bulk temperature, °R

T_{AA} = daily average ambient temperature, °R, as calculated in Note 4

α = tank paint solar absorptance, dimensionless; see Table 7.1-7

Vapor Space Expansion Factor, K_E -

The vapor space expansion factor, K_E, is calculated using the following equation:

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \tag{1-16}$$

where:

ΔT_V = daily vapor temperature range, °R; see Note 1

ΔP_V = daily vapor pressure range, psi; see Note 2

ΔP_B = breather vent pressure setting range, psi; see Note 3

T_{LA} = daily average liquid surface temperature, °R; see Note 3 for Equation 1-9

P_A = atmospheric pressure, 14.7 psia

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2 for Equation 1-9

Notes:

1. The daily vapor temperature range ΔT_V, is calculated using the following equation:

$$\Delta T_V = 0.72\ \Delta T_A + 0.028\ \alpha I \tag{1-17}$$

where:

ΔT_V = daily vapor temperature range, °R

ΔT_A = daily ambient temperature range, °R; see Note 4

α = tank paint solar absorptance, dimensionless; see Table 7.1-7

I = daily total solar insolation factor, $Btu/ft^2 \cdot day$; see Table 7.1-6

2. The daily vapor pressure range, ΔP_V, can be calculated using the following equation:

$$\Delta P_V = P_{VX} - P_{VN} \tag{1-18}$$

where:

ΔP_V = daily vapor pressure range, psia

P_{VX} = vapor pressure at the daily maximum liquid surface temperature, psia; see Note 5

P_{VN} = vapor pressure at the daily minimum liquid surface temperature, psia; see Note 5

The following method can be used as an alternate means of calculating ΔP_V for petroleum liquids:

$$\Delta P_V = \frac{0.50\, B\, P_{VA}\, \Delta T_V}{T_{LA}^{\ 2}} \tag{1-19}$$

where:

ΔP_V = daily vapor pressure range, psia

B = constant in the vapor pressure equation, °R; see Note 2 to Equation 1-9

P_{VA} = vapor pressure at the daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

ΔT_V = daily vapor temperature range, °R; see Note 1

T_{LA} = daily average liquid surface temperature, °R; see Note 3 to Equation 1-9

3. The breather vent pressure setting range, ΔP_B, is calculated using the following equation:

$$\Delta P_B = P_{BP} - P_{BV} \tag{1-20}$$

where:

ΔP_B = breather vent pressure setting range, psig

P_{BP} = breather vent pressure setting, psig

P_{BV} = breather vent vacuum setting, psig

If specific information on the breather vent pressure setting and vacuum setting is not available, assume 0.03 psig for P_{BP} and -0.03 psig for P_{BV} as typical values. If the fixed roof tank is of bolted or riveted construction in which the roof or shell plates are not vapor tight, assume that $\Delta P_B = 0$, even if a breather vent is used. The estimating equations for fixed roof tanks do not apply to either low or high pressure tanks. If the breather vent pressure or vacuum setting exceeds 1.0 psig, the standing storage losses could potentially be negative.

4. The daily ambient temperature range, ΔT_A, is calculated using the following equation:

$$\Delta T_A = T_{AX} - T_{AN} \tag{1-21}$$

where:

ΔT_A = daily ambient temperature range, °R

T_{AX} = daily maximum ambient temperature, °R

T_{AN} = daily minimum ambient temperature, °R

Table 7.1-6 gives values of T_{AX} and T_{AN} for selected cities in the United States.[11]

5. The vapor pressures associated with daily maximum and minimum liquid surface temperature, P_{VX} and P_{VN}, respectively, are calculated by substituting the corresponding temperatures, T_{LX} and T_{LN}, into the pressure function discussed in Notes 1 and 2 to Equation 1-9. If T_{LX} and T_{LN} are unknown, Figure 7.1-16 can be used to calculate their values.

Vented Vapor Saturation Factor, K_S -

The vented vapor saturation factor, K_S, is calculated using the following equation:

$$K_S = \frac{1}{1 + 0.053 P_{VA} H_{VO}} \tag{1-22}$$

where:

K_S = vented vapor saturation factor, dimensionless

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

H_{VO} = vapor space outage, ft, as calculated in Equation 1-4

Working Loss -

The working loss, L_W, can be estimated from:

$$L_W = 0.0010\, M_V P_{VA} Q K_N K_P, \tag{1-23}$$

where:

L_W = working losses, lb/yr

M_V = vapor molecular weight, lb/lb-mole; see Note 1 to Equation 1-9

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

Q = annual net throughput, bbl/yr

K_N = turnover factor, dimensionless; see Figure 7.1-17
for turnovers > 36, $K_N = (180 + N)/6N$
for turnovers ≤ 36, $K_N = 1$

N = number of turnovers per year, dimensionless

$$N = \frac{5.614Q}{V_{LX}} \tag{1-24}$$

where:

N = number of turnovers per year, dimensionless

Q = annual net throughput, bbl/yr

V_{LX} = tank maximum liquid volume, ft^3

$$V_{LX} = \frac{\pi}{4} D^2 H_{LX} \qquad (1\text{-}25)$$

where:

D = diameter, ft

H_{LX} = maximum liquid height, ft

K_P = working loss product factor, dimensionless, 0.75 for crude oils. For all other organic liquids, $K_P = 1$

7.1.3.2 Total Losses From External Floating Roof Tanks[3-4,11] -

Total external floating roof tank emissions are the sum of rim seal, withdrawal, and roof fitting losses. The equations presented in this part apply only to external floating roof tanks. The equations are not intended to be used in the following applications:

1. To estimate losses from unstable or boiling stocks, or from mixtures of hydrocarbons or petrochemicals for which the vapor pressure is not known or cannot readily be predicted; or

2. To estimate losses from tanks in which the materials used in the rim seal and/or roof fitting are either deteriorated or significantly permeated by the stored liquid.

Total losses from external floating roof tanks may be written as:

$$L_T = L_R + L_{WD} + L_F \qquad (2\text{-}1)$$

where:

L_T = total loss, lb/yr

L_R = rim seal loss, lb/yr; see Equation 2-2

L_{WD} = withdrawal loss, lb/yr; see Equation 2-4

L_F = roof fitting loss, lb/yr; see Equation 2-5

Rim Seal Loss -

Rim seal loss from floating roof tanks can be estimated using the following equation:

$$L_R = K_R v^n P^* D M_V K_C \qquad (2\text{-}2)$$

where:

L_R = rim seal loss, lb/yr

K_R = seal factor, lb-mole/(mph)^{n}ft•yr; see Table 7.1-8 or Note 3

v = average wind speed at tank site, mph; see Note 1 and Note 3

n = seal-related wind speed exponent, dimensionless; see Table 7.1-8 or Note 3

P* = vapor pressure function, dimensionless; see Note 2

$$P^* = \frac{P_{VA}/P_A}{[1 + (1 - [P_{VA}/P_A])^{0.5}]^2} \qquad (2\text{-}3)$$

where:

P_{VA} = vapor pressure at daily average liquid surface temperature, psia; See Notes 1 and 2 to Equation 1-9 and Note 4 below

P_A = atmospheric pressure, 14.7 psia

D = tank diameter, ft

M_V = average vapor molecular weight, lb/lb-mole; see Note 1 to Equation 1-9

K_C = product factor; K_C = 0.4 for crude oils; K_C = 1 for all other organic liquids

Notes:

1. If the wind speed at the tank site is not available, use wind speed data from the nearest local weather station or values from Table 7.1-9.

2. P* can be calculated or read directly from Figure 7.1-18.

3. The rim seal loss factor, $F_R = K_R v^n$, can also be read directly from Figure 7.1-19, Figure 7.1-20, Figure 7.1-21, and Figure 7.1-22. Figure 7.1-19, Figure 7.1-20, Figure 7.1-21, and Figure 7.1-22 present F_R for both average and tight-fitting seals. However, it is recommended that only the values for average-fitting seals be used in estimating rim seal losses because of the difficulty in ensuring the seals are tight fitting at all liquid heights in the tank.

4. The API recommends using the stock liquid temperature to calculate P_{VA} for use in Equation 2-3 in lieu of the liquid surface temperature. If the stock liquid temperature is unknown, API recommends the following equations to estimate the stock temperature:

Tank Color	Average Annual Stock Temperature, T_s (°F)
White	$T_a + 0.0^a$
Aluminum	$T_a + 2.5$
Gray	$T_a + 3.5$
Black	$T_a + 5.0$

$^a T_a$ is the average annual ambient temperature in degrees Fahrenheit.

Withdrawal Loss -

The withdrawal loss from floating roof storage tanks can be estimated using Equation 2-4.

$$L_{WD} = \frac{(0.943)QCW_L}{D} \qquad (2\text{-}4)$$

where:

L_{WD} = withdrawal loss, lb/yr

Q = annual throughput, bbl/yr, (tank capacity [bbl] times annual turnover rate)

C = shell clingage factor, bbl/1,000 ft^2; see Table 7.1-10

W_L = average organic liquid density, lb/gal; see Note 1

D = tank diameter, ft

0.943 = constant, 1,000 ft^3 x gal/bbl^2

Note:

1. A listing of the average organic liquid density for select petrochemicals is provided in Tables 7.1-2 and 7.1-3. If W_L is not known for gasoline, an average value of 6.1 lb/gal can be assumed.

Roof Fitting Loss -

The roof fitting loss from external floating roof tanks can be estimated by the following equation:

$$L_F = F_F \, P^* M_V K_C \qquad (2\text{-}5)$$

where:

L_F = the roof fitting loss, lb/yr

F_F = total roof fitting loss factor, lb-mole/yr; see Figure 7.1-23 and Figure 7.1-24

$$F_F = [(N_{F1} K_{F1}) + (N_{F2} K_{F2}) + \ldots + (N_{Fn} K_{Fn})] \qquad (2\text{-}6)$$

where:

N_{F_i} = number of roof fittings of a particular type ($i = 0,1,2,\ldots,n_f$), dimensionless

K_{F_i} = roof fitting loss factor for a particular type fitting ($i = 0,1,2,\ldots,n_f$), lb-mole/yr; see Equation 2-7

n_f = total number of different types of fittings, dimensionless

P^*, M_V, K_C are as defined for Equation 2-2.

The value of F_F may be calculated by using actual tank-specific data for the number of each fitting type (N_F) and then multiplying by the fitting loss factor for each fitting (K_F).

The roof fitting loss factor, K_{F_i} for a particular type of fitting, can be estimated by the following equation:

$$K_{F_i} = K_{F_{ai}} + K_{F_{bi}} v^{m_i} \tag{2-7}$$

where:

K_{F_i} = loss factor for a particular type of roof fitting, lb-moles/yr

$K_{F_{ai}}$ = loss factor for a particular type of roof fitting, lb-moles/yr

$K_{F_{bi}}$ = loss factor for a particular type of roof fitting, lb-mole/(mph)$^m \cdot$yr

m_i = loss factor for a particular type of roof fitting, dimensionless

i = 1, 2, ..., n, dimensionless

v = average wind speed, mph

Loss factors K_{F_a}, K_{F_b}, and m are provided in Table 7.1-11 for the most common roof fittings used on external floating roof tanks. These factors apply only to typical roof fitting conditions and when the average wind speed is between 2 and 15 mph. Typical numbers of fittings are presented in Tables 7.1-11, 7.1-12, and 7.1-13. Where tank-specific data for the number and kind of deck fittings are unavailable, F_F can be approximated according to tank diameter. Figure 7.1-23 and Figure 7.1-24 present F_F plotted against tank diameter for pontoon and double-deck external floating roofs, respectively.

7.1.3.3 Total Losses From Internal Floating Roof Tanks[4] -

Total internal floating roof tank emissions are the sum of rim seal, withdrawal, deck fitting, and deck seam losses.

The equations provided in this section apply only to freely vented internal floating roof tanks. These equations are not intended to estimate losses from closed internal floating roof tanks (tanks vented only through a pressure/vacuum vent).

Emissions from internal floating roof tanks may be estimated as:

$$L_T = L_R + L_{WD} + L_F + L_D \qquad (3\text{-}1)$$

where:

L_T = total loss, lb/yr

L_R = rim seal loss, lb/yr; see Equation 3-2

L_{WD} = withdrawal loss, lb/yr; see Equation 3-4

L_F = deck fitting loss, lb/yr; see Equation 3-5

L_D = deck seam loss, lb/yr; see Equation 3-6

Rim Seal Loss -

Rim seal losses from floating roof tanks can be estimated by the following equation:

$$L_R = K_R P^* D M_V K_C \qquad (3\text{-}2)$$

where:

L_R = rim seal loss, lb/yr

K_R = seal factor, lb-mole/(ft-yr); see Table 7.1-14

P^* = vapor pressure function, dimensionless; see Note 2 to Equation 2-2

$$P^* = \frac{P_{VA}/P_A}{[1 + (1 - [P_{VA}/P_A])^{0.5}]^2} \qquad (3\text{-}3)$$

where: P_{VA} and P_A are as defined for Equation 2-3

D = tank diameter, ft

M_V = average vapor molecular weight, lb/lb-mole; see Note 1 to Equation 1-9

K_C = product factor; $K_C = 0.4$ for crude oils; $K_C = 1.0$ for all other organic liquids

Withdrawal Loss -

The withdrawal loss from internal floating roof storage tanks can be estimated using Equation 3-4:

$$L_{WD} = \frac{(0.943)QCW_L}{D}\left[1 + \left(\frac{N_C F_C}{D}\right)\right] \qquad (3\text{-}4)$$

where:

N_C = number of columns, dimensionless; see Note 1

F_C = effective column diameter, ft (column perimeter [ft])/π); see Note 2

0.943 = constant, 1,000 ft^3 x gal/bbl^2

L_{WD}, Q, C, W_L, and D are as defined for Equation 2-4.

Notes:

1. For a self-supporting fixed roof or an external floating roof tank:

   $N_C = 0$

   For a column-supported fixed roof:

   N_C = use tank-specific information or see Table 7.1-15

2. Use tank-specific effective column diameter or

   F_C = 1.1 for 9-inch by 7-inch built-up columns, 0.7 for 8-inch-diameter pipe columns, and 1.0 if column construction details are not known

Deck Fitting Losses -

Fitting losses from internal floating roof tanks can be estimated by the following equation:

$$L_F = F_F P^* M_V K_C \qquad (3\text{-}5)$$

where:

F_F = total deck fitting loss factor, lb-mole/yr

= $[(N_{F1}K_{F1}) + (N_{F2}K_{F2}) \ldots + (N_{F_n}K_{F_n})]$

where:

N_{F_i} = number of deck fittings of a particular type (i = 0, 1, 2, ..., n_f), dimensionless; see Table 7.1-16[4]

K_{F_i} = deck fitting loss factor for a particular type fitting (i = 0, 1, 2, ..., n_f), lb-mole/yr; see Table 7.1-16[4]

n_f = total number of different types of fittings

P^*, M_V, and K_C are as defined in Equations 2-2 and 2-5.

The value of F_F may be calculated by using actual tank-specific data for the number of each fitting type (N_F) and then multiplying by the fitting loss factor for each fitting (K_F). Values of fitting loss factors and typical number of fittings are presented in Table 7.1-16. Where tank-specific data for the number and kind of deck fittings are unavailable, then F_F can be approximated according to tank diameter. Figure 7.1-25 and Figure 7.1-26 present F_F plotted against tank diameter for column-supported fixed roofs and self-supported fixed roofs, respectively.

Deck Seam Loss -

Welded internal floating roof tanks do not have deck seam losses. Tanks with bolted decks may have deck seam losses. Deck seam loss can be estimated by the following equation:

$$L_D = K_D S_D D^2 P^* M_V K_C \tag{3-6}$$

where:

K_D = deck seam loss per unit seam length factor, lb-mole/ft-yr

= 0.0 for welded deck

= 0.34 for bolted deck; see Note 1

S_D = deck seam length factor, ft/ft^2

$= \dfrac{L_{seam}}{A_{deck}}$

where:

L_{seam} = total length of deck seams, ft

A_{deck} = area of deck, ft^2 = $\pi D^2/4$

D, P^*, M_V, and K_C are as defined for Equation 2-2.

If the total length of the deck seam is not known, Table 7.1-17 can be used to determine S_D. For a deck constructed from continuous metal sheets with a 7-ft spacing between the seams, a value of 0.14 ft/ft^2 can be used. A value of 0.33 ft/ft^2 can be used for S_D when a deck is constructed from rectangular panels 5 ft by 7.5 ft. Where tank-specific data concerning width of deck sheets or size of deck panels are unavailable, a default value for S_D can be assigned. A value of 0.20 ft/ft^2 can be assumed to represent the most common bolted decks currently in use.

Note:

1. Recently vendors of bolted decks have been using various techniques in an effort to reduce deck seam losses. However, emission factors are not currently available in AP-42 that represent the emission reduction achieved by these techniques. Some vendors have developed specific factors for their deck designs; however, use of these factors is not recommended until approval has been obtained from the governing regulatory agency or permitting authority.

7.1.3.4 Variable Vapor Space Tanks[13] -

Variable vapor space filling losses result when vapor is displaced by liquid during filling operations. Since the variable vapor space tank has an expandable vapor storage capacity, this loss is not as large as the filling loss associated with fixed roof tanks. Loss of vapor occurs only when the tank's vapor storage capacity is exceeded.

Variable vapor space system filling losses can be estimated from:

$$L_V = (2.40 \times 10^{-2})\ M_V P_{VA}/V_1\ [(V_1) - (0.25 V_2 N_2)] \qquad (4\text{-}1)$$

where:

L_V = variable vapor space filling loss, lb/1,000 gal throughput

M_V = molecular weight of vapor in storage tank, lb/lb-mole; see Note 1 to Equation 1-9

P_{VA} = true vapor pressure at the daily average liquid surface temperature, psia; see Notes 1 and 2 to Equation 1-9

V_1 = volume of liquid pumped into system, throughput, bbl/yr

V_2 = volume expansion capacity of system, bbl; see Note 1

N_2 = number of transfers into system, dimensionless; see Note 2

Notes:

1. V_2 is the volume expansion capacity of the variable vapor space achieved by roof lifting or diaphragm flexing.

2. N_2 is the number of transfers into the system during the time period that corresponds to a throughput of V_1.

The accuracy of Equation 4-1 is not documented. Special tank operating conditions may result in actual losses significantly different from the estimates provided by Equation 4-1. It should also be noted that, although not developed for use with heavier petroleum liquids such as kerosenes and fuel oils, the equation is recommended for use with heavier petroleum liquids in the absence of better data.

7.1.3.5 Pressure Tanks -

Losses occur during withdrawal and filling operations in low-pressure (2.5 to 15 psig) tanks when atmospheric venting occurs. High-pressure tanks are considered closed systems, with virtually no emissions. Vapor recovery systems are often found on low-pressure tanks. Fugitive losses are also associated with pressure tanks and their equipment, but with proper system maintenance, these losses are considered insignificant. No appropriate correlations are available to estimate vapor losses from pressure tanks.

7.1.3.6 Variations Of Emission Estimation Procedures -

All of the emission estimation procedures presented in Part 7.1.3 can be used to estimate emissions for shorter time periods by manipulating the inputs to the equations for the time period in question. For all of the emission estimation procedures, the daily average liquid surface temperature should be based on the appropriate temperature and solar insolation data for the time period over which the estimate is to be evaluated. The subsequent calculation of the vapor pressure should be based on the corrected daily liquid surface temperature. For example, emission calculations for the month of June would be based only on the meteorological data for June. It is important to note that a 1-month time frame is recommended as the shortest time period for which emissions should be estimated.

In addition to the temperature and vapor pressure corrections, the constant in the standing storage loss equation for fixed roof tanks would need to be revised based on the actual time frame used. The constant, 365, is the number of days in a year. To change the equation for a different time period, the constant should be changed to the appropriate number of days in the time period for which emissions are being estimated. The only change that would need to be made to the working loss equation for fixed roof tanks would be to change the throughput per year to the throughput during the time period for which emissions are being estimated.

Other than changing the meteorological data and the vapor pressure data, the only changes needed for the floating roof rim seal, fitting, and deck seam losses would be to modify the time frame by dividing the individual losses by the appropriate number of days or months. The only change to the withdrawal losses would be to change the throughput to the throughput for the time period for which emissions are being estimated.

Another variation that is frequently made to the emission estimation procedures is an adjustment in the working or withdrawal loss equations if the tank is operated as a surge tank or constant-level tank. For constant-level tanks or surge tanks where the throughput and turnovers are high but the liquid level in the tank remains relatively constant, the actual throughput or turnovers should not be used in the working loss or withdrawal loss equations. For these tanks, the turnovers should be estimated by determining the average change in the liquid height. The average change in height should then be divided by the total shell height. This estimated turnover value should then be multiplied by the tank volume to obtain the net throughput for the loss equations. Alternatively, a default turnover rate of 4 could be used based on data from these type tanks.

7.1.4 Hazardous Air Pollutants (HAP) Speciation Methodology

In some cases it may be important to know the annual emission rate for a component (e. g., HAP) of a stored liquid mixture. There are 2 basic approaches that can be used to estimate emissions for a single component of a stored liquid mixture. One approach involves calculating the total losses based upon the known physical properties of the mixture (i. e., gasoline) and then determining the individual component losses by multiplying the total loss by the weight fraction of the desired component. The second approach is similar to the first approach except that the mixture properties are unknown; therefore, the mixture properties are first determined based on the composition of the liquid mixture.

Case 1 -

If the physical properties of the mixture are known (P_{VA}, M_V, M_L and W_L), the total losses from the tank should be estimated using the procedures described previously for the particular tank type. The component losses are then determined from either Equation 5-1 or 5-2. For fixed roof tanks, the emission rate for each individual component can be estimated by:

$$L_{T_i} = (Z_{i,V})(L_T) \qquad (5-1)$$

where:

L_{T_i} = emission rate of component i, lb/yr

$Z_{i,V}$ = weight fraction of component i in the vapor, lb/lb

L_T = total losses, lb/yr

For floating roof tanks, the emission rate for each individual component can be estimated by:

$$L_{T_i} = (Z_{i,V})(L_R + L_F + L_D) + (Z_{i,L})(L_{WD}) \qquad (5\text{-}2)$$

where:

L_{T_i} = emission rate of component i, lb/yr

$Z_{i,V}$ = weight fraction of component i in the vapor, lb/lb

L_R = rim seal losses, lb/yr

L_F = roof fitting losses, lb/yr

L_D = deck seam losses, lb/yr

$Z_{i,L}$ = weight fraction of component i in the liquid, lb/lb

L_{WD} = withdrawal losses, lb/yr

If Equation 5-1 is used in place of Equation 5-2 for floating roof tanks, the value obtained will be approximately the same value as that achieved with Equation 5-2 because withdrawal losses are typically minimal for floating roof tanks.

In order to use Equations 5-1 and 5-2, the weight fraction of the desired component in the liquid and vapor phase is needed. The liquid weight fraction of the desired component is typically known or can be readily calculated for most mixtures. In order to calculate the weight fraction in the vapor phase, Raoult's law must first be used to determine the partial pressure of the component. The partial pressure of the component can then be divided by the total vapor pressure of the mixture to determine the mole fraction of the component in the vapor phase. Raoult's law states that the mole fraction of the component in the liquid (x_i) multiplied by the vapor pressure of the pure component (at the daily average liquid surface temperature) (P) is equal to the partial pressure (P_i) of that component:

$$P_i = (P)(x_i) \qquad (5\text{-}3)$$

where:

P_i = partial pressure of component i, psia

P = vapor pressure of pure component i at the daily average liquid surface temperature, psia

x_i = liquid mole fraction, lb-mole/lb-mole

The vapor pressure of each component can be calculated from Antoine's equation or found in standard references, as shown in Part 7.1.3.1. In order to use Equation 5-3, the liquid mole fraction must be determined from the liquid weight fraction by:

$$x_i = (Z_{i,L})\ (M_L)\ /\ (M_i) \qquad (5\text{-}4)$$

where:

x_i = liquid mole fraction of component i, lb-mole/lb-mole

$Z_{i,L}$ = weight fraction of component i, lb/lb

M_L = molecular weight of liquid stock, lb/lb-mole

M_i = molecular weight of component i, lb/lb-mole

If the molecular weight of the liquid is not known, the liquid mole fraction can be determined by assuming a total weight of the liquid mixture (see Example 1 in Part 7.1.5).

The liquid mole fraction and the vapor pressure of the component at the daily average liquid surface temperature can then be substituted into Equation 5-3 to obtain the partial pressure of the component. The vapor mole fraction of the component can be determined from the following equation:

$$y_i = \frac{P_i}{P_{VA}} \qquad (5\text{-}5)$$

where:

y_i = vapor mole fraction of component i, lb-mole/lb-mole

P_i = partial pressure of component i, psia

P_{VA} = total vapor pressure of liquid mixture, psia

The weight fractions in the vapor phase are calculated from the mole fractions in the vapor phase.

$$Z_{i,V} = \frac{y_i M_i}{M_V} \qquad (5\text{-}6)$$

where:

$Z_{i,V}$ = vapor weight fraction of component i, lb/lb

y_i = vapor mole fraction of component i, lb/lb-mole

M_i = molecular weight of component i, lb/lb-mole

M_V = molecular weight of vapor stock, lb/lb-mole

The liquid and vapor weight fractions of each desired component and the total losses can be substituted into either Equation 5-1 or 5-2 to estimate the individual component losses.

Case 2 -

For cases where the mixture properties are unknown but the composition of the liquid is known (i. e., nonpetroleum organic mixtures), the equations presented above can be used to obtain a reasonable estimate of the physical properties of the mixture. For nonaqueous organic mixtures, Equation 5-3 can be used to determine the partial pressure of each component. If Equation 5-4 is used to determine the liquid mole fractions, the molecular weight of the liquid stock must be known. If the molecular weight of the liquid stock is unknown, then the liquid mole fractions can be determined by assuming a weight basis and calculating the number of moles (see Example 1 in Part 7.1.5). The partial pressure of each component can then be determined from Equation 5-3.

For special cases, such as waste water, where the liquid mixture is a dilute aqueous solution, Henry's law should be used instead of Raoult's law in calculating total losses. Henry's law states that the mole fraction of the component in the liquid phase (x_i) multiplied by the Henry's law constant for the component in the mixture is equal to the partial pressure (P_i) for that component. For waste water, Henry's law constants are typically provided in the form of atm • m^3/g-mole.

Therefore, the appropriate form of Henry's law equation is:

$$P_i = (H_A)(C_i) \qquad (5\text{-}7)$$

where:

P_i = partial pressure of component i, atm

H_A = Henry's law constant for component i, atm • m^3/g-mole

C_i = concentration of component i in the waste water, g-mole/m^3; see Note 1

Section 4.3, "Waste Water Collection, Treatment, And Storage," presents Henry's law constants for selected organic liquids. The partial pressure calculated from Equation 5-7 will need to be converted from atmospheres to psia (1 atm = 14.7 psia).

Note:

1. Typically waste water concentrations are given in mg/liter, which is equivalent to g/m^3. To convert the concentrations to g-mole/m^3 divide the concentration by the molecular weight of the component.

The total vapor pressure of the mixture can be calculated from the sum of the partial pressures:

$$P_{VA} = \Sigma P_i \qquad (5\text{-}8)$$

where:

P_{VA} = vapor pressure at daily average liquid surface temperature, psia

P_i = partial pressure of component i, psia

This procedure can be used to determine the vapor pressure at any temperature. After computing the total vapor pressure, the mole fractions in the vapor phase are calculated using Equation 5-5. The vapor mole fractions are used to calculate the molecular weight of the vapor, M_V. The molecular weight of the vapor can be calculated by:

$$M_V = \Sigma M_i y_i \tag{5-9}$$

where:

M_V = molecular weight of the vapor, lb/lb-mole

M_i = molecular weight of component i, lb/lb-mole

y_i = vapor mole fraction of component i, lb-mole/lb-mole

Another variable that may need to be calculated before estimating the total losses if it is not available in a standard reference is the density of the liquid, W_L. If the density of the liquid is unknown, it can be estimated based on the liquid weight fractions of each component (see Part 7.1.5, Example 3).

All of the mixture properties are now known (P_{VA}, M_V, and W_L); therefore, these values can be inputted into the emission estimation procedures outlined in Part 7.1.3 to estimate total losses. After calculating the total losses, the component losses can be calculated by using either Equation 5-1 or 5-2. Prior to calculating component losses, Equation 5-6 must be used to determine the vapor weight fractions of each component.

7.1.5 Sample Calculations[14]

Example 1 - Chemical Mixture In A Fixed Roof Tank -
Determine the yearly emission rate of the total product mixture and each component for a chemical mixture stored in a vertical cone roof tank in Denver, Colorado. The chemical mixture contains (for every 3,171 lb of mixture) 2,812 lb of benzene, 258 lb of toluene, and 101 lb of cyclohexane. The tank is 6 ft in diameter, 12 ft high, usually holds about 8 ft of product, and is painted white. The tank working volume is 1,690 gallons. The number of turnovers per year for the tank is 5 (i. e., the throughput of the tank is 8,450 gal/yr).

Solution -

1. Determine tank type. The tank is a fixed-cone roof, vertical tank.

2. Determine estimating methodology. The product is made up of 3 organic liquids, all of which are miscible in each other, which makes a homogenous mixture if the material is well mixed. The tank emission rate will be based upon the properties of the mixture. Raoult's law (as discussed in Part 7.1.4) is assumed to apply to the mixture and will be used to determine the properties of the mixture.

3. Select equations to be used. For a vertical, fixed roof storage tank, the following equations apply:

$$L_T = L_S + L_W \tag{1-1}$$

$$L_S = 365\ W_V V_V K_E K_S \qquad (1\text{-}2)$$

$$L_W = 0.0010\ M_V P_{VA} Q K_N K_P \qquad (1\text{-}23)$$

where:

L_T = total loss, lb/yr

L_S = standing storage loss, lb/yr

L_W = working loss, lb/yr

V_V = tank vapor space volume, ft^3

$$V_v = \pi/4\ D^2\ H_{VO} \qquad (1\text{-}3)$$

W_V = vapor density, lb/ft^3

$$W_v = \frac{M_v P_{VA}}{RT_{LA}} \qquad (1\text{-}9)$$

K_E = vapor space expansion factor, dimensionless

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \qquad (1\text{-}16)$$

K_S = vented vapor space saturation factor, dimensionless

$$K_S = \frac{1}{1 + 0.053\ P_{VA} H_{VO}} \qquad (1\text{-}22)$$

D = diameter, ft

H_{VO} = vapor space outage, ft

M_V = molecular weight of vapor, lb/lb-mole

P_{VA} = vapor pressure at the daily average liquid surface temperature, psia

R = the ideal gas constant, 10.731 psia • ft^3/lb-mole • °R

T_{LA} = daily average liquid surface temperature, °R

ΔT_V = daily vapor temperature range, °R

ΔP_V = daily vapor pressure range, psia

ΔP_B = breather vent pressure setting range, psi

P_A = atmospheric pressure, psia

Q = annual net throughput, bbl/yr

K_N = working loss turnover factor, dimensionless

K_P = working loss product factor, dimensionless

4. Calculate each component of the standing storage loss and working loss functions.

a. Tank vapor space volume, V_V.

$$V_V = \pi/4\ D^2\ H_{VO} \tag{1-3}$$

$D = 6$ ft (given)

For a cone roof, the vapor space outage, H_{VO}, is calculated by:

$$H_{VO} = H_S - H_L + H_{RO} \tag{1-4}$$

where:

H_S = tank shell height, 12 ft (given)

H_L = stock liquid height, 8 ft (given)

H_{RO} = roof outage, $1/3\ H_R = 1/3(S_R)(R_S)$ (1-6)

S_R = tank cone roof slope, 0.0625 ft/ft (given) (see Note 1 to Equation 1-4)

R_S = tank shell radius = $1/2\ D = 1/2\ (6) = 3$

Substituting values in Equation 1-6 yields

$$H_{RO} = \frac{1}{3}(0.0625)(3) = 0.0625 \text{ ft}$$

Then use Equation 1-4 to calculate H_{VO},

$$H_{VO} = 12 - 8 + 0.0625 = 4.0625 \text{ ft}$$

Therefore,

$$V_V = \frac{\pi}{4}(6)^2(4.0625) = 114.86 \text{ ft}^3$$

b. Vapor density, W_V

$$W_V = \frac{M_V P_{VA}}{R\ T_{LA}} \qquad (1\text{-}9)$$

R = ideal gas constant = 10.731 psia · ft^3/lb-mole · °R

M_V = stock vapor molecular weight, lb/lb-mole

P_{VA} = stock vapor pressure at the daily average liquid surface temperature, psia

T_{LA} = daily average liquid surface temperature, °R

First, calculate T_{LA} using Equation 1-13.

$$T_{LA} = 0.44\ T_{AA} + 0.56\ T_B + 0.0079\ \alpha\ I \qquad (1\text{-}13)$$

where:

T_{AA} = daily average ambient temperature, °R

T_B = liquid bulk temperature, °R

I = daily total solar absorptance, Btu/ft·day = 1,568 (see Table 7.1-6)

α = tank paint solar absorptance = 0.17 (see Table 7.1-7)

T_{AA} and T_B must be calculated from Equations 1-14 and 1-15.

$$T_{AA} = \frac{T_{AX} + T_{AN}}{2} \qquad (1\text{-}14)$$

From Table 7.1-6, for Denver, Colorado:

T_{AX} = daily maximum ambient temperature = 64.3°F

T_{AN} = daily minimum ambient temperature = 36.2°F

Converting to °R:

T_{AX} = 64.3 + 460 = 524.3°R

T_{AN} = 36.2 + 460 = 496.2°R

Therefore,

T_{AA} = (524.3 + 496.2)/2 = 510.25 °R

$$T_B = \text{liquid bulk temperature} = T_{AA} + 6\alpha - 1 \qquad (1\text{-}15)$$

T_{AA} = 510.25 °R from previous calculation

α = paint solar absorptance = 0.17 (see Table 7.1-7)

I = daily total solar insolation on a horizontal surface = 1,568 Btu/ft^2·day (see Table 7.1-6)

Substituting values in Equation 1-15,

$$T_B = 510.25 + 6\ (0.17) - 1 = 510.27\ °R$$

Using Equation 1-13,

$$T_{LA} = (0.44)\ (510.25°R) + 0.56\ (510.27°R) + 0.0079\ (0.17)\ (1{,}568) = 512.36°R$$

Second, calculate P_{VA} using Raoult's law.

According to Raoult's law, the partial pressure of a component is the product of its pure vapor pressure and its liquid mole fraction. The sum of the partial pressures are equal to the total vapor pressure of the component mixture stock.

The pure vapor pressure for benzene, toluene, and cyclohexane can be calculated from Antoine's equation. For benzene, Table 7.1-5 provides the Antoine's coefficients, which are A = 6.905, B = 1,211.033, and C = 220.79. For toluene, A = 6.954, B = 1,344.8, and C = 219.48. For cyclohexane, A = 6.841, B = 1,201.53, and C = 222.65. Therefore:

$$\log P = A - \frac{B}{T + C}$$

T_{LA}, average liquid surface temperature (°C) = (512.36 - 492)/1.8 = 11

For benzene,

$$\log P = 6.905 - \frac{1{,}211.033}{(11°C + 220.79)}$$

P = 47.90 mmHg = 0.926 psia

Similarly for toluene and cyclohexane,

P = 0.255 psia for toluene

P = 0.966 psia for cyclohexane

In order to calculate the mixture vapor pressure, the partial pressures need to be calculated for each component. The partial pressure is the product of the pure vapor pressures of each component (calculated above) and the mole fractions of each component in the liquid.

The mole fractions of each component are calculated as follows:

Component	Amount, lb	$\div M_i$	Moles	x_i
Benzene	2,812	78.1	36.0	0.90
Toluene	258	92.1	2.80	0.07
Cyclohexane	101	84.2	1.20	0.03
Total			40.0	1.00

where:

M_i = molecular weight of component

x_i = liquid mole fraction

The partial pressures of the components can then be calculated by multiplying the pure vapor pressure by the liquid mole fraction as follows:

Component	P at 52°F	x_i	$P_{partial}$
Benzene	0.926	0.90	0.833
Toluene	0.255	0.07	0.018
Cyclohexane	0.966	0.03	0.029
Total		1.0	0.880

The vapor pressure of the mixture is then 0.880 psia.

Third, calculate the molecular weight of the vapor, M_V. Molecular weight of the vapor depends upon the mole fractions of the components in the vapor.

$$M_V = \sum M_i y_i$$

where:

M_i = molecular weight of the component

y_i = vapor mole fraction

The vapor mole fractions, y_i, are equal to the partial pressure of the component divided by the total vapor pressure of the mixture. Therefore,

$$y_{benzene} = P_{partial}/P_{total} = 0.833/0.880 = 0.947$$

Similarly, for toluene and cyclohexane,

$$y_{toluene} = P_{partial}/P_{total} = 0.020$$

$$y_{cyclohexane} = P_{partial}/P_{total} = 0.033$$

The mole fractions of the vapor components sum to 1.0.

The molecular weight of the vapor can be calculated as follows:

Component	M_i	y_i	M_v
Benzene	78.1	0.947	74.0
Toluene	92.1	0.020	1.84
Cyclohexane	84.2	0.033	2.78
Total			78.6

Since all variables have now been solved, the stock density, W_V, can be calculated:

$$W_v = \frac{M_V P_{VA}}{R\ T_{LA}}$$

$$\frac{(78.6)\ (0.880)}{(10.731)\ (512.36)} = 1.26 \times 10^{-2}\ \frac{\text{lb}}{\text{ft}^3}$$

c. Vapor space expansion factor, K_E.

$$K_E = \frac{\Delta T_V}{T_{LA}} + \frac{\Delta P_V - \Delta P_B}{P_A - P_{VA}} \qquad (1\text{-}16)$$

where:

ΔT_v = daily vapor temperature range, °R

ΔP_v = daily vapor pressure range, °R

ΔP_B = breather vent pressure setting range, psia

P_A = atmospheric pressure, 14.7 psia (given)

P_{VA} = vapor pressure at daily average liquid surface temperature, psia = 0.880 psia (from Step 4b)

T_{LA} = daily average liquid surface temperature, °R = 512.36°R (from Step 4b)

First, calculate the daily vapor temperature range from Equation 1-17,

$$\Delta T_V = 0.72 \Delta T_A + 0.028 \alpha I \qquad (1\text{-}17)$$

where:

ΔT_V = daily vapor temperature range, °R

ΔT_A = daily ambient temperature range = $T_{AX} - T_{AN}$

α = tank paint solar absorptance, 0.17 (given)

I = daily total solar insolation, 1,568 $\text{Btu/ft}^3 \cdot \text{day}$ (given)

From Table 7.1-6, for Denver, Colorado:

T_{AX} = 64.3°F

T_{AN} = 36.2°F

Converting to °R,

$T_{AX} = 64.3 + 460 = 524.3°R$

$T_{AN} = 36.2 + 460 = 496.2°R$

From Equation 1-17 and $\Delta T_A = T_{AX} - T_{AN}$

$\Delta T_A = 524.3 - 496.2 = 28.1°R$

Therefore,

$\Delta T_V = 0.72\ (28.1) + (0.028)(0.17)(1568) = 27.7°R$

Second, calculate the daily vapor pressure range using Equation 1-18,

$$\Delta P_V = P_{VX} - P_{VN} \tag{1-18}$$

where:

P_{VX}, P_{VN} = vapor pressures at the daily maximum, minimum liquid temperatures can be calculated in a manner similar to the P_{VA} calculation shown earlier.

T_{LX} = maximum liquid temperature, $T_{LA} + 0.25\ \Delta T_V$ (from Figure 7.1-16)

T_{LN} = minimum liquid temperature, $T_{LA} - 0.25\ \Delta T_V$ (from Figure 7.1-16)

T_{LA} = 512.36 (from Step 4b)

ΔT_V = 27.7°R

$T_{LX} = 512.36 + (0.25)\ (27.7) = 519.3°R$ or 59°F

$T_{LN} = 512.36 - (0.25)\ (27.7) = 505.4°R$ or 45°F

Using Antoine's equation, the pure vapor pressures of each component at the minimum liquid surface temperature are:

$$P_{benzene} = 0.758 \text{ psia}$$

$$P_{toluene} = 0.203 \text{ psia}$$

$$P_{cyclohexane} = 0.794 \text{ psia}$$

The partial pressures for each component at T_{LN} can then be calculated as follows:

Component	P at 45°F	x_i	$P_{partial}$
Benzene	0.758	0.90	0.68
Toluene	0.203	0.07	0.01
Cyclohexane	0.794	0.03	0.02
Total		1.0	0.71

Using Antoine's equation, the pure vapor pressure of each component at the maximum liquid surface temperature are:

$$P_{benzene} = 1.14 \text{ psia}$$

$$P_{toluene} = 0.32 \text{ psia}$$

$$P_{cyclohexane} = 1.18 \text{ psia}$$

The partial pressures for each component at T_{LX} can then be calculated as follows:

Component	P	x_i	$P_{partial}$
Benzene	1.14	0.90	1.03
Toluene	0.32	0.07	0.02
Cyclohexane	1.18	0.03	0.04
Total		1.0	1.09

Therefore, the vapor pressure range, $\Delta P_V = P_{LX} - P_{LN} = 1.09 - 0.710 = 0.38$ psia.

Next, calculate the breather vent pressure, ΔP_B, from Equation 1-20:

$$\Delta P_B = P_{BP} - P_{BV} \tag{1-20}$$

where:

P_{BP} = breather vent pressure setting = 0.03 psia (given) (see Note 3 to Equation 1-16)

P_{BV} = breather vent vacuum setting = -0.03 psig (given) (see Note 3 to Equation 1-16)

ΔP_B = 0.03 - (-0.03) = 0.06 psig

Finally, K_E can be calculated by substituting values into Equation 1-16.

$$K_E = \frac{(27.7)}{(512.36)} + \frac{0.38 - 0.06 \text{ psia}}{14.7 \text{ psia} - 0.880 \text{ psia}} = 0.077$$

d. Vented vapor space saturation factor, K_S

$$K_S = \frac{1}{1 + 0.053\, P_{VA}\, H_{VO}} \tag{1-22}$$

where:

P_{VA} = 0.880 psia (from Step 4b)

H_{VO} = 4.0625 ft (from Step 4a)

$$K_S = \frac{1}{1 + 0.053(0.880)(4.0625)} = 0.841$$

5. Calculate standing storage losses.

$$L_S = 365\ W_V V_V K_E K_S$$

Using the values calculated above:

W_V = 1.26 x 10^{-2} $\underline{\text{ft}^3}$ (from Step 4b)

V_V = 114.86 ft^3 (from Step 4a)

K_E = 0.077 (from Step 4c)

K_S = 0.841 (from Step 4d)

L_S = 365 $(1.26\text{x}10^{-2})$(114.86)(0.077)(0.841) = 34.2 lb/yr

6. Calculate working losses. The amount of VOCs emitted as a result of filling operations can be calculated from the following equation:

$$L_W = (0.0010)\ (M_V)(P_{VA})(Q)(K_N)(K_P) \tag{1-23}$$

From Step 4:

M_V = 78.6 (from Step 4b)

P_{VA} = 0.880 psia (from Step 4b)

Q = 8,450 gal/yr x 2.381 bbl/100 gal = 201 bbl/yr (given)

K_P = product factor, dimensionless = 1 for volatile organic liquids, 0.75 for crude oils

K_N = 1 for turnovers ≤36 (given)

N = turnovers per year = 5 (given)

L_W = (0.0010)(78.6)(0.880)(201)(1)(1) = 13.9 lb/yr

7. Calculate total losses, L_T.

$$L_T = L_S + L_W$$

where:

L_S = 34.2 lb/yr

L_W = 13.9 lb/yr

L_T = 34.2 + 13.9 = 48.1 lb/yr

8. Calculate the amount of each component emitted from the tank. The amount of each component emitted is equal to the weight fraction of the component in the vapor times the amount of total VOC emitted. Assuming 100 moles of vapor are present, the number of moles of each component will be equal to the mole fraction multiplied by 100. This assumption is valid regardless of the actual number of moles present. The vapor mole fractions were determined in 4b. The weight of a component present in a mixture is equal to the product of the number of moles and molecular weight, M_i, of the component. The weight fraction of each component is calculated as follows:

$$\text{Weight fraction} = \frac{\text{pounds}_i}{\text{total pounds}}$$

Therefore,

Component	No. of Moles	x	M_i	=	Pounds_i	Weight Fraction
Benzene	(0.947 x 100) = 94.7		78.1		7,396	0.94
Toluene	(0.02 x 100) = 2.0		92.1		184	0.02
Cyclohexane	(0.033 x 100) = 3.3		84.3		278	0.04
Total	100				7,858	1.0

The amount of each component emitted is then calculated as:

$$\text{Emissions of component}_i = (\text{weight fraction}_i)(L_T)$$

Component	Weight Fraction	x	Total VOC Emitted, lb/yr	=	Emissions, lb/yr
Benzene	0.94		48.1		45.2
Toluene	0.02		48.1		0.96
Cyclohexane	0.04		48.1		1.92
Total					48.1

Example 2 - Chemical Mixture In A Horizontal Tank -

Assuming that the tank mentioned in Example 1 is now horizontal, calculate emissions. (Tank diameter is 6 ft and length is 12 ft.)

Solution -

Emissions from horizontal tanks can be calculated by adjusting parameters in the fixed roof equations. Specifically, an effective diameter, D_E, is used in place of the tank diameter, D. The vapor space height, H_{VO}, is assumed to be half the actual tank diameter.

1. Horizontal tank adjustments. Make adjustments to horizontal tank values so that fixed roof tank equations can be used. The effective diameter, D_E, is calculated as follows:

$$D_E = \sqrt{\frac{DL}{0.785}}$$

$$D_E = \sqrt{\frac{(6)(12)}{0.785}} = 9.577 \text{ ft}$$

The vapor space height, H_{VO} is calculated as follows:

$$H_{VO} = 1/2\ D = 1/2\ (6) = 3 \text{ ft}$$

2. Given the above adjustments, the standing storage loss, L_S, can be calculated. Calculate values for each affected variable on the standing loss equation.

$$L_S = 365\ (V_V)\ (W_V)\ (K_E)\ (K_S)$$

V_V and K_S depend on the effective tank diameter, D_E, and vapor space height, H_{VO}.

These variables can be calculated using the values derived in Step 1:

$$V_V = \frac{\pi}{4} (D_E)^2 H_{VO}$$

$$V_V = \frac{\pi}{4} (9.577)^2 (3) = 216.10 \text{ ft}^3$$

$$K_S = \frac{1}{1 + (0.053)\,(P_{VA})\,(H_{VO})}$$

$$K_S = \frac{1}{1 + (0.053)\,(0.880)\,(3)} = 0.877$$

3. Calculate standing storage loss using the values calculated in Step 2.

$L_S = 365\,(V_V)(W_V)(K_E)(K_S)$

$V_V = 216.10\ \text{ft}^3$ (from Step 2)

$W_V = 1.26 \times 10^{-2}\ \text{lb/ft}^3$ (from Step 4b, example 1)

$K_E = 0.077$ (from Step 4c, example 1)

$K_S = 0.877$ (from Step 2)

$L_S = (365)(1.26 \times 10^{-2})(216.10)(0.077)(0.877)$

$L_S = 67.1$ lb/yr

4. Calculate working loss. Since the parameters for working loss do not depend on diameter or vapor space height, the working loss for a horizontal tank of the same capacity as the tank in Example 1 will be the same.

$L_W = 13.9$ lb/yr

5. Calculate total emissions.

$L_T = L_S + L_W$

$L_T = 67.1 + 13.9 = 81$ lb/yr

Example 3 - Chemical Mixture In An External Floating Roof Tank -

Determine the yearly emission rate of a mixture that is 75 percent benzene, 15 percent toluene, and 10 percent cyclohexane, by weight, from a 100,000-gallon external floating roof tank with a pontoon roof. The tank is 20 feet in diameter. The tank has 10 turnovers per year. The tank has a mechanical shoe seal (primary seal) and a shoe-mounted secondary seal. The tank is made of welded steel and has a light rust covering the inside surface of the shell. The tank shell is painted white, and the tank is located in Newark, New Jersey. The floating roof is equipped with the following fittings: (1) an ungasketed access hatch with an unbolted cover, (2) an unspecified number of ungasketed vacuum breakers with weighted mechanical actuation, and (3) ungasketed gauge hatch/sample wells with weighted mechanical actuation.

Solution -

1. Determine tank type. The tank is an external floating roof storage tank.

2. <u>Determine estimating methodology</u>. The product consists of 3 organic liquids, all of which are miscible in each other, which make a homogenous mixture if the material is well mixed. The tank emission rate will be based upon the properties of the mixture. Because the components have similar structures and molecular weights, Raoult's law is assumed to apply to the mixture.

3. <u>Select equations to be used</u>. For an external floating roof tank,

$$L_T = L_{WD} + L_R + L_F \tag{2-1}$$

$$L_{WD} = (0.943)\ QCW_L/D \tag{2-4}$$

$$L_R = K_R v^n P^* D M_V K_C \tag{2-2}$$

$$L_F = F_F P^* M_V K_C \tag{2-5}$$

where:

L_T = total loss, lb/yr

L_{WD} = withdrawal loss, lb/yr

L_R = rim seal loss from external floating roof tanks, lb/yr

L_F = roof fitting loss, lb/yr

Q = product average throughput, bbl/yr

C = product withdrawal shell clingage factor, bbl/1,000 ft^2; see Table 7.1-10

W_L = density of product, lb/gal

D = tank diameter, ft

K_R = seal factor, lb-mole/[ft(mph)^n • ft • yr)]

v = average wind speed for the tank site, mph

n = seal wind speed exponent, dimensionless

P* = the vapor pressure function, dimensionless

$= (P_{VA}/P_A)/(1 + [1-(P_{VA}/P_A)]^{0.5})^2$

where:

P_{VA} = the true vapor pressure of the materials stored, psia

P_A = atmospheric pressure, psia = 14.7

M_V = molecular weight of product vapor, lb/lb-mole

K_C = product factor, dimensionless

F_F = the total deck fitting loss factor, lb-mole/yr

$$= \sum_{i}^{n_f} = 1(N_{F_i}K_{F_i}) = [(N_{F_1}K_{F_1}) + (N_{F_2}K_{F_2}) + \ldots + N_{F_{n_f}}K_{F_{n_f}})] \quad (2\text{-}6)$$

where:

N_{F_i} = number of fittings of a particular type, dimensionless. N_{F_i} is determined for the specific tank or estimated from Tables 7.1-11, 7.1-12, or 7.1-13

K_{F_i} = roof fitting loss factor for a particular type of fitting, lb-mol/yr. K_{F_i} is determined for each fitting type from Equation 2-7 and the loss factors in Table 7.1-11.

n_f = number of different types of fittings, dimensionless; $n_f = 3$ (given)

4. Identify parameters to be calculated/determined from tables. In this example, the following parameters are not specified: W_L, F_F, C, K_R, v, n, P_{VA}, P*, M_V, and K_C. Some typical assumptions that can be made are as follows:

v = average wind speed for the tank site = 10.2 mph (see Table 7.1-9)

K_C = 1.0 for volatile organic liquids (given in Part 7.1.3.2)

C = 0.0015 bbl/1,000 ft^2 for tanks with light rust (from Table 7.1-10)

K_R = 0.8 (from Table 7.1-8)

n = 1.2 (from Table 7.1-8)

F_F, W_L, P_{VA}, P*, and M_V still need to be calculated.

F_F is estimated by calculating the individual K_{F_i} and N_{F_i} for each of the 3 types of roof fittings used in this example. For the ungasketed access hatches with unbolted covers, the K_F value can be calculated using information in Table 7.1-11. For this fitting, $K_{Fa} = 2.7$, $K_{Fb} = 7.1$, and m = 1. There is normally 1 access hatch. So,

$$K_{Faccess} = K_{Fa} + K_{Fb}(v^m)$$

$$= 2.7 + (7.1)(10.2)^1$$

$K_{Faccess\ hatch}$ = 75.1 lb-mole/yr

$N_{Faccess\ hatch}$ = 1

The number of vacuum breakers can be taken from Table 7.1-12. For tanks with a diameter of 20 feet and a pontoon roof, the number of vacuum breakers is 1. Table 7.1-11 provides fitting factors for weighted mechanical action, ungasketed vacuum breakers when the average wind speed is 10.2 mph. Based on this table, $K_{Fa} = 1.1$, $K_{Fb} = 3.0$, and $m = 1$. So,

$$K_{F\text{vacuum breaker}} = K_{Fa} + K_{Fb}\,(v^m)$$

$$K_{F\text{vacuum breaker}} = 1.1 + 3.0\,(10.2)^1$$

$$K_{F\text{vacuum breaker}} = 31.7 \text{ lb-mole/yr}$$

$$N_{F\text{vacuum breaker}} = 1$$

For the ungasketed gauge-hatch/sample wells with weighted mechanical actuation, Table 7.1-11 indicates that tanks normally have only 1. This table also indicates that $K_{Fa} = 0.91$, $K_{Fb} = 2.4$, and $m = 1$. Therefore,

$$K_{F\text{gauge-hatch/sample well}} = K_{Fa} + K_{Fb}\,(v^m)$$

$$K_F = 0.91 + 2.4\,(10.2)^1$$

$$K_{F\text{gauge-hatch/sample well}} = 25.4 \text{ lb-mol/yr}$$

$$N_{F\text{gauge-hatch/sample well}} = 1$$

F_F can be calculated from Equation 2-6:

$$F_F = \sum_{i=1}^{3}(K_{F_i})(N_{F_i})$$

$$= (75.1)(1)+(31.7)(1)+(25.4)(1)$$

$$= 132.2 \text{ lb-mole/yr}$$

5. <u>Calculate mole fractions in the liquid</u>. The mole fractions of components in the liquid must be calculated in order to estimate the vapor pressure of the liquid using Raoult's law. For this example, the weight fractions (given as 75 percent benzene, 15 percent toluene, and 10 percent cyclohexane) of the mixture must be converted to mole fractions. First, assume that there are 1000 lb of liquid mixture. Using this assumption, the mole fractions calculated will be valid no matter how many pounds of liquid actually are present. The corresponding amount (pounds) of each component is equal to the product of the weight fraction and the assumed total pounds of mixture of 1000. The number of moles of each component is calculated by dividing the weight of each component by the molecular weight of the component. The mole fraction of each component is equal to the number of moles of each component divided by the total number of moles. For this example the following values are calculated:

Component	Weight Fraction	Weight, lb	Molecular Weight, M_i, lb/lb-moles	Moles	Mole Fraction
Benzene	0.75	750	78.1	9.603	0.773
Toluene	0.15	150	92.1	1.629	0.131
Cyclohexane	0.10	100	84.2	1.188	0.096
Total	1.00	1,000		12.420	1.000

For example, the mole fraction of benzene in the liquid is 9.603/12.420 = 0.773.

6. <u>Determine the daily average liquid surface temperature</u>. The daily average liquid surface temperature is equal to:

$$T_{LA} = 0.44\ T_{AA} + 0.56\ T_B + 0.0079\ \alpha\ I$$

$$T_{AA} = (T_{AX} + T_{AN})/2$$

$$T_B = T_{AA} + 6\alpha - 1$$

For Newark, New Jersey (from Table 7.1-6):

$$T_{AX} = 62.5°F = 522.2°R$$

$$T_{AN} = 45.9°F = 505.6°R$$

$$I = 1{,}165\ Btu/ft^2 \cdot d$$

From Table 7.1-7, $\alpha = 0.17$

Therefore;

$$T_{AA} = (522.2 + 505.6)/2 = 513.9°R$$

$$T_B = 513.9°R + 6\ (0.17) - 1 = 513.92°R$$

$$T_{LA} = 0.44\ (513.9) + 0.56\ (513.92) + 0.0079\ (0.17)(1{,}165)$$

$$= 515.5°R = 55.8°F = 56°F$$

7. <u>Calculate partial pressures and total vapor pressure of the liquid</u>. The vapor pressure of each component at 56°F can be determined using Antoine's equation. Since Raoult's law is assumed to apply in this example, the partial pressure of each component is the liquid mole fraction (x_i) times the vapor pressure of the component (P).

Component	P at 56°F	x_i	$P_{partial}$
Benzene	1.04	0.773	0.80
Toluene	0.29	0.131	0.038
Cyclohexane	1.08	0.096	0.104
Total		1.00	0.942

The total vapor pressure of the mixture is estimated to be 0.942 psia.

8. Calculate mole fractions in the vapor. The mole fractions of the components in the vapor phase are based upon the partial pressure that each component exerts (calculated in Step 7).

So for benzene,

$$y_{benzene} = P_{partial}/P_{total} = 0.80/0.942 = 0.85$$

where:

$y_{benzene}$ = mole fraction of benzene in the vapor

$P_{partial}$ = partial pressure of benzene in the vapor, psia

P_{total} = total vapor pressure of the mixture, psia

Similarly,

$y_{toluene} = 0.038/0.942 = 0.040$

$y_{cyclohexane} = 0.104/0.942 = 0.110$

The vapor phase mole fractions sum to 1.0.

9. Calculate molecular weight of the vapor. The molecular weight of the vapor depends upon the mole fractions of the components in the vapor.

$$M_V = \Sigma M_i y_i$$

where:

M_v = molecular weight of the vapor

M_i = molecular weight of the component

y_i = mole fraction of component in the vapor

Component	M_i	y_i	$M_V = \Sigma(M_i)(y_i)$
Benzene	78.1	0.85	66.39
Toluene	92.1	0.040	3.68
Cyclohexane	84.2	0.110	9.26
Total		1.00	79.3

The molecular weight of the vapor is 79.3 lb/lb-mole.

10. Calculate weight fractions of the vapor. The weight fractions of the vapor are needed to calculate the amount (in pounds) of each component emitted from the tank. The weight fractions are related to the mole fractions calculated in Step 7 and molecular weight calculated in Step 9:

$$Z_{i,v} = \frac{y_i M_i}{M_v}$$

$$Z_{i,v} = \frac{(0.85)(78.1)}{79.3} = 0.84 \text{ for benzene}$$

$$Z_{i,v} = \frac{(0.040)(92.1)}{79.3} = 0.04 \text{ for toluene}$$

$$Z_{i,v} = \frac{(0.110)(84.2)}{79.3} = 0.12 \text{ for cyclohexane}$$

11. Calculate total VOC emitted from the tank. The total VOC emitted from the tank is calculated using the equations identified in Step 3 and the parameters calculated in Steps 4 through 9.

$$L_T = L_{WD} + L_R + L_F$$

a. Calculate withdrawal losses:

$$L_{WD} = 0.943\ QCW_L/D$$

where:

Q = 100,000 gal x 10 turnovers/yr (given)

= 1,000,000 gal x 2.381 bbl/100 gal = 23,810 bbl/yr

C = 0.0015 bbl/10^3 ft^2 (from Table 7.1-10)

W_L = 1/[Σ (wt fraction in liquid)/(liquid component density from Table 7.1-3)]

Weight fractions

Benzene = 0.75 (given)

Toluene = 0.15 (given)

Cyclohexane = 0.10 (given)

Liquid densities

Benzene = 7.4 (see Table 7.1-3)

Toluene = 7.3 (see Table 7.1-3)

Cyclohexane = 6.5 (see Table 7.1-3)

W_L = 1/[(0.75/7.4) + (0.15/7.3) + (0.10/6.5)]

= 1/(0.101 + 0.0205 + 0.0154)

= 1/0.1369

= 7.3 lb/gal

D = 20 ft (given)

L_{WD} = 0.943 QCW_L/D

= [0.943(23,810)(0.0015)(7.3)/20]

= 12.3 lb of VOC/yr from withdrawal losses

b. Calculate rim seal losses:

$$L_R = K_R v^n P^* D M_V K_C$$

where:

K_R = 0.8 (from Step 4)

v = 10.2 mph (from Step 4)

n = 1.2 (from Step 4)

P_{VA} = 0.942 psia (from Step 7)

P^* = $(0.942/14.7)/(1+[1-(0.942/14.7)]^{0.5})^2$ = 0.017 (formula from Step 3)

M_V = 79.3 lb/lb-mole (from Step 9)

L_R = $(0.8)(10.2)^{1.2}(0.017)(20)(79.3)(1.0)$

= 350 lb of VOC/yr from rim seal losses

c. Calculate roof fitting losses:

$$L_F = F_F P^* M_V K_C$$

where:

F_F = 132.2 lb-mole/yr (from Step 4)

P^* = 0.017

M_V = 79.3 lb/lb-mole

K_C = 1.0 (from Step 4)

L_F = (132.2)(0.017)(79.3)(1.0)

= 178 lb/yr of VOC emitted from roof fitting losses

d. Calculate total losses:

$L_T = L_{WD} + L_R + L_F$

$= 12.3 + 350 + 178$

= 540 lb/yr of VOC emitted from tank

12. Calculate amount of each component emitted from the tank. For an external floating roof tank, the individual component losses are determined by a simplified version of Equation 5-2 where L_D (deck seam losses) are negligible:

$$L_{T_i} = (Z_{i,v})(L_R + L_F) + (Z_{i,L})(L_{WD})$$

Therefore,

$L_{Tbenzene}$ = (0.84)(528) + (0.75)(12.3) = 453 lb/yr benzene

$L_{Ttoluene}$ = (0.040)(528) + (0.15)(12.3) = 23 lb/yr toluene

$L_{Tcyclohexane}$ = (0.12)(528) + (0.10)(12.3) = 65 lb/yr cyclohexane

Example 4 - Gasoline In An Internal Floating Roof Tank -

Determine emissions of product from a 1 million gallon, internal floating roof tank containing gasoline (RVP 13). The tank is painted white and is located in Tulsa, Oklahoma. The annual number of turnovers for the tank is 50. The tank is 70 ft in diameter and 35 ft high, and is equipped with a liquid-mounted primary seal plus a secondary seal. The tank has a column-supported fixed roof. The tank's deck is welded and equipped with the following: (1) 2 access hatches with an unbolted, ungasketed cover; (2) an automatic gauge-float well with an unbolted, ungasketed cover; (3) a pipe column well with a flexible fabric sleeve seal; (4) a sliding cover, gasketed ladder well; (5) fixed roof legs; (6) a slotted sample pipe well with a gasketed sliding cover; and (7) a weighted, gasketed vacuum breaker.

Solution -

1. Determine tank type. The following information must be known about the tank in order to use the internal floating roof equations:

- the number of columns
- the effective column diameter
- the system seal description (vapor- or liquid-mounted, primary or secondary seal)
- the deck fitting types and the deck seam length

Some of this information depends on specific construction details, which may not be known. In these instances, approximate values are provided for use.

2. Determine estimating methodology. Gasoline consists of many organic compounds, all of which are miscible in each other, which form a homogenous mixture. The tank emission rate will be based on the properties of RVP 13 gasoline. Since vapor pressure data have already been compiled, Raoult's law will not be used. The molecular weight of gasoline also will be taken from a table and will not be calculated. Weight fractions of components will be assumed to be available from *SPECIATE* database.

3. Select equations to be used.

$$L_T = L_{WD} + L_R + L_F + L_D \qquad (3\text{-}1)$$

$$L_{WD} = \frac{(0.943)\ QCW_L}{D}\left[1 + \left(\frac{NcFc}{D}\right)\right] \qquad (3\text{-}4)$$

$$L_R = K_R P^* D M_v K_c \qquad (3\text{-}2)$$

$$L_F = F_F P^* M_V K_C \qquad (3\text{-}5)$$

$$L_D = K_D S_D D^2 P^* M_V K_C \qquad (3\text{-}6)$$

where:

L_T = total loss, lb/yr

L_{WD} = withdrawal loss, lb/yr

L_R = rim seal loss, lb/yr

L_F = deck fitting loss, lb/yr

L_D = deck seam loss, lb/yr

For this example:

Q = product average throughput, bbl/yr [tank capacity (bbl/turnover) x turnovers/yr]

C = product withdrawal shell clingage factor, bbl/1,000 ft^2

W_L = density of liquid, lb/gal

D = tank diameter, ft

N_C = number of columns, dimensionless

F_C = effective column diameter, ft

K_R = seal factor, lb-mole/ft • yr

M_V = the average molecular weight of the product vapor, lb/lb-mole

K_C = the product factor, dimensionless

P^* = the vapor pressure function, dimensionless

$= (P_{VA}/P_A)/[1 + (1-([P_{VA}/P_A]))^{0.5})]^2$

where:

P_{VA} = the vapor pressure of the material stored, psia

P_A = average atmospheric pressure at tank location, psia

F_F = the total deck fitting loss factor, lb-mole/yr

$$= \sum_{i=1}^{n_f}(N_{F_i}K_{F_i}) = [(N_{F_1}K_{F_1}) + (N_{F_2}K_{F_2}) + \ldots + (N_{F_{n_f}}K_{F_{n_f}})]$$

where:

N_{F_i} = number of fittings of a particular type, dimensionless. N_{F_i} is determined for the specific tank or estimated from Table 7.1-16

K_{F_i} = deck fitting loss factor for a particular type of fitting, lb-mole/yr. K_{F_i} is determined for each fitting type from Table 7.1-16

n_f = number different types of fittings, dimensionless

K_D = the deck seam loss factor, lb-mole/ft • yr -

= 0.34 for nonwelded roofs

= 0 for welded decks

S_D = deck seam length factor, ft/ft^2

$= L_{seam}/A_{deck}$

where:

L_{seam} = total length of deck seams, ft

A_{deck} = area of deck, ft^2 = $\pi D^2/4$

4. Identify parameters to be calculated or determined from tables. In this example, the following parameters are not specified: N_C, F_C, P, M_V, K_S, P*, K_C, F_F, K_D, and S_D. The density of the liquid (W_L) and the vapor pressure of the liquid (P) can be read from tables and do not need to be calculated. Also, the weight fractions of components in the vapor can be obtained from speciation manuals. Therefore, several steps required in preceding examples will not be required in this example. In each case, if a step is not required, the reason is presented.

The following parameters can be obtained from tables or assumptions:

K_C = 1.0 (for volatile organic liquids)

N_C = 1 (from Table 7.1-15)

F_C = 1.0 (assumed)

K_R = 1.6 (from Table 7.1-14)

M_V = 62 lb/lb-mol (from Table 7.1-2)

W_L = 4.9 lb/gal (from Table 7.1-2)

C = 0.0015 bbl/1,000 ft^2 (from Table 7.1-10)

K_D = 0 (for welded roofs)

S_D = 0.2 ft/ft^2 (from Table 7.1-17)

$F_F = \Sigma (K_{F_i} N_{F_i})$

Substituting values taken from Table 7.1-16 for access hatches, gauge-float wells, pipe column well, ladder well, roof leg, sample pipe well, and vacuum breaker, respectively, yields:

$$F_F = (25)(2) + (28)(1) + (10)(1) + (56)(1) + 0\,[5 + (70/10) + (70^2/600)] + (44)(1) + (0.7)(1)$$

$$= 188.7 \text{ lb-mole/yr}$$

5. Calculate mole fractions in the liquid. This step is not required because liquid mole fractions are only used to calculate liquid vapor pressure, which is given in this example.

6. Calculate the daily average liquid surface temperature. The daily average liquid surface temperature is equal to:

$$T_{LA} = 0.44\ T_{AA} + 0.56\ T_B + 0.0079\ \alpha\ I$$

$$T_{AA} = (T_{AX} + T_{AN})/2$$

$$T_B = T_{AA} + 6\alpha - 1$$

For Tulsa, Oklahoma (from Table 7.1-6):

$$T_{AX} = 71.3°F = 530.97°R$$

$$T_{AN} = 49.2°F = 508.87°R$$

$$I = 1{,}373\ Btu/ft^2 \cdot day$$

From Table 7.1-7, $\alpha = 0.17$

Therefore,

$$T_{AA} = (530.97 + 508.87)/2 = 519.92°R$$

$$T_B = 519.92 + 6(0.17) - 1 = 519.94°R$$

$$T_{LA} = 0.44\ (519.92) + 0.56\ (519.94) + 0.0079(0.17)(1{,}373)$$

$$T_{LA} = 228.76 + 291.17 + 1.84$$

$$T_{LA} = 521.77 \text{ or } 62°F$$

7. Calculate partial pressures and total vapor pressure of the liquid. The vapor pressure of gasoline RVP 13 can be interpolated from Table 7.1-2. The interpolated vapor pressure at 62°F is equal to 7.18 psia. Therefore,

$$P^* = (7.18/14.7)/[1 + (1-(7.18/14.7))^{0.5}]^2$$

$$= 0.166$$

8. Calculate mole fractions of components in the vapor. This step is not required because vapor mole fractions are needed to calculate the weight fractions and the molecular weight of the vapor, which are already specified.

9. Calculate molecular weight of the vapor. This step is not required because the molecular weight of gasoline vapor is already specified.

10. Calculate weight fractions of components of the vapor. The weight fractions of components in gasoline vapor can be obtained from a VOC speciation manual.

11. Calculate total VOC emitted from the tank. The total VOC emitted from the tank is calculated using the equations identified in Step 3 and the parameters specified in Step 4.

$$L_T = L_{WD} + L_R + L_F + L_D$$

a. Calculate withdrawal losses:

$$L_{WD} = [(0.943)QCW_L]/D \text{ X } [1 + (N_CF_C)/D]$$

where:

$Q = (1{,}000{,}000 \text{ gal}) \text{ X } (50 \text{ turnovers/yr})$

$= (50{,}000{,}000 \text{ gal}) \text{ X } (2.381 \text{ bbl}/100 \text{ gal}) = 1{,}190{,}500 \text{ bbl/yr}$

$C = 0.0015 \text{ bbl}/1{,}000 \text{ ft}^2$

$W_L = 4.9 \text{ lb/gal}$

$D = 70 \text{ ft}$

$N_C = 1$

$F_C = 1$

$L_{WD} = [(0.943)(1{,}190{,}500)(0.0015)(4.9)]/70 \text{ X } [1 + (1)(1)/70] = 119.6$ lb/yr VOC for withdrawal losses

b. Calculate rim seal losses:

$$L_R = K_RDP^*M_VK_C$$

where:

$K_R = 1.6 \text{ lb-mole/ft} \cdot \text{yr}$

$P^* = 0.166$

$D = 70 \text{ ft}$

$M_V = 62 \text{ lb/lb-mole}$

$K_C = 1.0$

$L_R = (1.6)(0.166)(70)(62)(1.0) = 1{,}153$ lb/yr VOC from rim seal losses

c. Calculate deck fitting losses:

$$L_F = F_FP^*M_VK_C$$

where:

$F_F = 188.7 \text{ lb-mole/yr}$

$P^* = 0.166$

M_V = 62 lb/lb-mole

K_C = 1

L_F = (188.7)(0.166)(62)(1.0) = 1,942 lb/yr VOC from deck fitting losses

d. Calculate deck seam losses:

$$L_D = K_D S_D D^2 P^* M_V K_C$$

where:

K_D = 0

S_D = 0.2

D = 70 ft

P^* = 0.166

M_V = 62 lb/lb-mole

K_C = 1.0

L_D = $(0.0)(0.2)(70)^2(0.166)(62)(1.0)$ = 0 lb/yr VOC from deck seam losses

e. Calculate total losses

$L_T = L_{WD} + L_R + L_F + L_D$

= 119.6 + 1,153 + 1,942 + 0 = 3,215 lb/yr of VOC emitted from the tank

12. <u>Calculate amount of each component emitted from the tank</u>. The individual component losses are equal to:

$$L_{T,i} = (Z_{i,v})(L_R + L_F + L_D) + (Z_{i,L})(L_{WD})$$

Since the liquid weight fractions are unknown, the individual component losses are calculated based on the vapor weight fraction and the total losses. This procedure should yield approximately the same values as the above equation because withdrawal losses are typically low for floating roof tanks. The amount of each component emitted is the weight fraction of that component in the vapor (obtained from a VOC species data manual and shown below) times the total amount of VOC emitted from the tank. The amount emitted for each component is shown in the following example:

EMISSIONS FOR EXAMPLE 4

Constituent	Weight Percent In Vapor x 3,215 lb/yr	= Pounds Emitted/yr
Air toxics		
Benzene	0.77	24.8
Toluene	0.66	21.2
Ethylbenzene	0.04	1.29
O-xylene	0.05	1.61
Nontoxics		
Isomers of pentane	26.78	861
N-butane	22.95	738
Iso-butane	9.83	316
N-pentane	8.56	275
Isomers of hexane	4.78	154
3-methyl pentane	2.34	75.2
Hexane	1.84	59.2
Others	21.40	688
Total	100	3,215

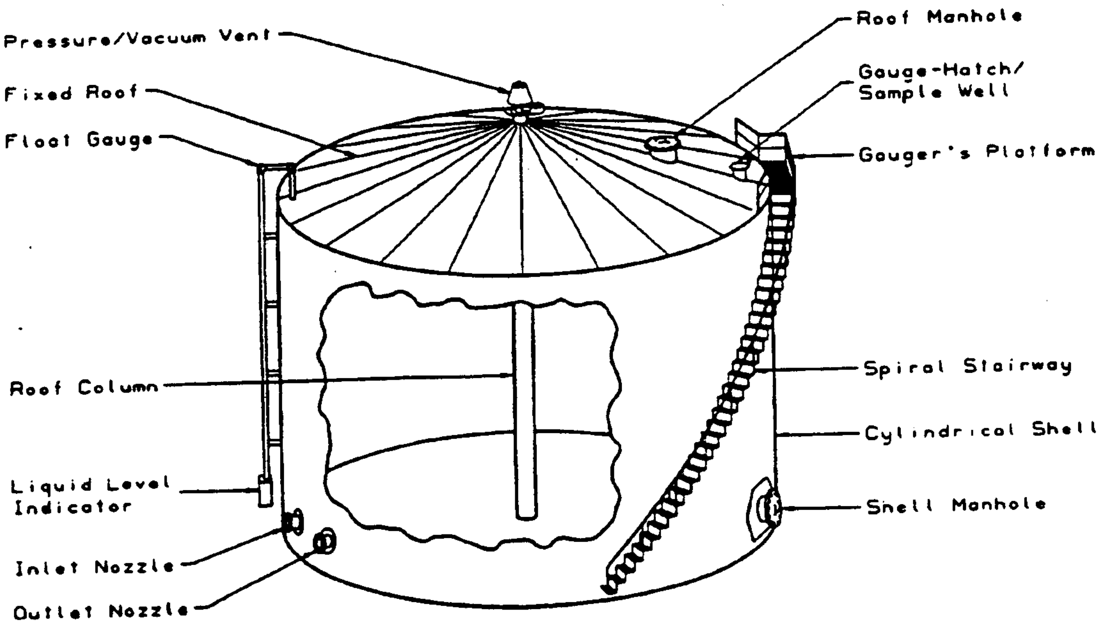


Figure 7.1-1. Typical fixed-roof tank.[1]

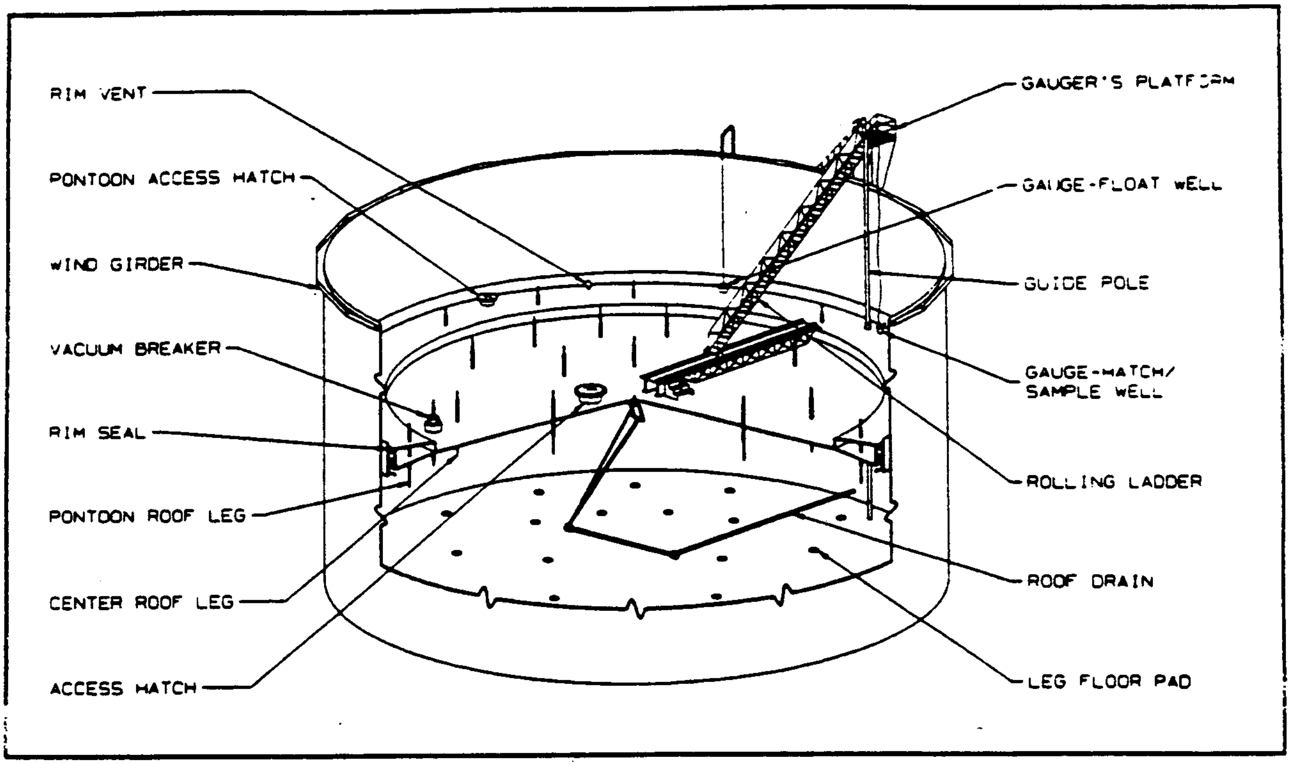


Figure 7.1-2. External floating roof tank (pontoon type).

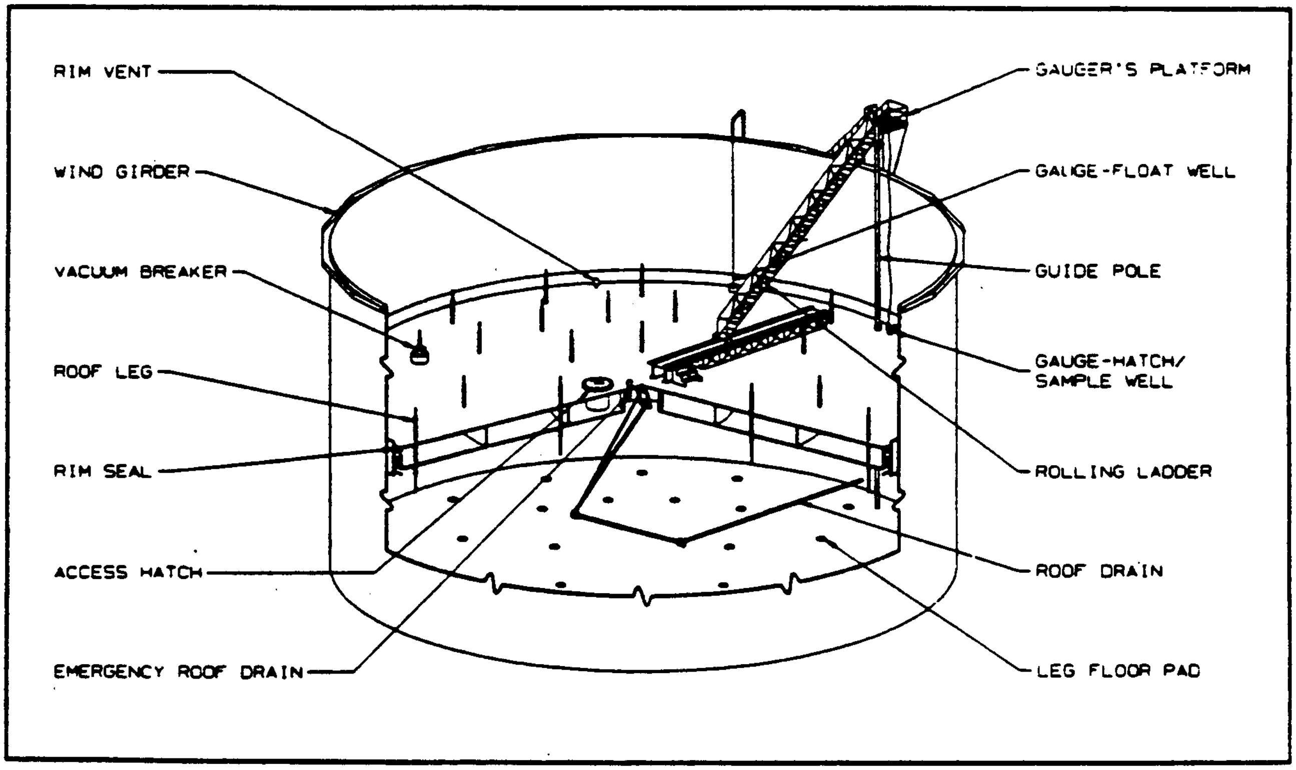
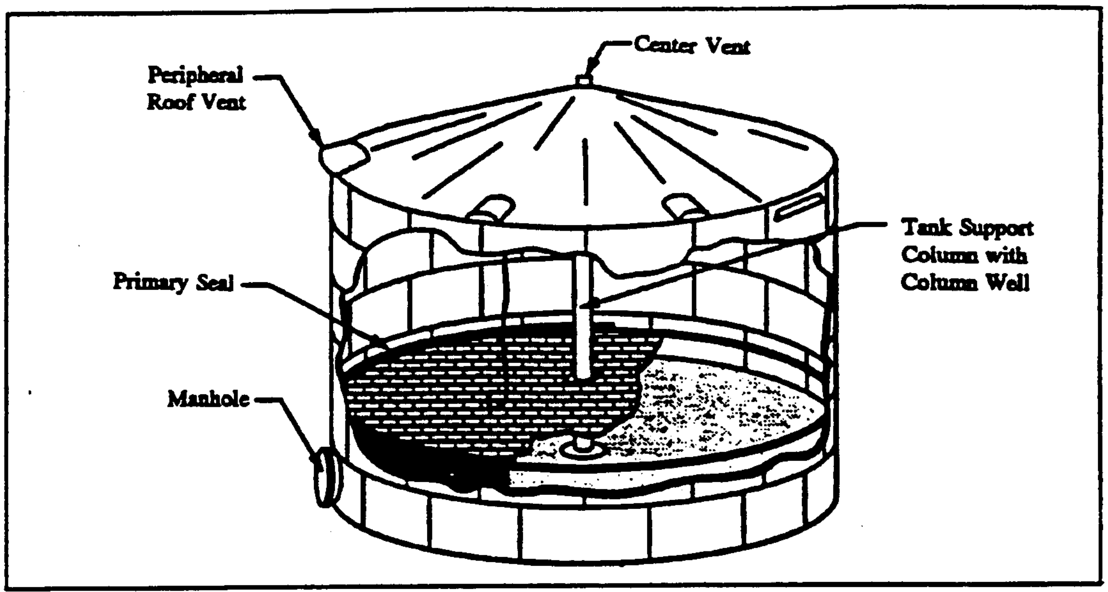
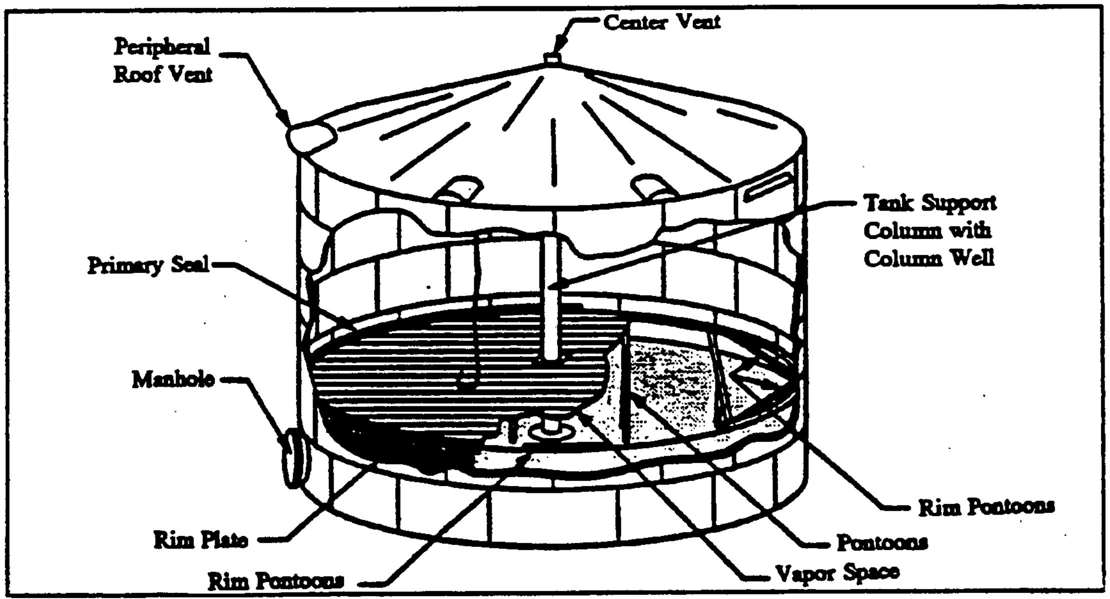


Figure 7.1-3. External floating roof tank (double-deck type).[1]

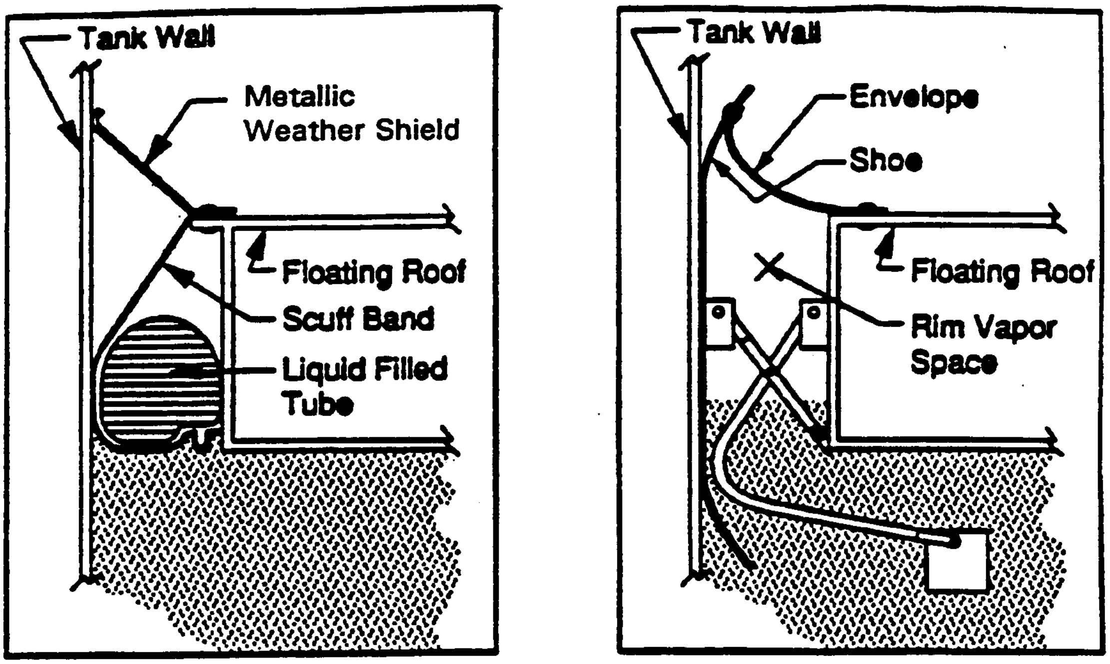


a. Contact internal floating roof



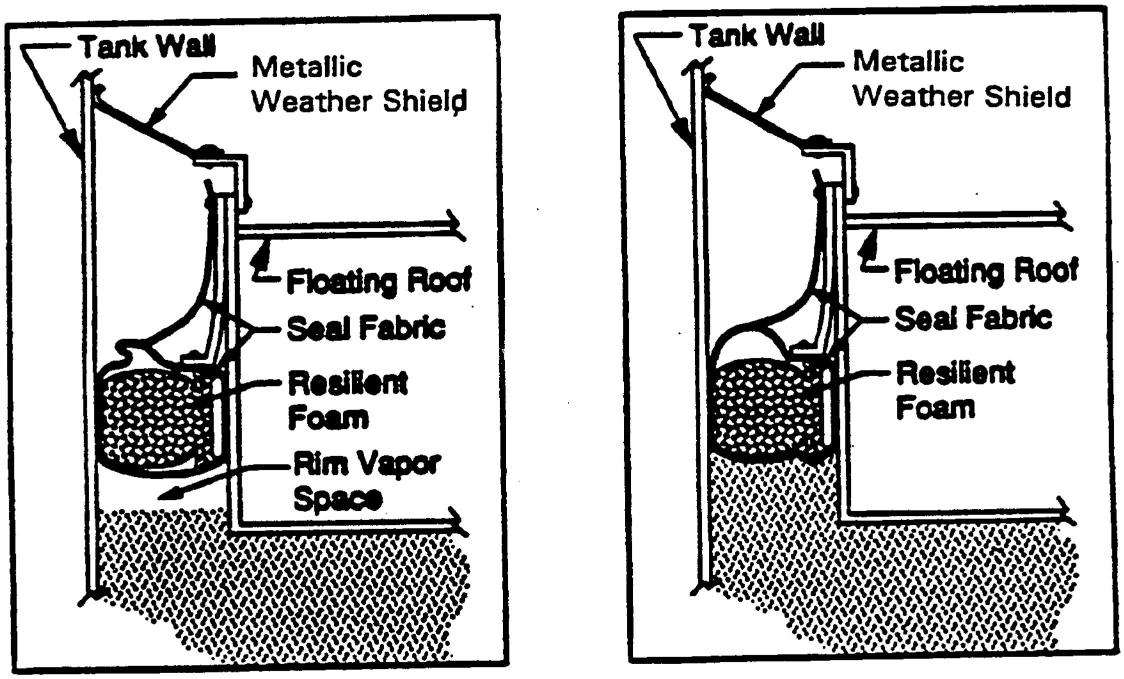
b. Noncontact internal floating roof.

Figure 7.1-4. Internal floating roof tanks.[2]



a. Liquid-filled seal with weather shield.

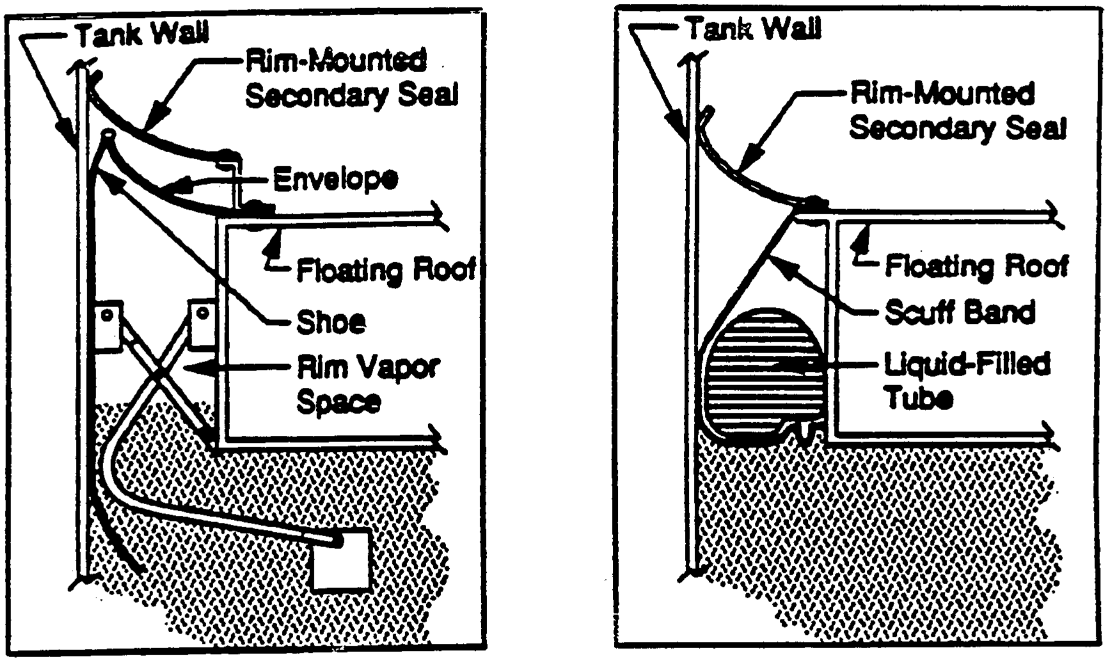
b. Metallic shoe seal.



c. Vapor-mounted resilient foam-filled seal with weather shield.

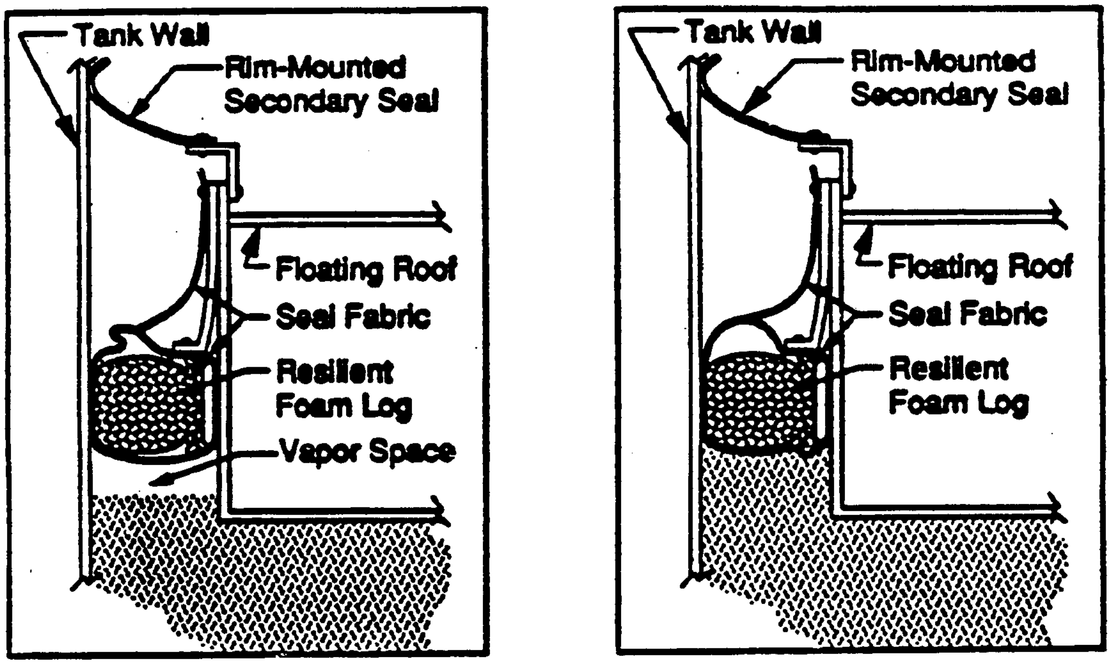
d. Liquid-mounted resilient foam-filled seal with weather shield.

Figure 7.1-5. Primary seals.[2]



a. Shoe seal with rim-mounted secondary seal.

b. Liquid-filled seal with rim-mounted secondary seal.



c. Resilient foam seal (vapor-mounted) with rim-mounted secondary seal.

d. Resilient foam seal (liquid mounted) with rim-mounted secondary seal.

Figure 7.1-6. Rim-mounted secondary seals on external floating roofs.

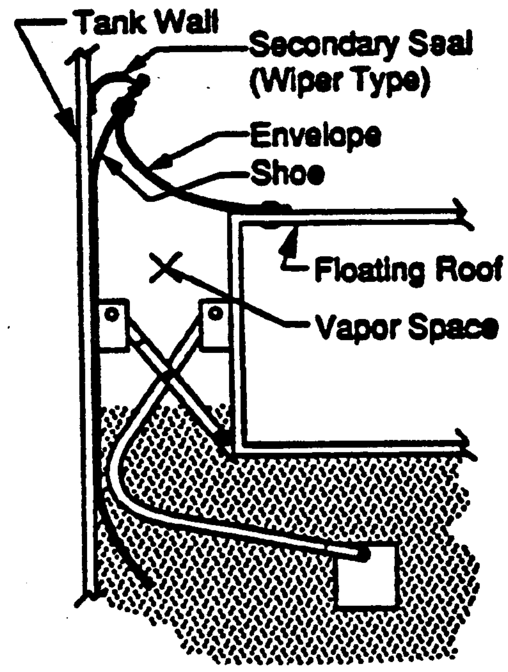
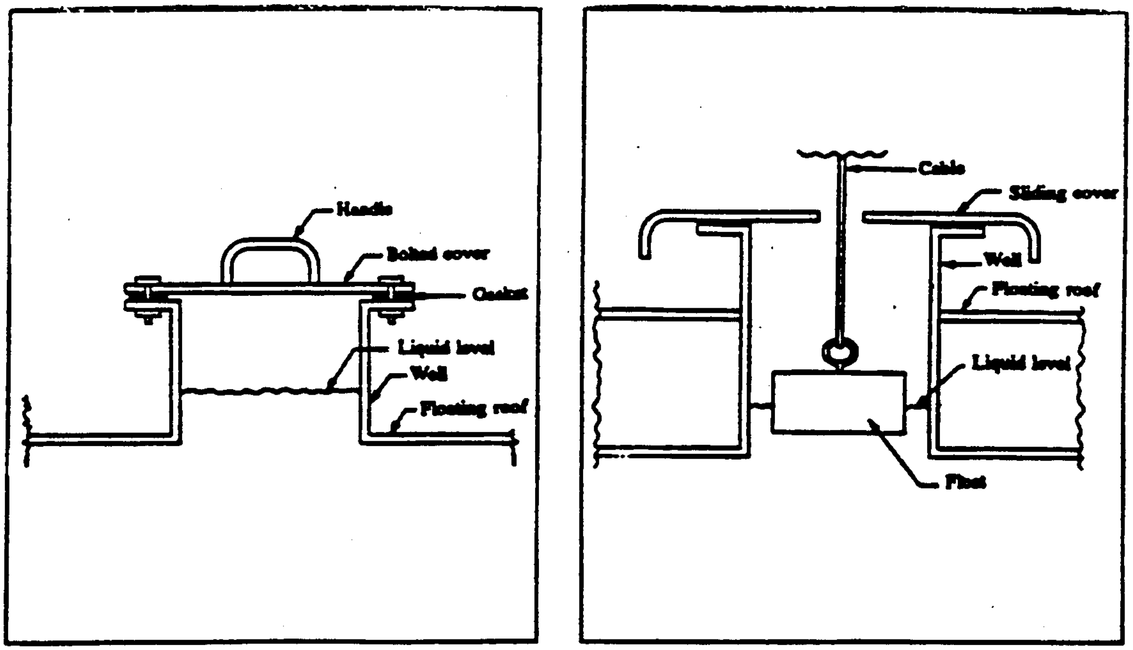
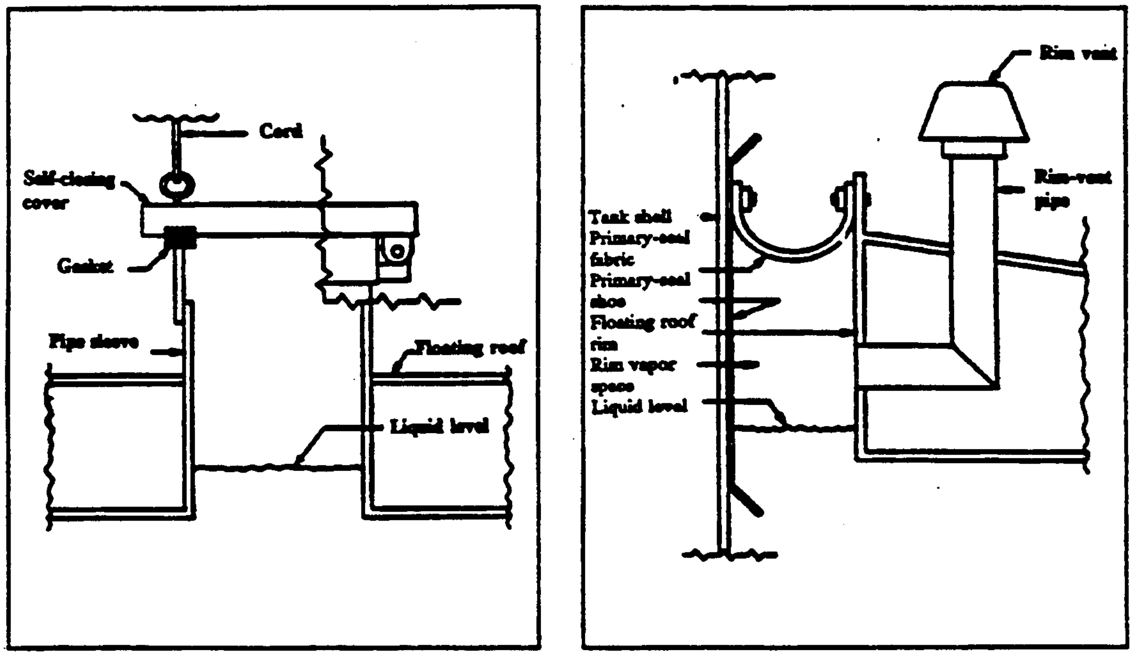


Figure 7.1-7. Metallic shoe seal with shoe-mounted secondary seal.[3]

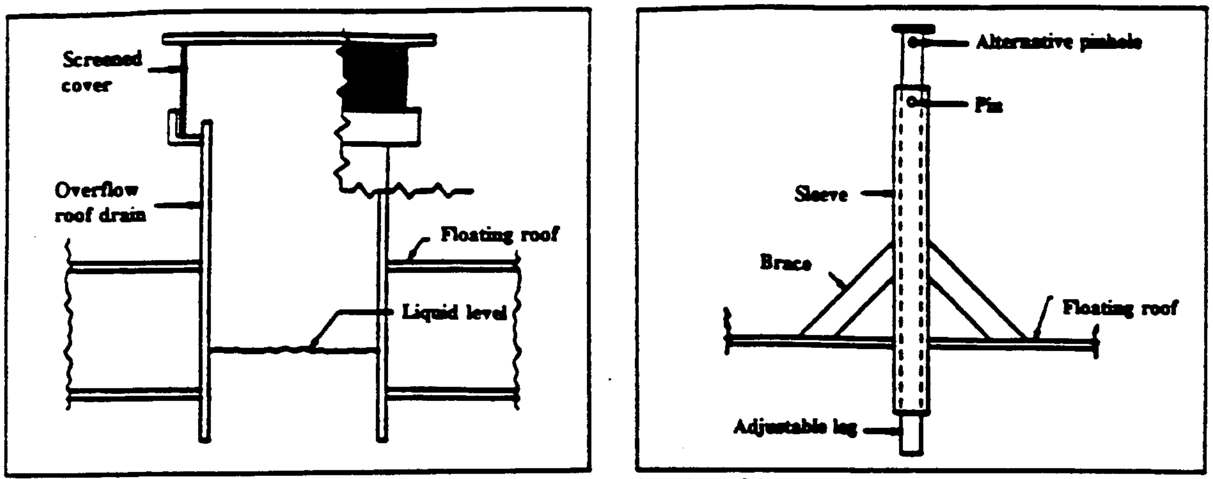


a. Access hatch b. Gauge-float well



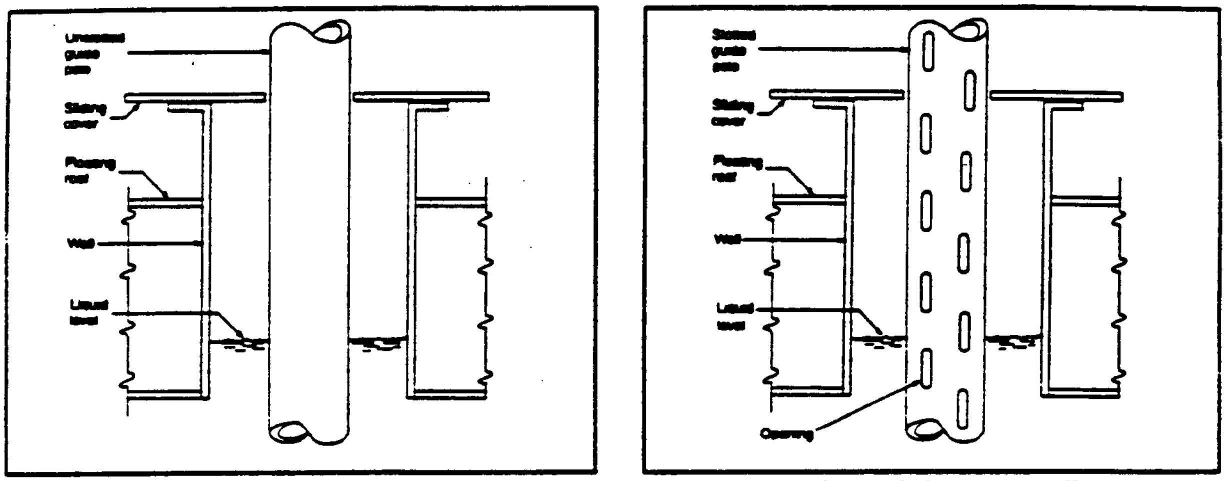
c. Gauge-hatch/sample well d. Rim vent

Figure 7.1-8. Roof fittings for external floating roof tanks.[3]



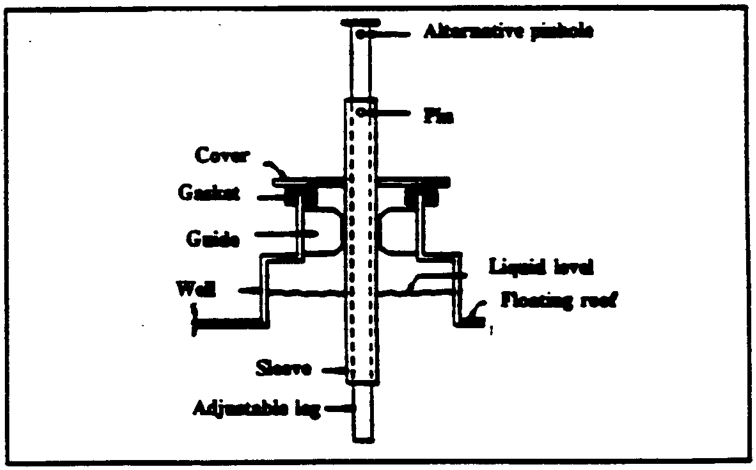
a. Overflow drain

b. Roof leg



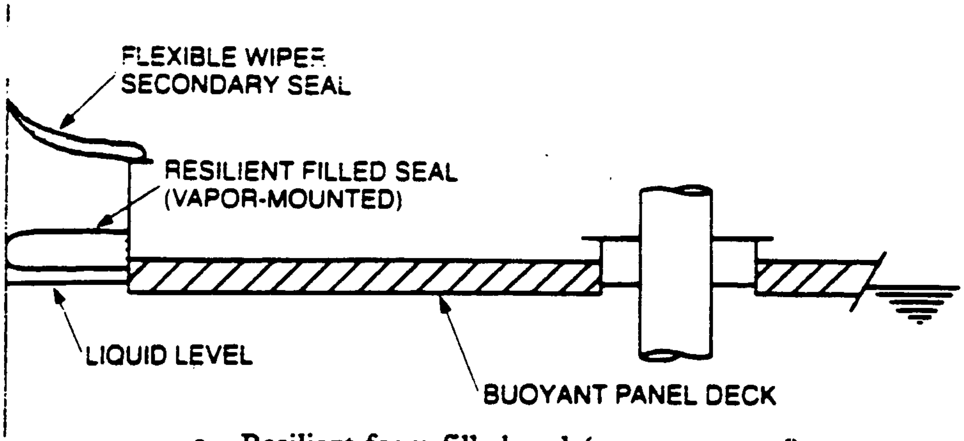
c. Unslotted guide pole well

d. Slotted guide pole/sample well

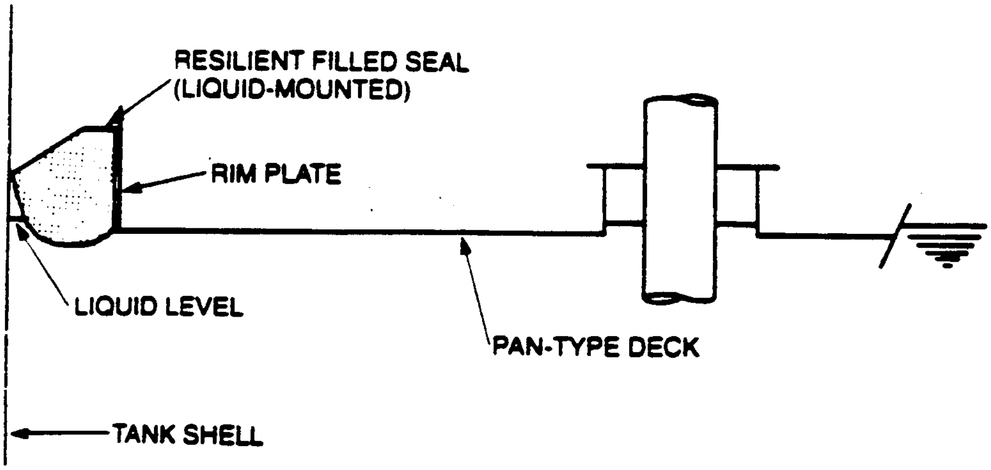


e. Vacuum breaker

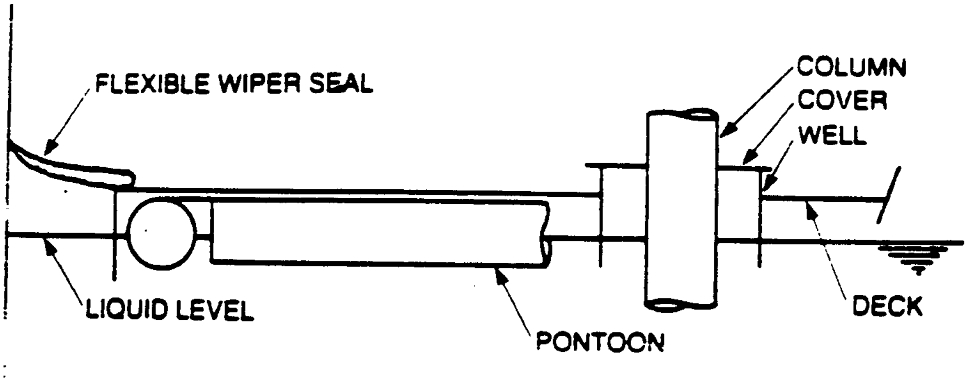
Figure 7.1-9. Roof fittings for external floating roof tanks.[3]



a. **Resilient foam-filled seal (vapor-mounted).**



b. **Resilient foam-filled seal (liquid-mounted).**



c. **Elastomeric wiper seal.**

Figure 7.1-10. Typical floatation devices and perimeter seals for internal floating roofs.[4]

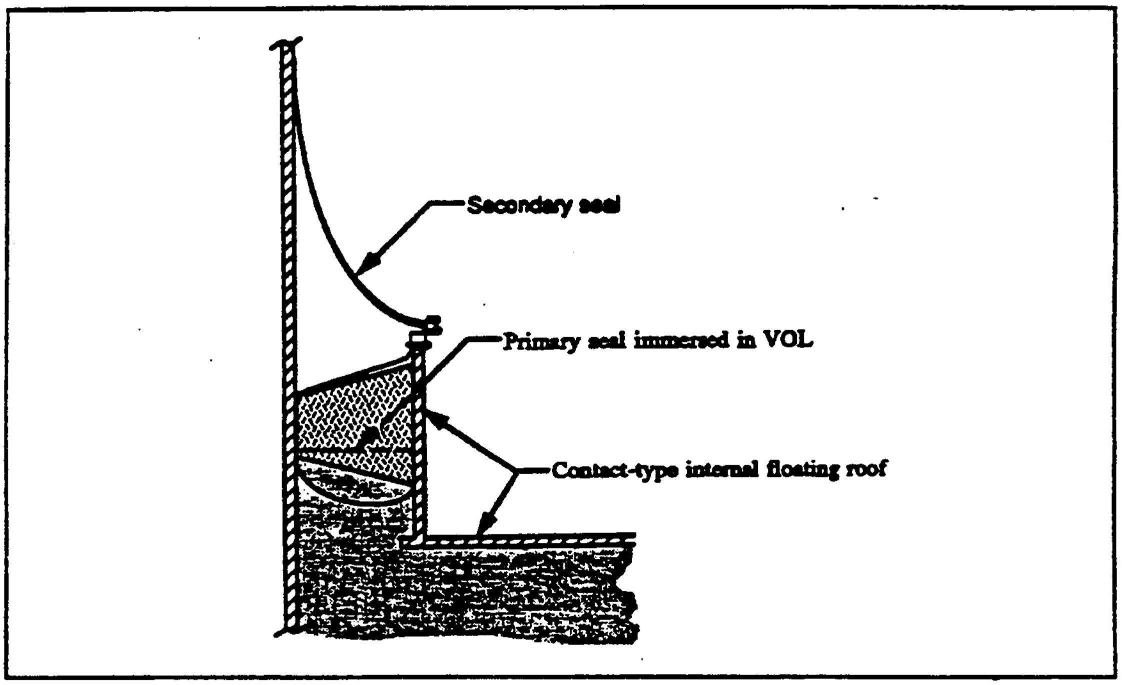


Figure 7.1-11. Rim-mounted secondary seal on an internal floating roof.[5]

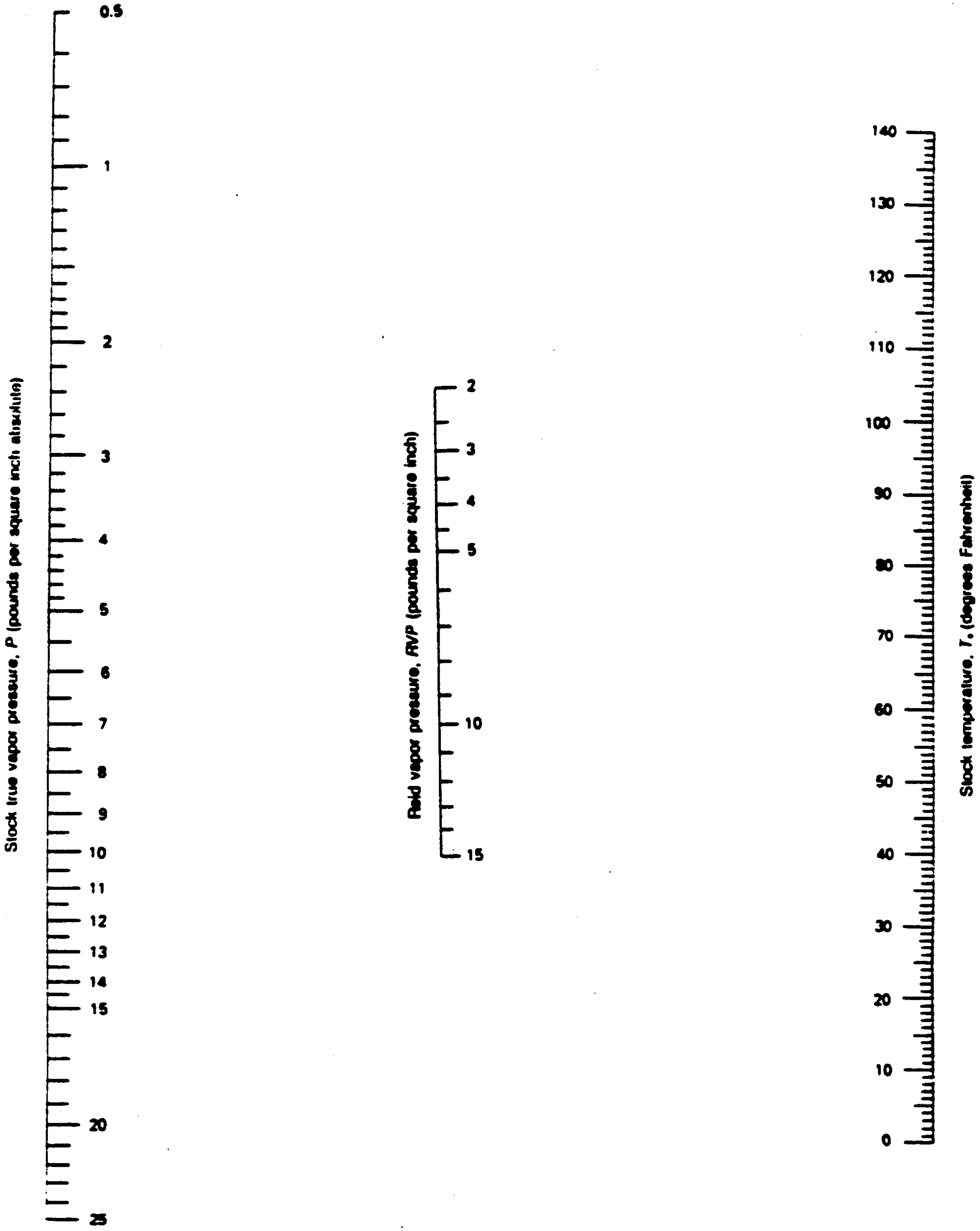
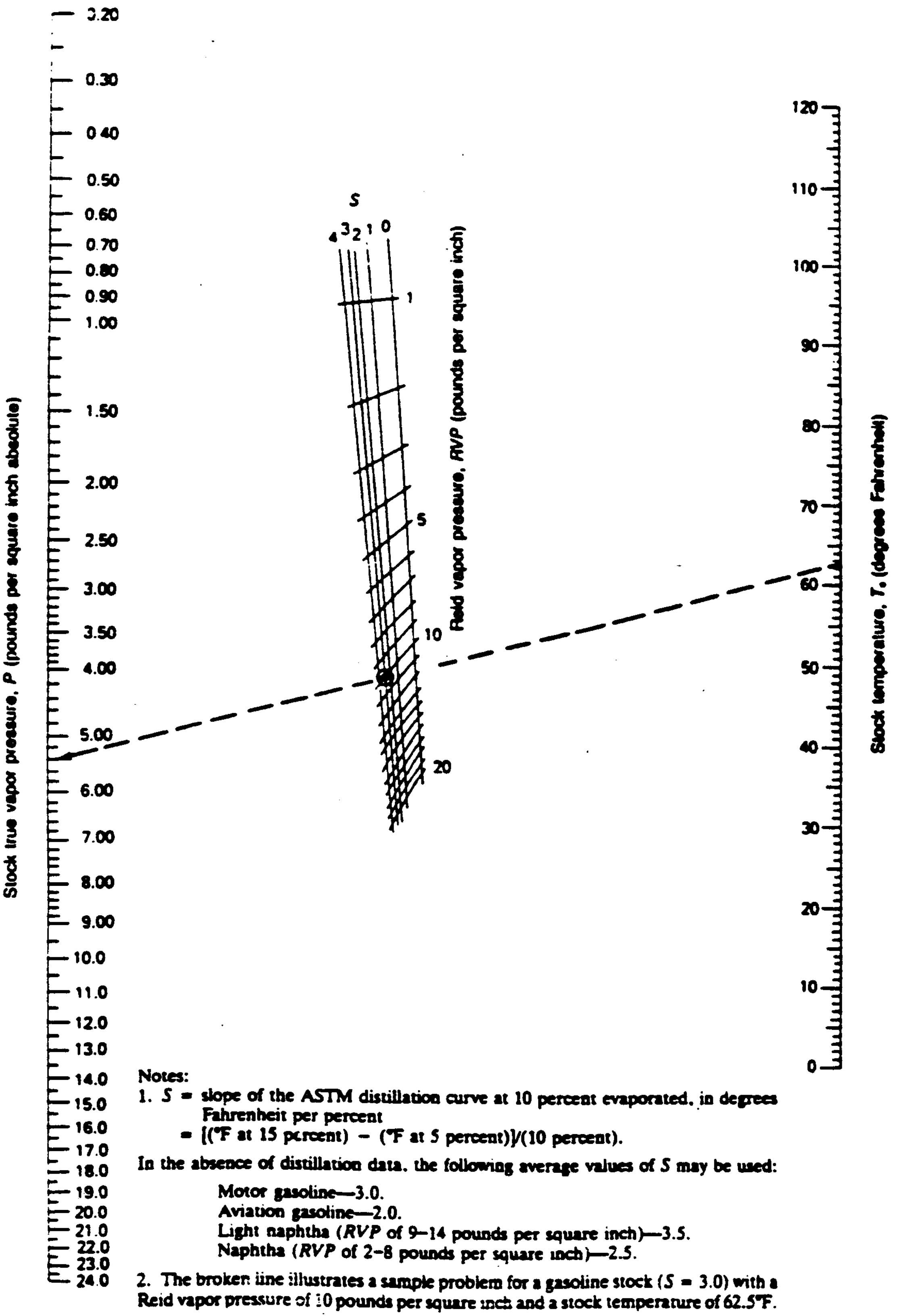


Figure 7.1-12a. True vapor pressure of crude oils with a Reid vapor pressure of 2 to 15 pounds per square inch.[4]



Notes:

1. S = slope of the ASTM distillation curve at 10 percent evaporated, in degrees Fahrenheit per percent
   = [(°F at 15 percent) − (°F at 5 percent)]/(10 percent).

In the absence of distillation data, the following average values of S may be used:

Motor gasoline—3.0.
Aviation gasoline—2.0.
Light naphtha (*RVP* of 9–14 pounds per square inch)—3.5.
Naphtha (*RVP* of 2–8 pounds per square inch)—2.5.

2. The broken line illustrates a sample problem for a gasoline stock (S = 3.0) with a Reid vapor pressure of 10 pounds per square inch and a stock temperature of 62.5°F.

Figure 7.1-13a. True vapor pressure of refined petroleum stocks with a Reid vapor pressure of 1 to 20 pounds per square inch.[4]

$$P = \exp\left\{ \left[\left(\frac{2{,}799}{T + 459.6} \right) \right] \log_{10}(\mathrm{RVP}) - \left(\frac{7{,}261}{T + 459.6} \right) + 12.82 \right\}$$

where:

P = stock true vapor pressure, in pounds per square inch absolute.
T = stock temperature, in degrees Fahrenheit.
RVP = Reid vapor pressure, in pounds per square inch.

Note: This equation was derived from a regression analysis of points read off Figure 7.1-12a over the full range of Reid vapor pressures, slopes of the ASTM distillation curve at 10 percent evaporated, and stock temperatures. In general, the equation yields *P* values that are within +0.05 pound per square inch absolute of the values obtained directly from the nomograph.

Figure 7.1-12b. Equation for true vapor pressure of crude oils with a Reid vapor pressure of 2 to 15 pounds per square inch.[4]

$$P = \exp\left\{ \left[0.7553 - \left(\frac{413.0}{T + 459.6} \right) \right] S^{0.5} \log_{10}(\mathrm{RVP}) - \left[1.854 - \left(\frac{1{,}042}{T + 459.6} \right) \right] S^{0.5} + \left[\left(\frac{2{,}416}{T + 459.6} \right) - 2{,}013 \right] \log_{10}(\mathrm{RVP}) - \left(\frac{8{,}742}{T + 459.6} \right) + 15.64 \right\}$$

where:

P = stock true vapor pressure, in pounds per square inch absolute.
T = stock temperature, in degrees Fahrenheit.
RVP = Reid vapor pressure, in pounds per square inch.
S = slope of the ASTM distillation curve at 10 percent evaporated, in degrees Fahrenheit per percent.

Note: This equation was derived from a regression analysis of points read off Figure 7.1-13a over the full range of Reid vapor pressures, slopes of the ASTM distillation curve at 10 percent evaporated, and stock temperatures. In general, the equation yields *P* values that are within +0.05 pound per square inch absolute of the values obtained directly from the nomograph.

Figure 7.1-13b. Equation for true vapor pressure of refined petroleum stocks with a Reid vapor pressure of 1 to 20 pounds per square inch.[4]

$$A = 15.64 - 1.854\, S^{0.5} - (0.8742 - 0.3280\, S^{0.5})\ln(\mathrm{RVP})$$

$$B = 8{,}742 - 1{,}042\, S^{0.5} - (1{,}049 - 179.4\, S^{0.5})\ln(\mathrm{RVP})$$

where:

RVP = stock Reid vapor pressure, in pounds per square inch
ln = natural logarithm function
S = stock ASTM-D86 distillation slope at 10 volume percent evaporation (°F/vol %)

Figure 7.1-14. Equations to determine vapor pressure constants A and B for refined petroleum stocks.[6]

$$A = 12.82 - 0.9672 \ln (RVP)$$

$$B = 7{,}261 - 1{,}216 \ln (RVP)$$

where:

RVP = Reid vapor pressure, psi

ln = natural logarithm function

Figure 7.1-15. Equations to determine vapor pressure constants A and B for crude oils stocks.[6]

Daily maximum and minimum liquid surface temperature, (°R)

$$T_{LX} = T_{LA} + 0.25 \, \Delta T_V$$

$$T_{LN} = T_{LA} - 0.25 \, \Delta T_V$$

where:

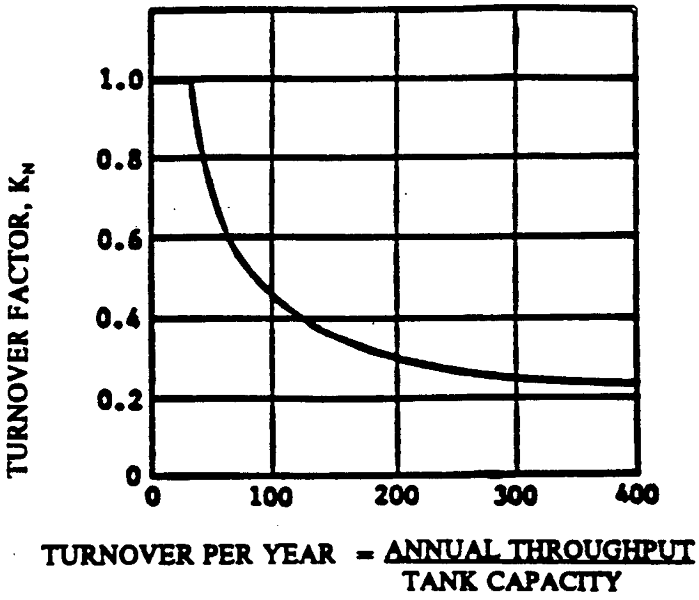
T_{LX} = daily maximum liquid surface temperature, °R

T_{LA} is as defined in Note 3 to Equation 1-9

ΔT_V is as defined in Note 1 to Equation 1-16

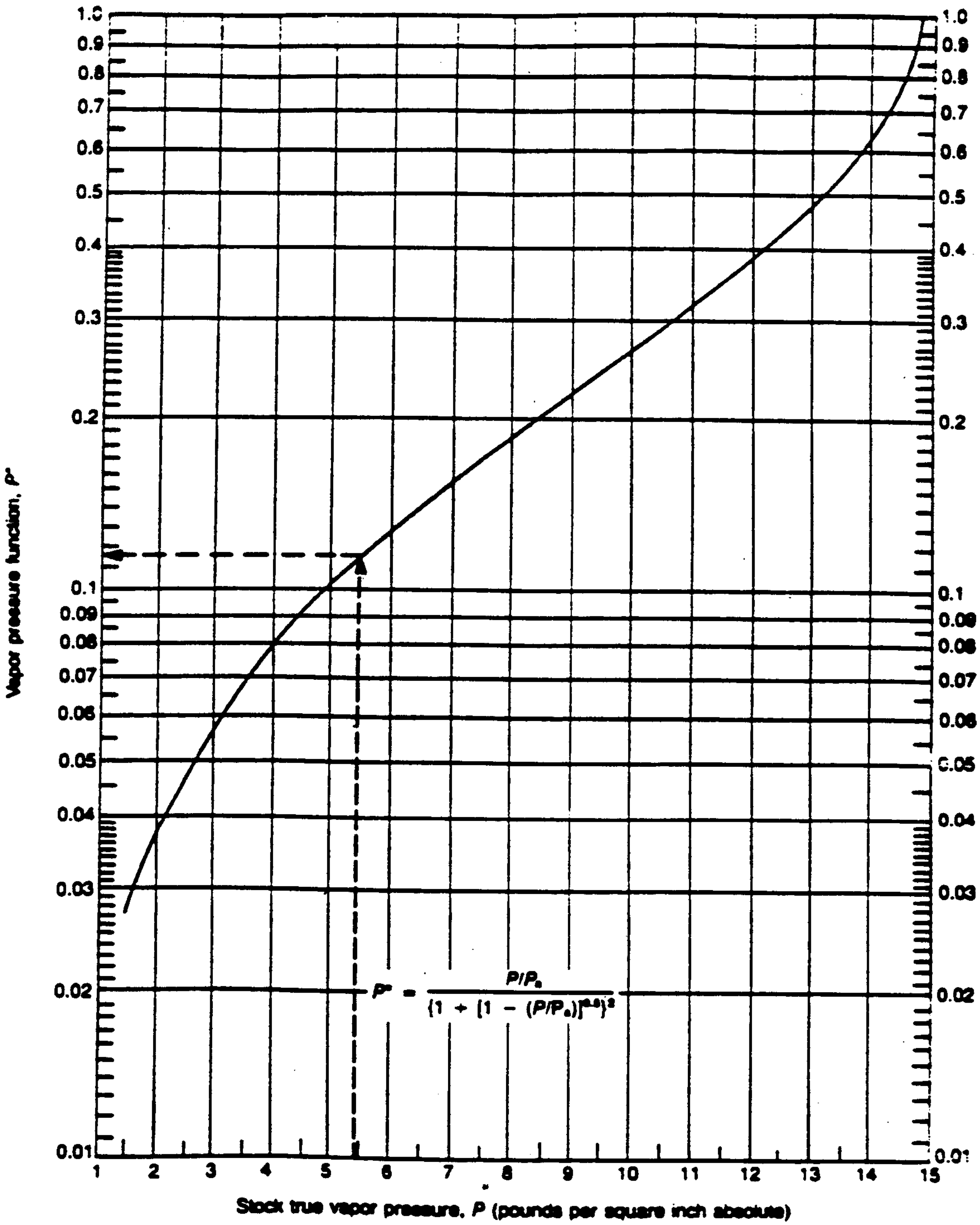
T_{LN} = daily minimum liquid surface temperature, °R

Figure 7.1-16. Equations for the daily maximum and minimum liquid surface temperatures.[6]



Note: For 36 turnovers per year or less, K_N = 1.0

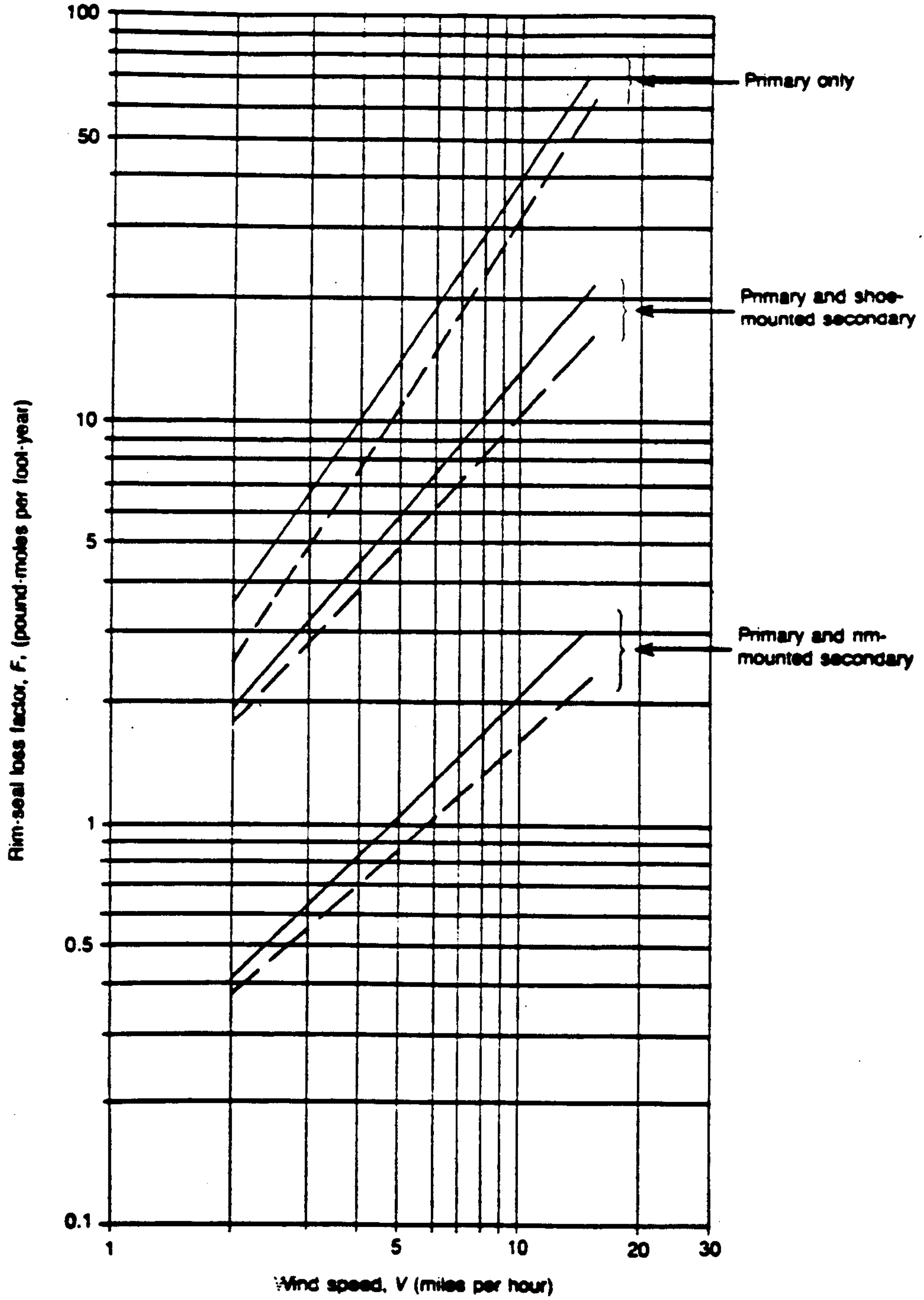
Figure 7.1-17. Turnover factor (K_N) for fixed roof tanks.[6]



Notes:

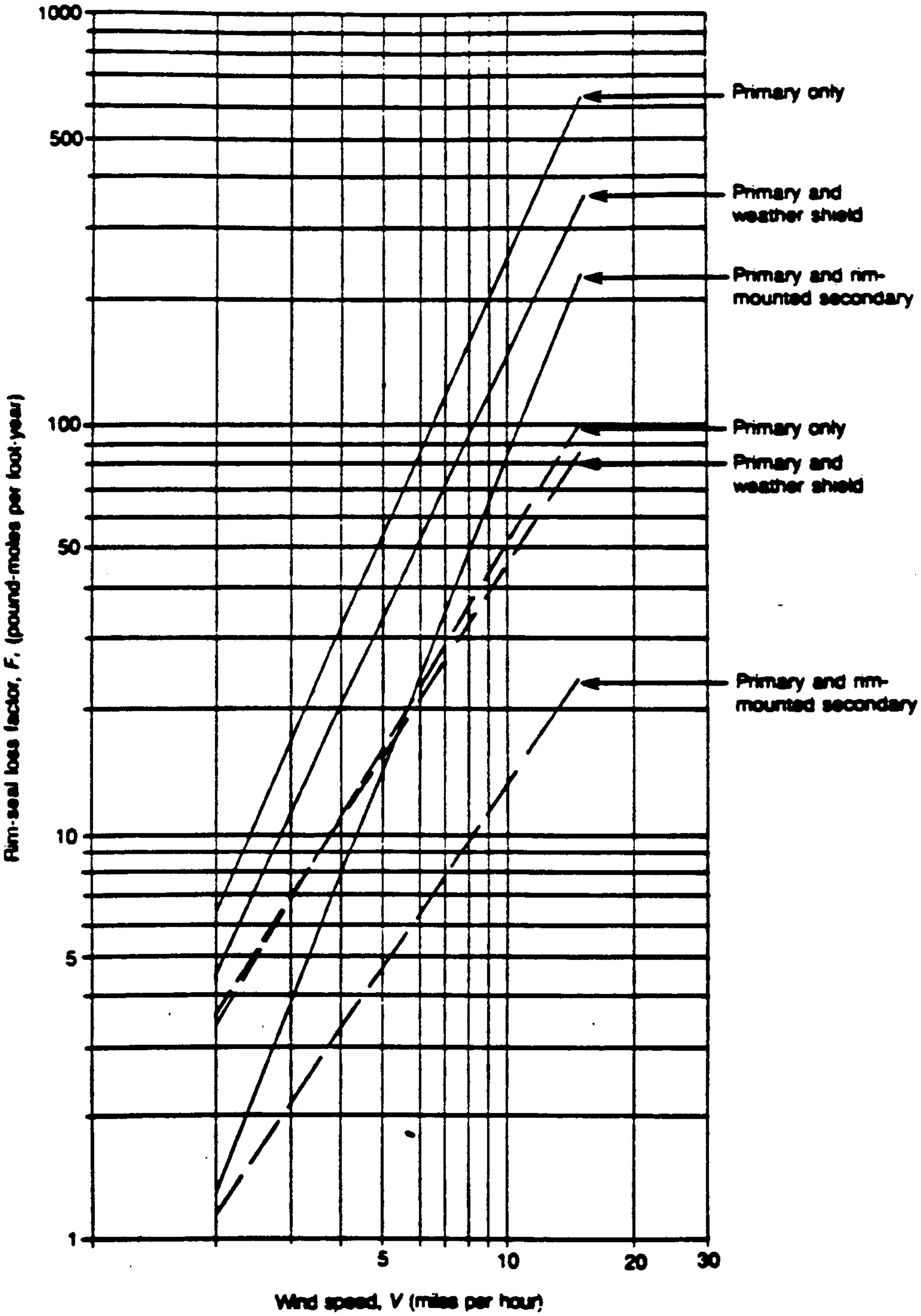
1. Broken line illustrates sample problem for $P = 5.4$ pounds per square inch absolute.
2. Curve is for atmospheric pressure, P_a, equal to 14.7 pounds per square inch absolute.

Figure 7.1-18. Vapor pressure function.[4]



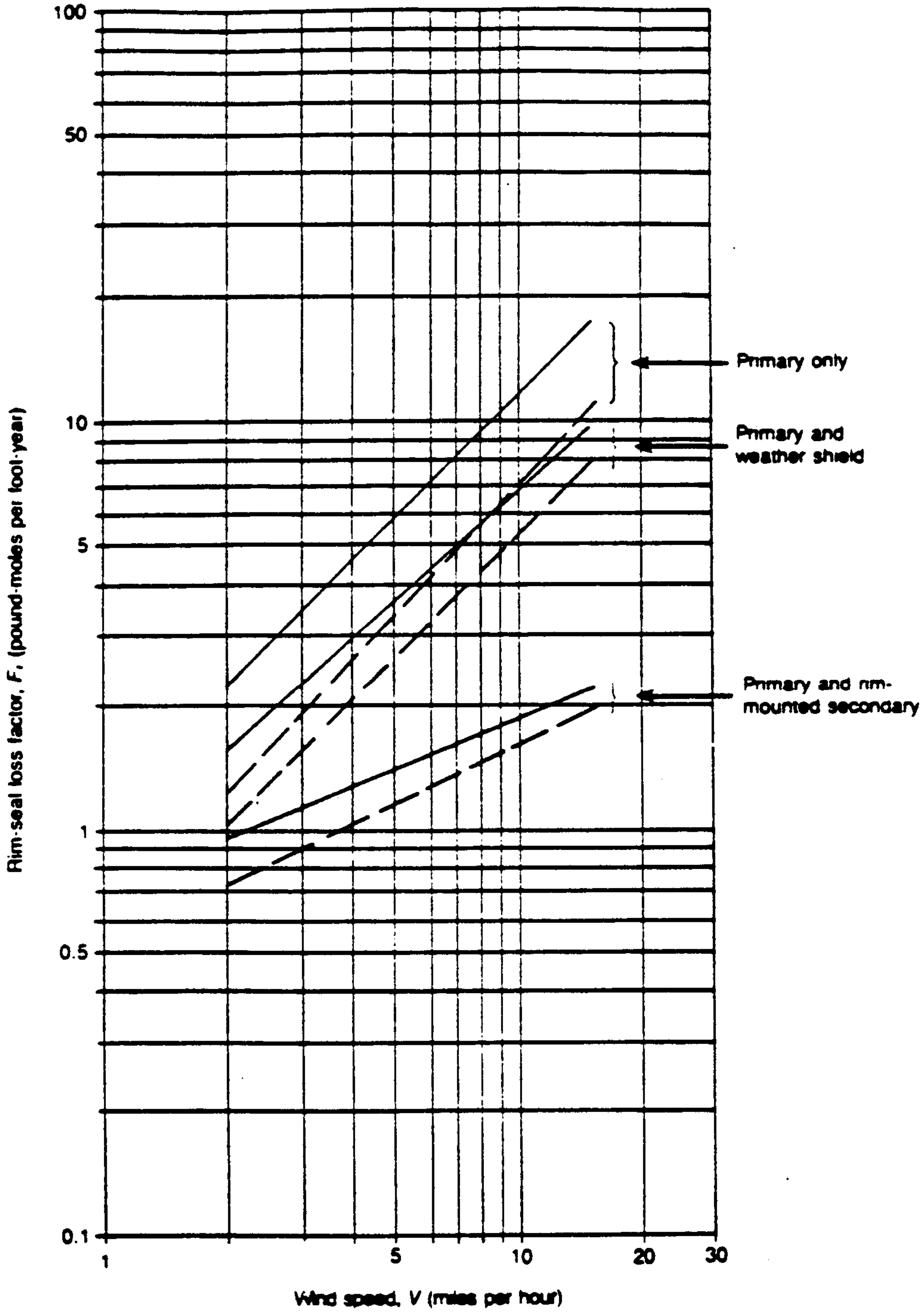
Note: Solid line indicates average-fitting seal; broken line indicates tight-fitting seal; $F_r = K_r V^n$.

Figure 7.1-19. Rim-seal loss factor for a welded tank with a mechanical-shoe primary seal.[3]



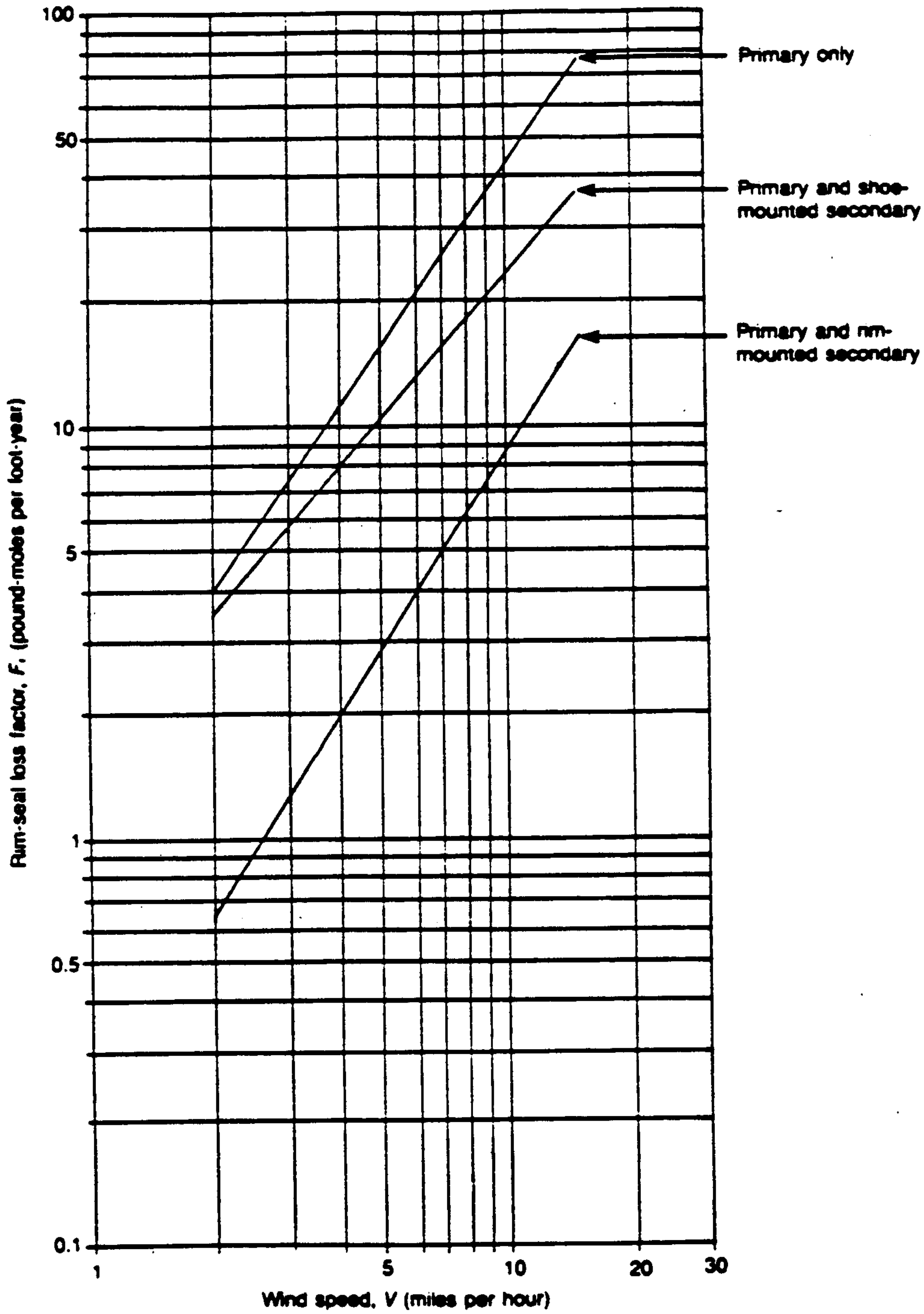
Note: Solid line indicates average-fitting seal; broken line indicates tight-fitting seal; $F_r = K_r V^n$.

Figure 7.1-20. Rim-seal loss factor a for a welded tank with a vapor-mounted, resilient-filled primary seal.[3]



Note: Solid line indicates average-fitting seal; broken line indicates tight-fitting seal; $F_r = K_r V^n$.

Figure 7.1-21. Rim-seal loss factor for a welded tank with a liquid-mounted, resilient-filled primary seal.[3]



Note: Solid line indicates average-fitting seal; $F_r = K_rV^n$.

Figure 7.1-22. Rim-seal loss factor for a riveted tank with a mechanical-shoe primary seal.[3]

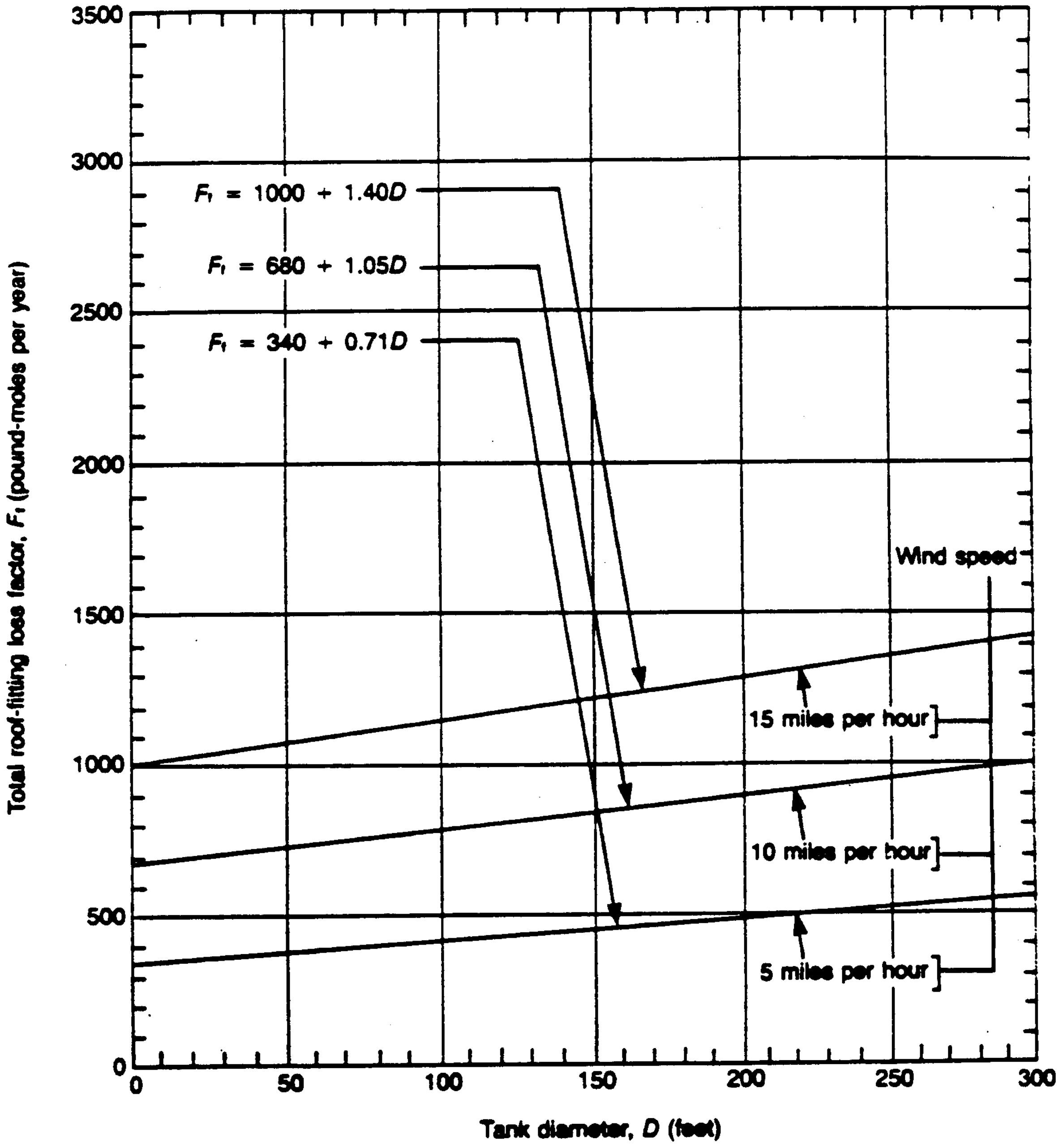


Figure 7.1-23. Total roof-fitting loss factor for typical fittings on pontoon floating roofs.[3]

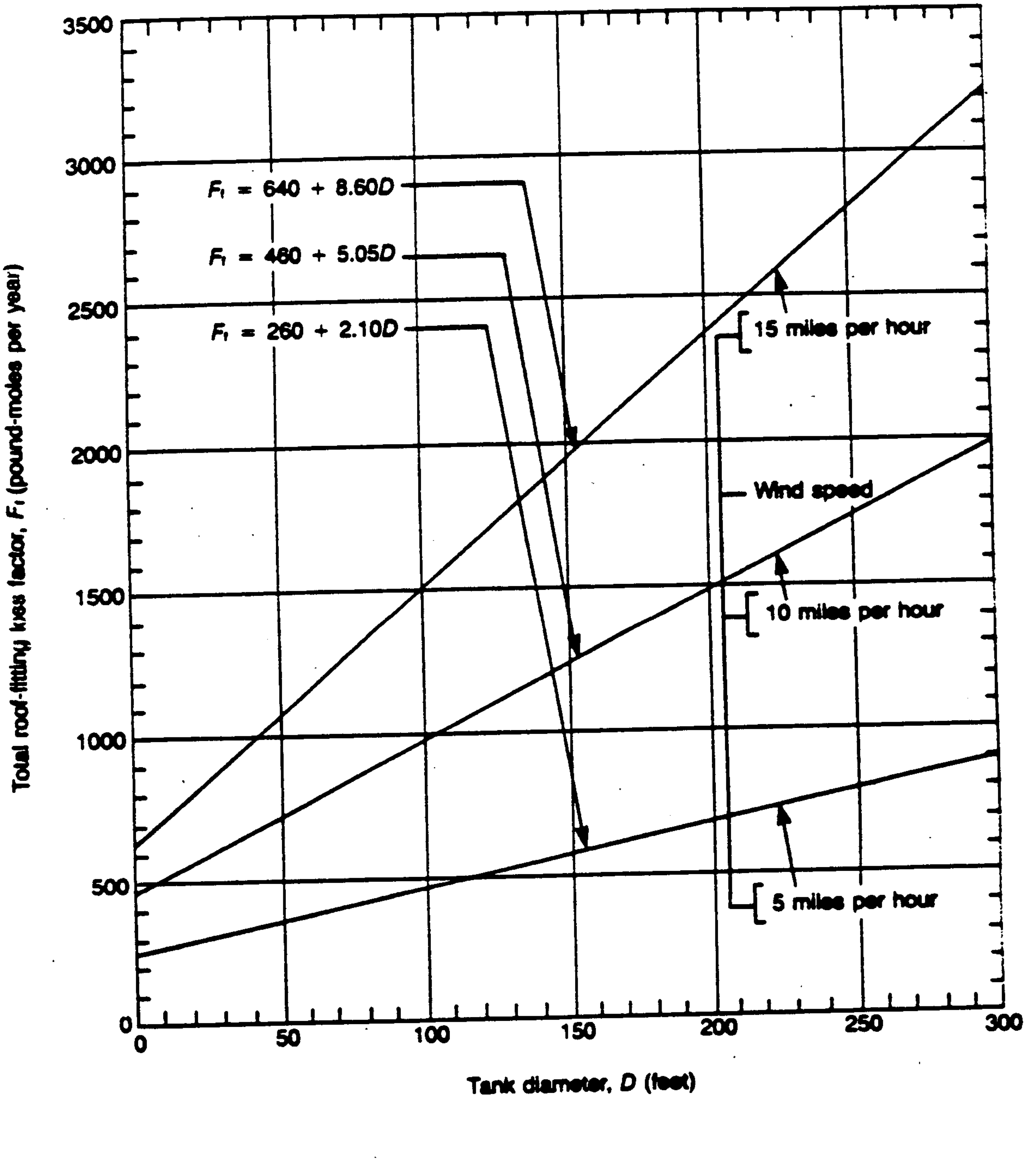
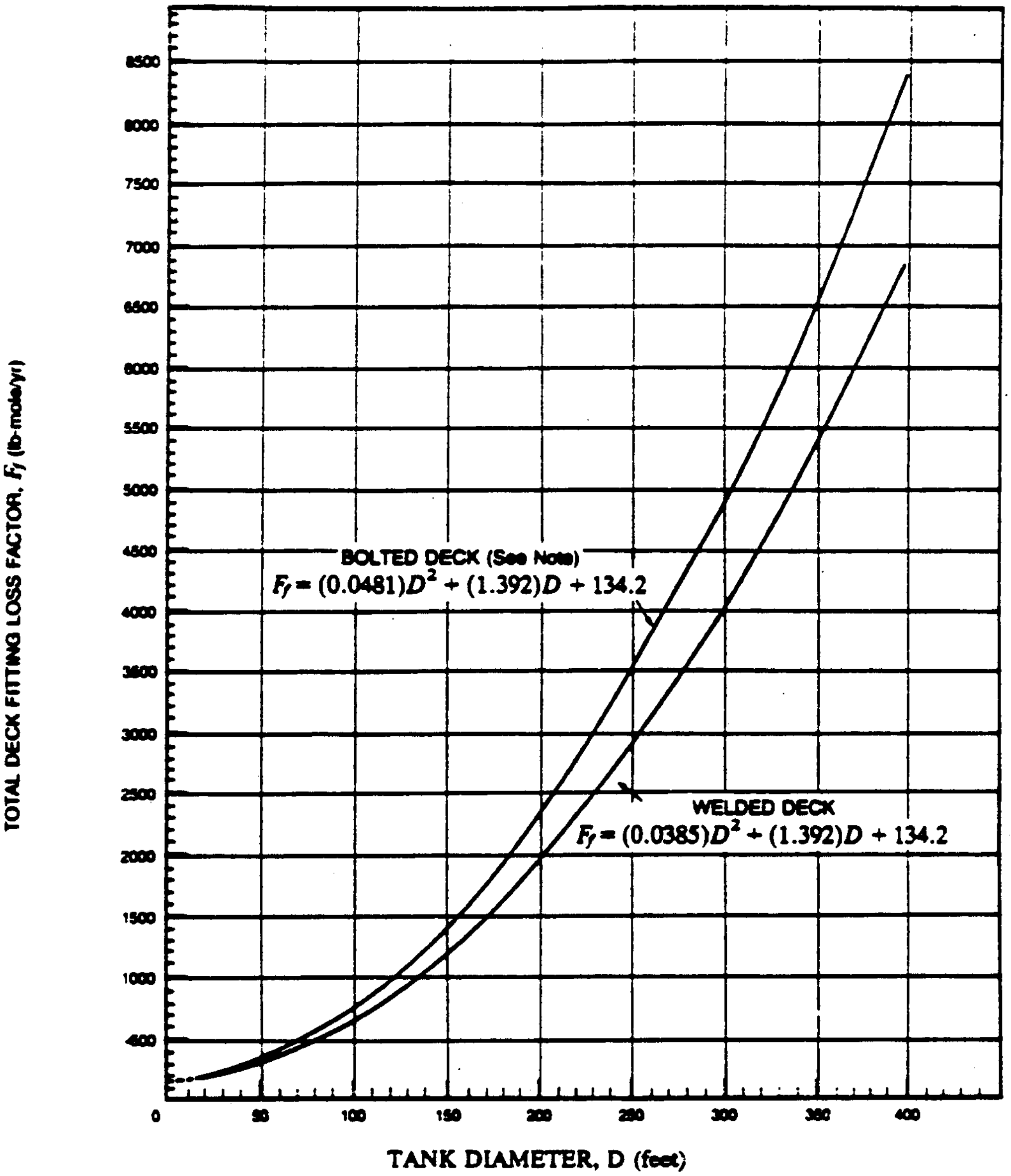


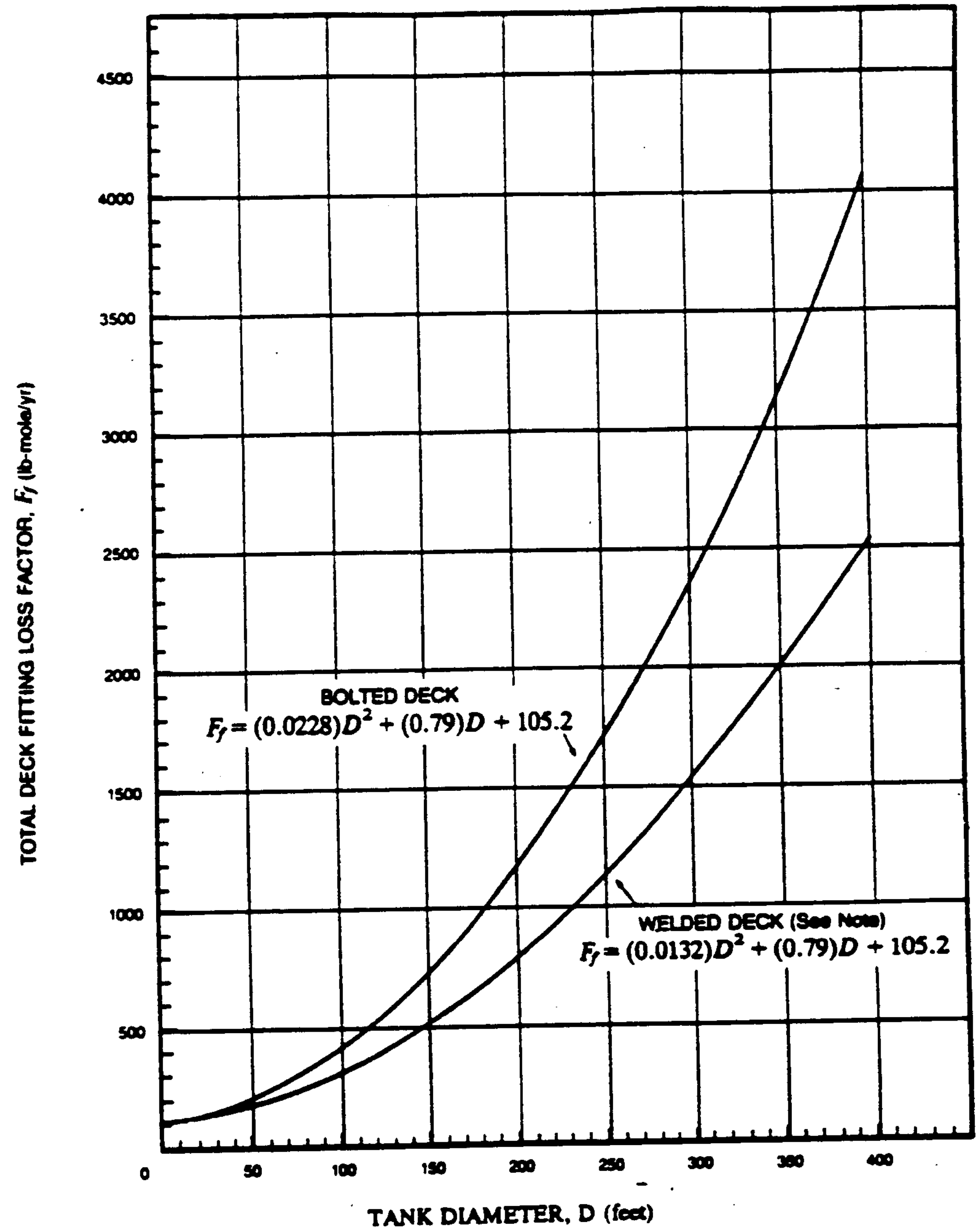
Figure 7.1-24. Total roof-fitting loss factor for typical fittings on double-deck floating roofs.[3]



Basis: Fittings include: (1) access hatch with ungasketed, unbolted cover, (2) built-up column wells with ungasketed sliding cover, (3) adjustable deck legs; (4) gauge float well with ungasketed unbolted cover, (5) ladder well with ungasketed sliding cover; (6) sample well with slit fabric seal (10 percent open area); (7) 1-inch-diameter stub drains (only on bolted deck); and (8) vacuum breaker with gasketed weighted mechanical actuation. This basis was derived from a survey of users and manufacturers. Other fittings may be typically used within particular companies or organizations to reflect standards and/or specifications of that group. This figure should not supersede information based on actual tank data.

NOTE: If no specification information is available, assume bolted decks are the most common/typical type currently in us in tanks with column-supported fixed roofs.

Figure 7.1-25. Approximated total deck fitting loss factors (F_f) for typical fittings in tanks with column-supported fixed roofs and either a bolted deck or a welded deck. (Use only when tank-specific data on the number and kind of deck fittings are unavailable.)[4]



Basis: Fittings include: (1) access hatch with ungasketed, unbolted cover, (2) adjustable deck legs; (3) gauge float well with ungasketed unbolted cover, (4) sample well with slit fabric seal (10 percent open area); (5) 1-inch-diameter stub drains (only on bolted deck); and (6) vacuum breaker with gasketed weighted mechanical actuation. This basis was derived from a survey of users and manufacturers. Other fittings may be typically used within particular companies or organizations to reflect standards and/or specifications of that group. This figure should not supersede information based on actual tank data.

NOTE: If no specification information is available, assume welded decks are the most common/typical type currently in use in tanks with column-supported fixed roofs.

Figure 7.1-26. Approximated total deck fitting loss factors (F_f) for typical fittings in tanks with self-supported fixed roofs and either a bolted deck or a welded deck. (Use only when tank-specific data on the number and kind of deck fittings are unavailable).[4]

Table 7.1-1. LIST OF ABBREVIATIONS USED IN THE TANK EQUATIONS

Variable	Description	Variable	Description	Variable	Description
L_T	total losses, lb/yr	P	true vapor pressure of component i, psia	P_{BP}	breather vent pressure setting, psig
L_S	standing storage losses, lb/yr	A	constant in vapor pressure equation, dimensionless	P_{BV}	breather vent vacuum setting, psig
L_W	working losses, lb/yr	B	constant in vapor pressure equation, °R	Q	annual net throughput, bbl/yr
V_V	vapor space volume, ft^3	T_{AA}	daily average ambient temperature, °R	K_N	turnover factor, dimensionless
W_V	vapor density, lb/ft^3	T_B	liquid bulk temperature, °R	N	number of turnovers per year, dimensionless
K_E	vapor space expansion factor, dimensionless	α	tank paint solar absorptance, dimensionless	π	constant, (3.14159)
K_S	vented vapor saturation factor, dimensionless	I	daily total solar insolation factor, $Btu/ft^2 \bullet day$	V_{LX}	tank maximum liquid volume, ft^3
D	tank diameter, ft	T_{AX}	daily maximum ambient temperature, °R	H_{LX}	maximum liquid height, ft
H_{VO}	vapor space outage, ft	T_{AN}	daily minimum ambient temperature, °R	K_P	working loss product factor for fixed roof tanks, dimensionless
H_S	tank shell height, ft	D_E	effective tank diameter, ft	L_R	rim seal loss, lb/yr
H_L	liquid height, ft	L	length of tank, ft	L_{WD}	withdrawal loss, lb/yr
H_{RO}	roof outage, ft	ΔT_V	daily vapor temperature range, °R	L_F	roof fitting loss, lb/yr
H_R	tank roof height, ft	ΔP_V	daily vapor pressure range, psi	K_R	seal factor, lb-mole/$mph^n \bullet ft \bullet yr$ for external floating roof tanks or lb-mole/ft•yr for internal floating roof tanks
S_R	tank cone roof slope, ft/ft	ΔP_B	breather vent pressure setting range, psig	v	average wind speed, mph
R_S	tank shell radius, ft	P_A	atmospheric pressure, psi	n	seal-related speed exponent, dimensionless
R_R	tank dome roof radius, ft	ΔT_A	daily ambient temperature range, °R	P^*	vapor pressure function, dimensionless
M_V	vapor molecular weight, lb/lb-mole	P_{VX}	vapor pressure at the daily maximum liquid surface temperature, psia	F_R	rim seal loss factor, lb-moles/ft•yr
R	ideal gas constant, (10.731 psia • ft^3/lb-mole•°R)	P_{VN}	vapor pressure at the daily minimum liquid surface temperature, psia	K_C	product factor for floating roof tanks, dimensionless
P_{VA}	vapor pressure at daily average liquid surface temperature, psia			C	shell clingage factor, bbl/1,000 ft^2
T_{LA}	daily average liquid surface temperature, °R			W_L	average organic liquid density, lb/gal
M_i	molecular weight of component i, lb/lb-mole			F_F	total roof fitting loss factor, lb-mole/yr
y_i	vapor mole fraction of component i, lb-mole/lb-mole				
x_i	liquid mole fraction of component i, lb-mole/lb-mole				

Table 7.1-1 (cont.).

Variable	Description	Variable	Description	Variable	Description
N_{Fi}	number of roof fittings of a particular type, dimensionless	$L_{T,i}$	emission rate of component i, lb/yr		
n_f	total number of different types of fittings, dimensionless	L_V	variable vapor space filling loss, lb/1,000 gal throughput		
K_{Fi}	loss factor for a particular type of roof fitting, lb-mole/yr	V_1	volume of liquid pumped into system, bbl/yr		
K_{Fai}	loss factor for a particular type of roof fitting, lb-mole/yr	V_2	volume expansion capacity, bbl		
K_{Fbi}	loss factor for a particular type of roof fitting, lb-mole/ $mph^m \bullet yr$	N_2	number of transfers into system, dimensionless		
m_i	loss factor for a particular type of roof fitting, dimensionless				
i	1,2,.....η, dimensionless				
L_D	deck seam loss, lb/yr				
N_C	number of columns, dimensionless				
F_C	effective column diameter, ft				
K_D	deck seam loss per unit seam length factor, lb-mol/ft-yr				
S_D	deck seam length factor, ft/ft^2				
L_{seam}	total length of deck seam, ft				
A_{deck}	area of deck, ft^2				
P_i	partial pressure of component i, psia				
$Z_{i,L}$	liquid weight fraction of component i, lb/lb				
M_L	molecular weight of liquid mixture, lb/lb-mole				
$Z_{i,V}$	vapor weight fraction of component i, lb/lb				
N_{TOTAL}	total number of moles in mixtures, lb-mole				
W_i	liquid density of component i, lb/ft^3				

Table 7.1-2. PROPERTIES (M_V, W_{VC}, P_{VA}, W_L) OF SELECTED PETROLEUM LIQUIDS[a]

Petroleum Liquid	Vapor Molecular Weight At 60°F, M_V (lb/lb-mole)	Condensed Vapor Density At 60°F, W_{VC} (lb/gal)	Liquid Density At 60°F, W_L (lb/gal)	True Vapor Pressure, P_{VA} (psi)						
				40°F	50°F	60°F	70°F	80°F	90°F	100°F
Gasoline RVP 13	62	4.9	5.6	4.7	5.7	6.9	8.3	9.9	11.7	13.8
Gasoline RVP 10	66	5.1	5.6	3.4	4.2	5.2	6.2	7.4	8.8	10.5
Gasoline RVP 7	68	5.2	5.6	2.3	2.9	3.5	4.3	5.2	6.2	7.4
Crude oil RVP 5	50	4.5	7.1	1.8	2.3	2.8	3.4	4.0	4.8	5.7
Jet naphtha (JP-4)	80	5.4	6.4	0.8	1.0	1.3	1.6	1.9	2.4	2.7
Jet kerosene	130	6.1	7.0	0.0041	0.0060	0.0085	0.011	0.015	0.021	0.029
Distillate fuel oil No. 2	130	6.1	7.1	0.0031	0.0045	0.0074	0.0090	0.012	0.016	0.022
Residual oil No. 6	190	6.4	7.9	0.00002	0.00003	0.00004	0.00006	0.00009	0.00013	0.00019

[a] References 7-8.

Table 7.1-3 (English Units). PHYSICAL PROPERTIES OF SELECTED PETROCHEMICALS[a]

Name	Formula	Molecular Weight	Boiling Point At 1 Atmosphere (°F)	Liquid Density At 60°F (lb/gal)	Vapor Pressure (psia) At						
					40°F	50°F	60°F	70°F	80°F	90°F	100°F
Acetone	CH_3COCH_3	58.08	133.0	6.628	1.682	2.185	2.862	3.713	4.699	5.917	7.251
Acetonitrile	CH_3CN	41.05	178.9	6.558	0.638	0.831	1.083	1.412	1.876	2.456	3.133
Acrylonitrile	$CH_2:CHCN$	53.06	173.5	6.758	0.812	0.967	1.373	1.779	2.378	3.133	4.022
Allyl alcohol	$CH_2:CHCH_2OH$	58.08	206.6	7.125	0.135	0.193	0.261	0.387	0.522	0.716	1.006
Allyl chloride	$CH_2:CHCH_2Cl$	76.53	113.2	7.864	2.998	3.772	4.797	6.015	7.447	9.110	11.025
Ammonium hydroxide (28.8% solution)	$NH_4OH\text{--}H_2O$	35.05	83.0	7.481	5.130	6.630	8.480	10.760	13.520	16.760	20.680
Benzene	C_6H_6	78.11	176.2	7.365	0.638	0.870	1.160	1.508	1.972	2.610	3.287
iso-Butyl alcohol	$(CH_3)_2CHCH_2OH$	74.12	227.1	6.712	0.058	0.097	0.135	0.193	0.271	0.387	0.541
tert-Butyl alcohol	$(CH_3)_3COH$	74.12	180.5	6.595	0.174	0.290	0.425	0.638	0.909	1.238	1.702
n-Butyl chloride	$CH_3CH_2CH_2CH_2Cl$	92.57	172.0	7.430	0.715	1.006	1.320	1.740	2.185	2.684	3.481
Carbon disulfide	CS_2	76.13	115.3	10.588	3.036	3.867	4.834	6.014	7.387	9.185	11.215
Carbon tetrachloride	CCl_4	153.84	170.2	13.366	0.793	1.064	1.412	1.798	2.301	2.997	3.771
Chloroform	$CHCl_3$	119.39	142.7	12.488	1.528	1.934	2.475	3.191	4.061	5.163	6.342
Chloroprene	$CH_2:CCl\cdot CH:CH_2$	88.54	138.9	8.046	1.760	2.320	2.901	3.655	4.563	5.685	6.981
Cyclohexane	C_6H_{12}	84.16	177.3	6.522	0.677	0.928	1.218	1.605	2.069	2.610	3.249
Cyclopentane	C_5H_{10}	70.13	120.7	6.248	2.514	3.287	4.177	5.240	6.517	8.063	9.668
1,1-Dichloroethane	CH_3CHCl_2	98.97	135.1	9.861	1.682	2.243	2.901	3.771	4.738	5.840	7.193
1,2-Dichloroethane	CH_2ClCH_2Cl	98.97	182.5	10.500	0.561	0.773	1.025	1.431	1.740	2.243	2.804
cis-1,2-Dichloroethylene	$CHCl:CHCl$	96.95	140.2	10.763	1.450	2.011	2.668	3.461	4.409	5.646	6.807
trans-1,2-Dichloroethylene	$CHCl:CHCl$	96.95	119.1	10.524	2.552	3.384	4.351	5.530	6.807	8.315	10.016
Diethylamine	$(C_2H_5)_2NH$	73.14	131.9	5.906	1.644	1.992	2.862	3.867	4.892	6.130	7.541
Diethyl ether	$C_2H_5OC_2H_5$	74.12	94.3	5.988	4.215	5.666	7.019	8.702	10.442	13.342	Boils
Di-*iso*-propyl ether	$(CH_3)_2CHOCH(CH_3)_2$	102.17	153.5	6.075	1.199	1.586	2.127	2.746	3.481	4.254	5.298
1,4-Dioxane	$O\cdot CH_2CH_2OCH_2CH_2$	88.10	214.7	8.659	0.232	0.329	0.425	0.619	0.831	1.141	1.508
Dipropyl ether	$CH_3CH_2CH_2OCH_2CH_2CH_3$	102.17	195.8	6.260	0.425	0.619	0.831	1.102	1.431	1.876	2.320
Ethyl acetate	$C_2H_5OOCCH_3$	88.10	170.9	7.551	0.580	0.831	1.102	1.489	1.934	2.514	3.191

Table 7.1-3 (cont.).

Name	Formula	Molecular Weight	Boiling Point At 1 Atmosphere (°F)	Liquid Density At 60°F (lb/gal)	Vapor Pressure (psia) At						
					40°F	50°F	60°F	70°F	80°F	90°F	100°F
Ethyl acrylate	$C_2H_5OOCCH{:}CH_2$	100.11	211.8	7.750	0.213	0.290	0.425	0.599	0.831	1.122	1.470
Ethyl alcohol	C_2H_5OH	46.07	173.1	6.610	0.193	0.406	0.619	0.870	1.218	1.682	2.320
Freon 11	CCl_3F	137.38	75.4	12.480	7.032	8.804	10.900	13.40	16.31	19.69	23.60
n-Heptane	$CH_3(CH_2)_5CH_3$	100.20	209.2	5.727	0.290	0.406	0.541	0.735	0.967	1.238	1.586
n-Hexane	$CH_3(CH_2)_4CH_3$	86.17	155.7	5.527	1.102	1.450	1.876	2.436	3.055	3.906	4.892
Hydrogen cyanide	HCN	27.03	78.3	5.772	6.284	7.831	9.514	11.853	15.392	18.563	22.237
Isooctane	$(CH_3)_3CCH_2CH(CH_3)_2$	114.22	210.6	5.794	0.213	0.387	0.580	0.812	1.093	1.392	1.740
Isopentane	$(CH_3)_2CHCH_2CH_3$	72.15	82.1	5.199	5.878	7.889	10.005	12.530	15.334	18.370	21.657
Isoprene	$(CH_2){:}C(CH_3)CH{:}CH_2$	68.11	93.5	5.707	4.757	6.130	7.677	9.668	11.699	14.503	17.113
Isopropyl alcohol	$(CH_3)_2 \cdot CHOH$	60.09	180.1	6.573	0.213	0.329	0.483	0.677	0.928	1.296	1.779
Methacrylonitrile	$CH_2{:}CH(CH_3)CN$	67.09	194.5	6.738	0.483	0.657	0.870	1.160	1.470	1.934	2.456
Methyl acetate	CH_3OOCCH_3	74.08	134.8	7.831	1.489	2.011	2.746	3.693	4.699	5.762	6.961
Methyl acrylate	$CH_3OOCCH{:}CH_2$	86.09	176.9	7.996	0.599	0.773	1.025	1.354	1.798	2.398	3.055
Methyl alcohol	CH_3OH	32.04	148.4	6.630	0.735	1.006	1.412	1.953	2.610	3.461	4.525
Methylcyclohexane	$CH_3 \cdot C_6H_{11}$	98.18	213.7	6.441	0.309	0.425	0.541	0.735	0.986	1.315	1.721
Methylcyclopentane	$CH_3C_5H_9$	84.16	161.3	6.274	0.909	1.160	1.644	2.224	2.862	3.616	4.544
Methylene chloride	CH_2Cl_2	84.94	104.2	11.122	3.094	4.254	5.434	6.787	8.702	10.329	13.342
Methyl ethyl ketone	$CH_3COC_2H_5$	72.10	175.3	6.747	0.715	0.928	1.199	1.489	2.069	2.668	3.345
Methyl methacrylate	$CH_3OOC(CH_3){:}CH_2$	100.11	212.0	7.909	0.116	0.213	0.348	0.541	0.773	1.064	1.373
Methyl propyl ether	$CH_3OC_3H_7$	74.12	102.1	6.166	3.674	4.738	6.091	7.058	9.417	11.602	13.729
Nitromethane	CH_3NO_2	61.04	214.2	9.538	0.213	0.251	0.348	0.503	0.715	1.006	1.334
n-Pentane	$CH_3(CH_2)_3CH_3$	72.15	96.9	5.253	4.293	5.454	6.828	8.433	10.445	12.959	15.474
n-Propylamine	$C_3H_7NH_2$	59.11	119.7	6.030	2.456	3.191	4.157	5.250	6.536	8.044	9.572
1,1,1-Trichloroethane	CH_3CCl_3	133.42	165.2	11.216	0.909	1.218	1.586	2.030	2.610	3.307	4.199
Trichloroethylene	$CHCl{:}CCl_2$	131.40	188.6	12.272	0.503	0.677	0.889	1.180	1.508	2.030	2.610
Toluene	$CH_3 \cdot C_6H_5$	92.13	231.1	7.261	0.174	0.213	0.309	0.425	0.580	0.773	1.006
Vinyl acetate	$CH_2{:}CHOOCCH_3$	86.09	162.5	7.817	0.735	0.986	1.296	1.721	2.262	3.113	4.022
Vinylidene chloride	$CH_2{:}CCl_2$	96.5	89.1	10.383	4.990	6.344	7.930	9.806	11.799	15.280	23.210

[a] Reference 9.

Table 7.1-4 (English Units). ASTM DISTILLATION SLOPE FOR SELECTED REFINED PETROLEUM STOCKS[a]

Refined Petroleum Stock	Reid Vapor Pressure, RVP (psi)	ASTM-D86 Distillation Slope At 10 Volume Percent Evaporated (°F/vol%)
Aviation gasoline	ND	2.0
Naptha	2 - 8	2.5
Motor gasoline	ND	3.0
Light naptha	9 - 14	3.5

[a] Reference 6. ND = no data.

Table 7.1-5 (Metric Units). VAPOR PRESSURE EQUATION CONSTANTS FOR ORGANIC LIQUIDS[a]

Name	Vapor Pressure Equation Constants		
	A	B	C
	(dimensionless)	(°C)	(°C)
Acetaldehyde	8.005	1600.017	291.809
Acetic acid	7.387	1533.313	222.309
Acetic anhydride	7.149	1444.718	199.817
Acetone	7.117	1210.595	229.664
Acetonitrile	7.119	1314.4	230
Acrylamide	11.2932	3939.877	273.16
Acrylic acid	5.652	648.629	154.683
Acrylonitrile	7.038	1232.53	222.47
Aniline	7.32	1731.515	206.049
Benzene	6.905	1211.033	220.79
Butanol (iso)	7.4743	1314.19	186.55
Butanol-(1)	7.4768	1362.39	178.77
Carbon disulfide	6.942	1169.11	241.59
Carbon tetrachloride	6.934	1242.43	230
Chlorobenzene	6.978	1431.05	217.55
Chloroform	6.493	929.44	196.03
Chloroprene	6.161	783.45	179.7
Cresol (-M)	7.508	1856.36	199.07
Cresol (-O)	6.911	1435.5	165.16
Cresol (-P)	7.035	1511.08	161.85
Cumene (isopropylbenzene)	6.963	1460.793	207.78
Cyclohexane	6.841	1201.53	222.65
Cyclohexanol	6.255	912.87	109.13
Cyclohexanone	7.8492	2137.192	273.16
Dichloroethane (1,2)	7.025	1272.3	222.9
Dichloroethylene (1,2)	6.965	1141.9	231.9
Diethyl (N,N) anilin	7.466	1993.57	218.5
Dimethyl formamide	6.928	1400.87	196.43
Dimethyl hydrazine (1,1)	7.408	1305.91	225.53
Dimethyl phthalate	4.522	700.31	51.42
Dinitrobenzene	4.337	229.2	-137
Dioxane (1,4)	7.431	1554.68	240.34
Epichlorohydrin	8.2294	2086.816	273.16
Ethanol	8.321	1718.21	237.52
Ethanolamine (mono-)	7.456	1577.67	173.37
Ethyl acrylate	7.9645	1897.011	273.16
Ethyl chloride	6.986	1030.01	238.61
Ethylacetate	7.101	1244.95	217.88
Ethylbenzene	6.975	1424.255	213.21
Ethylether	6.92	1064.07	228.8
Formic acid	7.581	1699.2	260.7

Table 7.1-5 (cont.).

Name	Vapor Pressure Equation Constants		
	A (dimensionless)	B (°C)	C (°C)
Furan	6.975	1060.87	227.74
Furfural	6.575	1198.7	162.8
Heptane (iso)	6.8994	1331.53	212.41
Hexane (-N)	6.876	1171.17	224.41
Hexanol (-1)	7.86	1761.26	196.66
Hydrocyanic acid	7.528	1329.5	260.4
Methanol	7.897	1474.08	229.13
Methyl acetate	7.065	1157.63	219.73
Methyl ethyl ketone	6.9742	1209.6	216
Methyl isobutyl ketone	6.672	1168.4	191.9
Methyl metharcrylate	8.409	2050.5	274.4
Methyl styrene (alpha)	6.923	1486.88	202.4
Methylene chloride	7.409	1325.9	252.6
Morpholine	7.7181	1745.8	235
Naphthalene	7.01	1733.71	201.86
Nitrobenzene	7.115	1746.6	201.8
Pentachloroethane	6.74	1378	197
Phenol	7.133	1516.79	174.95
Picoline (-2)	7.032	1415.73	211.63
Propanol (iso)	8.117	1580.92	219.61
Propylene glycol	8.2082	2085.9	203.540
Propylene oxide	8.2768	1656.884	273.16
Pyridine	7.041	1373.8	214.98
Resorcinol	6.9243	1884.547	186.060
Styrene	7.14	1574.51	224.09
Tetrachloroethane (1,1,1,2)	6.898	1365.88	209.74
Tetrachloroethane (1,1,2,2)	6.631	1228.1	179.9
Tetrachloroethylene	6.98	1386.92	217.53
Tetrahydrofuran	6.995	1202.29	226.25
Toluene	6.954	1344.8	219.48
Trichloro(1,1,2)trifluoroethane	6.88	1099.9	227.5
Trichloroethane (1,1,1)	8.643	2136.6	302.8
Trichloroethane (1,1,2)	6.951	1314.41	209.2
Trichloroethylene	6.518	1018.6	192.7
Trichlorofluoromethane	6.884	1043.004	236.88
Trichloropropane (1,2,3)	6.903	788.2	243.23
Vinyl acetate	7.21	1296.13	226.66
Vinylidene chloride	6.972	1099.4	237.2
Xylene (-m)	7.009	1426.266	215.11
Xylene (-o)	6.998	1474.679	213.69

[a] Reference 10.

Table 7.1-6 (English Units). METEOROLOGICAL DATA (T_{AX}, T_{AN}, I) FOR SELECTED U. S. LOCATIONS[a]

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Birmingham, AL	T_{AX}	°F	52.7	57.3	65.2	75.2	81.6	87.9	90.3	89.7	84.6	74.8	63.7	55.9	73.2
	T_{AN}	°F	33.0	35.2	42.1	50.4	58.3	65.9	69.8	69.1	63.6	50.4	40.5	35.2	51.1
	I	Btu/ft^2 day	707	967	1296	1674	1857	1919	1810	1724	1455	1211	858	661	1345
Montgomery, AL	T_{AX}	°F	57.0	60.9	68.1	77.0	83.6	89.8	91.5	91.2	86.9	77.5	67.0	59.8	75.9
	T_{AN}	°F	36.4	38.8	45.5	53.3	61.1	68.4	71.8	71.1	66.4	53.1	43.0	37.9	53.9
	I	Btu/ft^2 day	752	1013	1341	1729	1897	1972	1841	1746	1468	1262	915	719	1388
Homer, AK	T_{AX}	°F	27.0	31.2	34.4	42.1	49.8	56.3	60.5	60.3	54.8	44.0	34.9	27.7	43.6
	T_{AN}	°F	14.4	17.4	19.3	28.1	34.6	41.2	45.1	45.2	39.7	30.6	22.8	15.8	29.5
	I	Btu/ft^2 day	122	334	759	1248	1583	1751	1598	1189	791	437	175	64	838
Phoenix, AZ	T_{AX}	°F	65.2	69.7	74.5	83.1	92.4	102.3	105.0	102.3	98.2	87.7	74.3	66.4	85.1
	T_{AN}	°F	39.4	42.5	46.7	53.0	61.5	70.6	79.5	77.5	70.9	59.1	46.9	40.2	57.3
	I	Btu/ft^2 day	1021	1374	1814	2355	2677	2739	2487	2293	2015	1577	1151	932	1869
Tucson, AZ	T_{AX}	°F	64.1	67.4	71.8	80.1	88.8	98.5	98.5	95.9	93.5	84.1	72.2	65.0	81.7
	T_{AN}	°F	38.1	40.0	43.8	49.7	57.5	67.4	73.8	72.0	67.3	56.7	45.2	39.0	54.2
	I	Btu/ft^2 day	1099	1432	1864	2363	2671	2730	2341	2183	1979	1602	1208	996	1872
Fort Smith, AR	T_{AX}	°F	48.4	53.8	62.5	73.7	81.0	88.5	93.6	92.9	85.7	75.9	61.9	52.1	72.5
	T_{AN}	°F	26.6	30.9	38.5	49.1	58.2	66.3	70.5	68.9	62.1	49.0	37.7	30.2	49.0
	I	Btu/ft^2 day	744	999	1312	1616	1912	2089	2065	1877	1502	1201	851	682	1404
Little Rock, AR	T_{AX}	°F	49.8	54.5	63.2	73.8	81.7	89.5	92.7	92.3	85.6	75.8	62.4	53.2	72.9
	T_{AN}	°F	29.9	33.6	41.2	50.9	59.2	67.5	71.4	69.6	63.0	50.4	40.0	33.2	50.8
	I	Btu/ft^2 day	731	1003	1313	1611	1929	2107	2032	1861	1518	1228	847	674	1404
Bakersfield, CA	T_{AX}	°F	57.4	63.7	68.6	75.1	83.9	92.2	98.8	96.4	90.8	81.0	67.4	57.6	77.7
	T_{AN}	°F	38.9	42.6	45.5	50.1	57.2	64.3	70.1	68.5	63.8	54.9	44.9	38.7	53.3
	I	Btu/ft^2 day	766	1102	1595	2095	2509	2749	2684	2421	1992	1458	942	677	1749
Long Beach, CA	T_{AX}	°F	66.0	67.3	68.0	70.9	73.4	77.4	83.0	83.8	82.5	78.4	72.7	67.4	74.2
	T_{AN}	°F	44.3	45.9	47.7	50.8	55.2	58.9	62.6	64.0	61.6	56.6	49.6	44.7	53.5
	I	Btu/ft^2 day	928	1215	1610	1938	2065	2140	2300	2100	1701	1326	1004	847	1598
Los Angeles AP, CA	T_{AX}	°F	64.6	65.5	65.1	66.7	69.1	72.0	75.3	76.5	76.4	74.0	70.3	66.1	70.1
	T_{AN}	°F	47.3	48.6	49.7	52.2	55.7	59.1	62.6	64.0	62.5	58.5	52.1	47.8	55.0
	I	Btu/ft^2 day	926	1214	1619	1951	2060	2119	2308	2080	1681	1317	1004	849	1594
Sacramento, CA	T_{AX}	°F	52.6	59.4	64.1	71.0	79.7	87.4	93.3	91.7	87.6	77.7	63.2	53.2	73.4
	T_{AN}	°F	37.9	41.2	42.4	45.3	50.1	55.1	57.9	57.6	55.8	50.0	42.8	37.9	47.8
	I	Btu/ft^2 day	597	939	1458	2004	2435	2684	2688	2368	1907	1315	782	538	1643
San Francisco AP, CA	T_{AX}	°F	55.5	59.0	60.6	63.0	66.3	69.6	71.0	71.8	73.4	70.0	62.7	56.3	64.9
	T_{AN}	°F	41.5	44.1	44.9	46.6	49.3	52.0	53.3	54.2	54.3	51.2	46.3	42.2	48.3
	I	Btu/ft^2 day	708	1009	1455	1920	2226	2377	2392	2117	1742	1226	821	642	1608

Table 7.1-6 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Santa Maria, CA	T_{AX}	°F	62.8	64.2	63.9	65.6	67.3	69.9	72.1	72.8	74.2	73.3	68.9	64.6	68.3
	T_{AN}	°F	38.8	40.3	40.9	42.7	46.2	49.6	52.4	53.2	51.8	47.6	42.1	38.3	45.3
	I	Btu/ft^2 day	854	1141	1582	1921	2141	2349	2341	2106	1730	1353	974	804	1608
Denver, CO	T_{AX}	°F	43.1	46.9	51.2	61.0	70.7	81.6	88.0	85.8	77.5	66.8	52.4	46.1	64.3
	T_{AN}	°F	15.9	20.2	24.7	33.7	43.6	52.4	58.7	57.0	47.7	36.9	25.1	18.9	36.2
	I	Btu/ft^2 day	840	1127	1530	1879	2135	2351	2273	2044	1727	1301	884	732	1568
Grand Junction, CO	T_{AX}	°F	35.7	44.5	54.1	65.2	76.2	87.9	94.0	90.3	81.9	68.7	51.0	38.7	65.7
	T_{AN}	°F	15.2	22.4	29.7	38.2	48.0	56.6	63.8	61.5	52.2	41.1	28.2	17.9	39.6
	I	Btu/ft^2 day	791	1119	1554	1986	2380	2599	2465	2182	1834	1345	918	731	1659
Wilmington, DE	T_{AX}	°F	39.2	41.8	50.9	63.0	72.7	81.2	85.6	84.1	77.8	66.7	54.8	43.6	63.5
	T_{AN}	°F	23.2	24.6	32.6	41.8	51.7	61.2	66.3	65.4	58.0	45.9	36.4	27.3	44.5
	I	Btu/ft^2 day	571	827	1149	1480	1710	1883	1823	1615	1318	984	645	489	1208
Atlanta, GA	T_{AX}	°F	51.2	55.3	63.2	73.2	79.8	85.6	87.9	87.6	82.3	72.9	62.6	54.1	71.3
	T_{AN}	°F	32.6	34.5	41.7	50.4	58.7	65.9	69.2	68.7	63.6	51.4	41.3	34.8	51.1
	I	Btu/ft^2 day	718	969	1304	1686	1854	1914	1812	1709	1422	1200	883	674	1345
Savannah, GA	T_{AX}	°F	60.3	63.1	69.9	77.8	84.2	88.6	90.8	90.1	85.6	77.8	69.5	62.5	76.7
	T_{AN}	°F	37.9	40.0	46.8	54.1	62.3	68.5	71.5	71.4	67.6	55.9	45.5	39.4	55.1
	I	Btu/ft^2 day	795	1044	1399	1761	1852	1844	1784	1621	1364	1217	941	754	1365
Honolulu, HI	T_{AX}	°F	79.9	80.4	81.4	82.7	84.8	86.2	87.1	88.3	88.2	86.7	83.9	81.4	84.2
	T_{AN}	°F	65.3	65.3	67.3	68.7	70.2	71.9	73.1	73.6	72.9	72.2	69.2	66.5	69.7
	I	Btu/ft^2 day	1180	1396	1622	1796	1949	2004	2002	1967	1810	1540	1266	1133	1639
Chicago, IL	T_{AX}	°F	29.2	33.9	44.3	58.8	70.0	79.4	83.3	82.1	75.5	64.1	48.2	35.0	58.7
	T_{AN}	°F	13.6	18.1	27.6	38.8	48.1	57.7	62.7	61.7	53.9	42.9	31.4	20.3	39.7
	I	Btu/ft^2 day	507	760	1107	1459	1789	2007	1944	1719	1354	969	566	402	1215
Springield, IL	T_{AX}	°F	32.8	38.0	48.9	64.0	74.6	84.1	87.1	84.7	79.3	67.5	51.2	38.4	62.6
	T_{AN}	°F	16.3	20.9	30.3	42.6	52.5	62.0	65.9	63.7	55.8	44.4	32.9	23.0	42.5
	I	Btu/ft^2 day	585	861	1143	1515	1866	2097	2058	1806	1454	1068	677	490	1302
Indianapolis, IN	T_{AX}	°F	34.2	38.5	49.3	63.1	73.4	82.3	85.2	83.7	77.9	66.1	50.8	39.2	62.0
	T_{AN}	°F	17.8	21.1	30.7	41.7	51.5	60.9	64.9	62.7	55.3	43.4	32.8	23.7	42.2
	I	Btu/ft^2 day	496	747	1037	1398	1638	1868	1806	1644	1324	977	579	417	1165
Wichita, KS	T_{AX}	°F	39.8	46.1	55.8	68.1	77.1	87.4	92.9	91.5	82.0	71.2	55.1	44.6	67.6
	T_{AN}	°F	19.4	24.1	32.4	44.5	54.6	64.7	69.8	67.9	59.2	46.9	33.5	24.2	45.1
	I	Btu/ft^2 day	784	1058	1406	1783	2036	2264	2239	2032	1616	1250	871	690	1502

Table 7.1-6 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Louisville, KY	T_{AX}	°F	40.8	45.0	54.9	67.5	76.2	84.0	87.6	86.7	80.6	69.2	55.5	45.4	66.1
	T_{AN}	°F	24.1	26.8	35.2	45.6	54.6	63.3	67.5	66.1	59.1	46.2	36.6	28.9	46.2
	I	Btu/ft^2 day	546	789	1102	1467	1720	1904	1838	1680	1361	1042	653	488	1216
Baton Rouge, LA	T_{AX}	°F	61.1	64.5	71.6	79.2	85.2	90.6	91.4	90.8	87.4	80.1	70.1	63.8	78.0
	T_{AN}	°F	40.5	42.7	49.4	57.5	64.3	70.0	72.8	72.0	68.3	56.3	47.2	42.3	57.0
	I	Btu/ft^2 day	785	1054	1379	1681	1871	1926	1746	1677	1464	1301	920	737	1379
Lake Charles, LA	T_{AX}	°F	60.8	64.0	70.5	77.8	84.1	89.4	91.0	90.8	87.5	80.8	70.5	64.0	77.6
	T_{AN}	°F	42.2	44.5	50.8	58.9	65.6	71.4	73.5	72.8	68.9	57.7	48.9	43.8	58.3
	I	Btu/ft^2 day	728	1010	1313	1570	1849	1970	1788	1657	1485	1381	917	706	1365
New Orleans, LA	T_{AX}	°F	61.8	64.6	71.2	78.6	84.5	89.5	90.7	90.2	86.8	79.4	70.1	64.4	77.7
	T_{AN}	°F	43.0	44.8	51.6	58.8	65.3	70.9	73.5	73.1	70.1	59.0	49.9	44.8	58.7
	I	Btu/ft^2 day	835	1112	1415	1780	1968	2004	1814	1717	1514	1335	973	779	1437
Detroit, MI	T_{AX}	°F	30.6	33.5	43.4	57.7	69.4	79.0	83.1	81.5	74.4	62.5	47.6	35.4	58.2
	T_{AN}	°F	16.1	18.0	26.5	36.9	46.7	56.3	60.7	59.4	52.2	41.2	31.4	21.6	38.9
	I	Btu/ft^2 day	417	680	1000	1399	1716	1866	1835	1576	1253	876	478	344	1120
Grand Rapids, MI	T_{AX}	°F	29.0	31.7	41.6	56.9	69.4	78.9	83.0	81.1	73.4	61.4	46.0	33.8	57.2
	T_{AN}	°F	14.9	15.6	24.5	35.6	45.5	55.3	59.8	58.1	50.8	40.4	30.9	20.7	37.7
	I	Btu/ft^2 day	370	648	1014	1412	1755	1957	1914	1676	1262	858	446	311	1135
Minneapolis-St. Paul, MN	T_{AX}	°F	19.9	26.4	37.5	56.0	69.4	78.5	83.4	80.9	71.0	59.7	41.1	26.7	54.2
	T_{AN}	°F	2.4	8.5	20.8	36.0	47.6	57.7	62.7	60.3	50.2	39.4	25.3	11.7	35.2
	I	Btu/ft^2 day	464	764	1104	1442	1737	1928	1970	1687	1255	860	480	353	1170
Jackson, MS	T_{AX}	°F	56.5	60.9	68.4	77.3	84.1	90.5	92.5	92.1	87.6	78.6	67.5	60.0	76.3
	T_{AN}	°F	34.9	37.2	44.2	52.9	60.8	67.9	71.3	70.2	65.1	51.4	42.3	37.1	52.9
	I	Btu/ft^2 day	754	1026	1369	1708	1941	2024	1909	1781	1509	1271	902	709	1409
Billings, MT	T_{AX}	°F	29.9	37.9	44.0	55.9	66.4	76.3	86.6	84.3	72.3	61.0	44.4	36.0	57.9
	T_{AN}	°F	11.8	18.8	23.6	33.2	43.3	51.6	58.0	56.2	46.5	37.5	25.5	18.2	35.4
	I	Btu/ft^2 day	486	763	1190	1526	1913	2174	2384	2022	1470	987	561	421	1325
Las Vegas, NV	T_{AX}	°F	56.0	62.4	68.3	77.2	87.4	98.6	104.5	101.9	94.7	81.5	66.0	57.1	79.6
	T_{AN}	°F	33.0	37.7	42.3	49.8	59.0	68.6	75.9	73.9	65.6	53.5	41.2	33.6	52.8
	I	Btu/ft^2 day	978	1340	1824	2319	2646	2778	2588	2355	2037	1540	1086	881	1864
Newark, NJ	T_{AX}	°F	38.2	40.3	49.1	61.3	71.6	80.6	85.6	84.0	76.9	66.0	54.0	42.3	62.5
	T_{AN}	°F	24.2	25.3	33.3	42.9	53.0	62.4	67.9	67.0	59.4	48.3	39.0	28.6	45.9
	I	Btu/ft^2 day	552	793	1109	1449	1687	1795	1760	1565	1273	951	596	454	1165

Table 7.1-6 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Roswell, NM	T_{AX}	°F	55.4	60.4	67.7	76.9	85.0	93.1	93.7	91.3	84.9	75.8	63.1	56.7	75.3
	T_{AN}	°F	27.4	31.4	37.9	46.8	55.6	64.8	69.0	67.0	59.6	47.5	35.0	28.2	47.5
	I	Btu/ft^2 day	1047	1373	1807	2218	2459	2610	2441	2242	1913	1527	1131	952	1810
Buffalo, NY	T_{AX}	°F	30.0	31.4	40.4	54.4	65.9	75.6	80.2	78.2	71.4	60.2	47.0	35.0	55.8
	T_{AN}	°F	17.0	17.5	25.6	36.3	46.3	56.4	61.2	59.6	52.7	42.7	33.6	22.5	39.3
	I	Btu/ft^2 day	349	546	889	1315	1597	1804	1776	1513	1152	784	403	283	1034
New York, NY (LaGuardia Airport)	T_{AX}	°F	37.4	39.2	47.3	59.6	69.7	78.7	83.9	82.3	75.2	64.5	52.9	41.5	61.0
	T_{AN}	°F	26.1	27.3	34.6	44.2	53.7	63.2	68.9	68.2	61.2	50.5	41.2	30.8	47.5
	I	Btu/ft^2 day	548	795	1118	1457	1690	1802	1784	1583	1280	951	593	457	1171
Cleveland, OH	T_{AX}	°F	32.5	34.8	44.8	57.9	68.5	78.0	81.7	80.3	74.2	62.7	49.3	37.5	58.5
	T_{AN}	°F	18.5	19.9	28.4	38.3	47.9	57.2	61.4	60.5	54.0	43.6	34.3	24.6	40.7
	I	Btu/ft^2 day	388	601	922	1350	1681	1843	1828	1583	1240	867	466	318	1091
Columbus, OH	T_{AX}	°F	34.7	38.1	49.3	62.3	72.6	81.3	84.4	83.0	76.9	65.0	50.7	39.4	61.5
	T_{AN}	°F	19.4	21.5	30.6	40.5	50.2	59.0	63.2	61.7	54.6	42.8	33.5	24.7	41.8
	I	Btu/ft^2 day	459	677	980	1353	1647	1813	1755	1641	1282	945	538	387	1123
Toledo, OH	T_{AX}	°F	30.7	34.0	44.6	59.1	70.5	79.9	83.4	81.8	75.1	63.3	47.9	35.5	58.8
	T_{AN}	°F	15.5	17.5	26.1	36.5	46.6	56.0	60.2	58.4	51.2	40.1	30.6	20.6	38.3
	I	Btu/ft^2 day	435	680	997	1384	1717	1878	1849	1616	1276	911	498	355	1133
Oklahoma City, OK	T_{AX}	°F	46.6	52.2	61.0	71.7	79.0	87.6	93.5	92.8	84.7	74.3	59.9	50.7	71.2
	T_{AN}	°F	25.2	29.4	37.1	48.6	57.7	66.3	70.6	69.4	61.9	50.2	37.6	29.1	48.6
	I	Btu/ft^2 day	801	1055	1400	1725	1918	2144	2128	1950	1554	1233	901	725	1461
Tulsa, OK	T_{AX}	°F	45.6	51.9	60.8	72.4	79.7	87.9	93.9	93.0	85.0	74.9	60.2	50.3	71.3
	T_{AN}	°F	24.8	29.5	37.7	49.5	58.5	67.5	72.4	70.3	62.5	50.3	38.1	29.3	49.2
	I	Btu/ft^2 day	732	978	1306	1603	1822	2021	2031	1865	1473	1164	827	659	1373
Astoria, OR	T_{AX}	°F	46.8	50.6	51.9	55.5	60.2	63.9	67.9	68.6	67.8	61.4	53.5	48.8	58.1
	T_{AN}	°F	35.4	37.1	36.9	39.7	44.1	49.2	52.2	52.6	49.2	44.3	39.7	37.3	43.1
	I	Btu/ft^2 day	315	545	866	1253	1608	1626	1746	1499	1183	713	387	261	1000
Portland, OR	T_{AX}	°F	44.3	50.4	54.5	60.2	66.9	72.7	79.5	78.6	74.2	63.9	52.3	46.4	62.0
	T_{AN}	°F	33.5	36.0	37.4	40.6	46.4	52.2	55.8	55.8	51.1	44.6	38.6	35.4	44.0
	I	Btu/ft^2 day	310	554	895	1308	1663	1773	2037	1674	1217	724	388	260	1067
Philadelphia, PA	T_{AX}	°F	38.6	41.1	50.5	63.2	73.0	81.7	86.1	84.6	77.8	66.5	54.5	43.0	63.4
	T_{AN}	°F	23.8	25.0	33.1	42.6	52.5	61.5	66.8	66.0	58.6	46.5	37.1	28.0	45.1
	I	Btu/ft^2 day	555	795	1108	1434	1660	1811	1758	1575	1281	959	619	470	1169

Table 7.1-6 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Pittsburgh, PA	T_{AX}	°F	34.1	36.8	47.6	60.7	70.8	79.1	82.7	81.1	74.8	62.9	49.8	38.4	59.9
	T_{AN}	°F	19.2	20.7	29.4	39.4	48.5	57.1	61.3	60.1	53.3	42.1	33.3	24.3	40.7
	I	Btu/ft^2 day	424	625	943	1317	1602	1762	1689	1510	1209	895	505	347	1069
Providence, RI	T_{AX}	°F	36.4	37.7	45.5	57.5	67.6	76.6	81.7	80.3	73.1	63.2	51.9	40.5	59.3
	T_{AN}	°F	20.0	20.9	29.2	38.3	47.6	57.0	63.3	61.9	53.8	43.1	34.8	24.1	41.2
	I	Btu/ft^2 day	506	739	1032	1374	1655	1776	1695	1499	1209	907	538	419	1112
Columbia, SC	T_{AX}	°F	56.2	59.5	67.1	77.0	83.8	89.2	91.9	91.0	85.5	76.5	67.1	58.8	75.3
	T_{AN}	°F	33.2	34.6	41.9	50.5	59.1	66.1	70.1	69.4	63.9	50.3	40.6	34.7	51.2
	I	Btu/ft^2 day	762	1021	1355	1747	1895	1947	1842	1703	1439	1211	921	722	1380
Sioux Falls, SD	T_{AX}	°F	22.9	29.3	40.1	58.1	70.5	80.3	86.2	83.9	73.5	62.1	43.7	29.3	56.7
	T_{AN}	°F	1.9	8.9	20.6	34.6	45.7	56.3	61.8	59.7	48.5	36.7	22.3	10.1	33.9
	I	Btu/ft^2 day	533	802	1152	1543	1894	2100	2150	1845	1410	1005	608	441	1290
Memphis, TN	T_{AX}	°F	48.3	53.0	61.4	72.9	81.0	88.4	91.5	90.3	84.3	74.5	61.4	52.3	71.6
	T_{AN}	°F	30.9	34.1	41.9	52.2	60.9	68.9	72.6	70.8	64.1	51.3	41.1	34.3	51.9
	I	Btu/ft^2 day	683	945	1278	1639	1885	2045	1972	1824	1471	1205	817	629	1366
Amarillo, TX	T_{AX}	°F	49.1	53.1	60.8	71.0	79.1	88.2	91.4	89.6	82.4	72.7	58.7	51.8	70.7
	T_{AN}	°F	21.7	26.1	32.0	42.0	51.9	61.5	66.2	64.5	56.9	45.5	32.1	24.8	43.8
	I	Btu/ft^2 day	960	1244	1631	2019	2212	2393	2281	2103	1761	1404	1033	872	1659
Corpus Christi, TX	T_{AX}	°F	66.5	69.9	76.1	82.1	86.7	91.2	94.2	94.1	90.1	83.9	75.1	69.3	81.6
	T_{AN}	°F	46.1	48.7	55.7	63.9	69.5	74.1	75.6	75.8	72.8	64.1	54.9	48.8	62.5
	I	Btu/ft^2 day	898	1147	1430	1642	1866	2094	2186	1991	1687	1416	1043	845	1521
Dallas, TX	T_{AX}	°F	54.0	59.1	67.2	76.8	84.4	93.2	97.8	97.3	89.7	79.5	66.2	58.1	76.9
	T_{AN}	°F	33.9	37.8	44.9	55.0	62.9	70.8	74.7	73.7	67.5	56.3	44.9	37.4	55.0
	I	Btu/ft^2 day	822	1071	1422	1627	1889	2135	2122	1950	1587	1276	936	780	1468
Houston, TX	T_{AX}	°F	61.9	65.7	72.1	79.0	85.1	90.9	93.6	93.1	88.7	81.9	71.6	65.2	79.1
	T_{AN}	°F	40.8	43.2	49.8	58.3	64.7	70.2	72.5	72.1	68.1	57.5	48.6	42.7	57.4
	I	Btu/ft^2 day	772	1034	1297	1522	1775	1898	1828	1686	1471	1276	924	730	1351
Midland-Odessa, TX	T_{AX}	°F	57.6	62.1	69.8	78.8	86.0	93.0	94.2	93.1	86.4	77.7	65.5	59.7	77.0
	T_{AN}	°F	29.7	33.3	40.2	49.4	58.2	66.6	69.2	68.0	61.9	51.1	39.0	32.2	49.9
	I	Btu/ft^2 day	1081	1383	1839	2192	2430	2562	2389	2210	1844	1522	1176	1000	1802
Salt Lake City, UT	T_{AX}	°F	37.4	43.7	51.5	61.1	72.4	83.3	93.2	90.0	80.0	66.7	50.2	38.9	64.0
	T_{AN}	°F	19.7	24.4	29.9	37.2	45.2	53.3	61.8	59.7	50.0	39.3	29.2	21.6	39.3
	I	Btu/ft^2 day	639	989	1454	1894	2362	2561	2590	2254	1843	1293	788	570	1603

Table 7.1-6 (cont.).

Location	Property		Monthly Averages												Annual Average
	Symbol	Units	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Richmond, VA	T_{AX}	°F	46.7	49.6	58.5	70.6	77.9	84.8	88.4	87.1	81.0	70.5	60.5	50.2	68.8
	T_{AN}	°F	26.5	28.1	35.8	45.1	54.2	62.2	67.2	66.4	59.3	46.7	37.3	29.6	46.5
	I	Btu/ft^2 day	632	877	1210	1566	1762	1872	1774	1601	1348	1033	733	567	1248
Seattle, WA (Sea-Tac Airport)	T_{AX}	°F	43.9	48.8	51.1	56.8	64.0	69.2	75.2	73.9	68.7	59.5	50.3	45.6	58.9
	T_{AN}	°F	34.3	36.8	37.2	40.5	46.0	51.1	54.3	54.3	51.2	45.3	39.3	36.3	43.9
	I	Btu/ft^2 day	262	495	849	1294	1714	1802	2248	1616	1148	656	337	211	1053
Charleston, WV	T_{AX}	°F	41.8	45.4	55.4	67.3	76.0	82.5	85.2	84.2	78.7	67.7	55.6	45.9	65.5
	T_{AN}	°F	23.9	25.8	34.1	43.3	51.8	59.4	63.8	63.1	56.4	44.0	35.0	27.8	44.0
	I	Btu/ft^2 day	498	707	1010	1356	1639	1776	1683	1514	1272	972	613	440	1123
Huntington, WV	T_{AX}	°F	41.1	45.0	55.2	67.2	75.7	82.6	85.6	84.4	78.7	67.6	55.2	45.2	65.3
	T_{AN}	°F	24.5	26.6	35.0	44.4	52.8	60.7	65.1	64.0	57.2	44.9	35.9	28.5	45.0
	I	Btu/ft^2 day	526	757	1067	1448	1710	1844	1769	1580	1306	1004	638	467	1176
Cheyenne, WY	T_{AX}	°F	37.3	40.7	43.6	54.0	64.6	75.4	83.1	80.8	72.1	61.0	46.5	40.4	58.3
	T_{AN}	°F	14.8	17.9	20.6	29.6	39.7	48.5	54.6	52.8	43.7	34.0	23.1	18.2	33.1
	I	Btu/ft^2 day	766	1068	1433	1771	1995	2258	2230	1966	1667	1242	823	671	1491

[a] References 11-12. T_{AX} = maximum ambient temperature. T_{AN} = minimum ambient temperature. I = solar insolation factor.

Table 7.1-7. PAINT SOLAR ABSORPTANCE FOR FIXED ROOF TANKS[a]

		Paint Factors (α)	
		Paint Condition	
Paint Color	Paint Shade or Type	Good	Poor
Aluminum	Specular	0.39	0.49
Aluminum	Diffuse	0.60	0.68
Gray	Light	0.54	0.63
Gray	Medium	0.68	0.74
Red	Primer	0.89	0.91
White	NA	0.17	0.34

[a] Reference 6. If specific information is not available, a white shell and roof, with the paint in good condition, can be assumed to represent the most common or typical tank paint in use. If the tank roof and shell are painted a different color, α is determined from $\alpha = (\alpha_R + \alpha_S)/2$, where α_R is the tank roof paint solar absorptance and α_S is the tank shell paint solar absorptance. NA = not applicable.

Table 7.1-8. RIM-SEAL LOSS FACTORS, K_R AND n, FOR EXTERNAL FLOATING ROOF TANKS

	Average-Fitting Seals	
Tank Construction And Rim-Seal System	K_R (lb-mole/[mph]^n-ft-yr)	n (dimensionless)
Welded Tanks		
Mechanical-shoe seal		
Primary only	1.2[b]	1.5[b]
Shoe-mounted secondary	0.8	1.2
Rim-mounted secondary	0.2	1.0
Liquid-mounted resilient-filled seal		
Primary only	1.1	1.0
Weather shield	0.8	0.9
Rim-mounted secondary	0.7	0.4
Vapor-mounted resilient-filled seal		
Primary only	1.2	2.3
Weather shield	0.9	2.2
Rim-mounted secondary	0.2	2.6
Riveted Tanks		
Mechanical-shoe seal		
Primary only	1.3	1.5
Shoe-mounted secondary	1.4	1.2
Rim-mounted secondary	0.2	1.6

[a] Reference 3.

[b] If no specific information is available, a welded tank with an average-fitting mechanical-shoe primary seal can be used to represent the most common or typical construction and rim-seal system in use.

Table 7.1-9. AVERAGE ANNUAL WIND SPEED (v) FOR SELECTED U. S. LOCATIONS[a]

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
Alabama		Arizona (continued)		Delaware	
Birmingham	7.2	Winslow	8.9	Wilmington	9.1
Huntsville	8.2	Yuma	7.8		
Mobile	9.0			District of Columbia	
Montgomery	6.6	Arkansas		Dulles Airport	7.4
		Fort Smith	7.6	National Airport	9.4
Alaska		Little Rock	7.8		
Anchorage	6.9			Florida	
Annette	10.6	California		Apalachicola	7.8
Barrow	11.8	Bakersfield	6.4	Daytona Beach	8.7
Barter Island	13.2	Blue Canyon	6.8	Fort Meyers	8.1
Bethel	12.8	Eureka	6.8	Jacksonville	8.0
Bettles	6.7	Fresno	6.3	Key West	11.2
Big Delta	8.2	Long Beach	6.4	Miami	9.3
Cold Bay	17.0	Los Angeles (City)	6.2	Orlando	8.5
Fairbanks	5.4	Los Angeles Int'l. Airport	7.5	Pensacola	68.4
Gulkana	6.8	Mount Shasta	5.1	Tallahassee	6.3
Homer	7.6	Sacramento	7.9	Tampa	8.4
Juneau	8.3	San Diego	6.9	West Palm Beach	9.6
King Salmon	10.8	San Francisco (City)	8.7		
Kodiak	10.8	San Francisco Airport	10.6	Georgia	
Kotzebue	13.0	Santa Maria	7.0	Athens	7.4
McGrath	5.1	Stockton	7.5	Atlanta	9.1
Nome	10.7			Augusta	6.5
St. Paul Island	17.7	Colorado		Columbus	6.7
Talkeetna	4.8	Colorado Springs	10.1	Macon	7.6
Valdez	6.0	Denver	8.7	Savannah	7.9
Yakutat	7.4	Grand Junction	8.1		
		Pueblo	8.7	Hawaii	
Arizona				Hilo	7.2
Flagstaff	6.8	Connecticut		Honolulu	11.4
Phoenix	6.3	Bridgeport	12.0	Kahului	12.8
Tucson	8.3	Hartford	8.5	Lihue	12.2

Table 7.1-9 (cont.).

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
Idaho		Louisiana		Mississippi	
Boise	8.8	Baton Rouge	7.6	Jackson	7.4
Pocatello	10.2	Lake Charles	8.7	Meridian	6.1
		New Orleans	8.2		
Illinois		Shreveport	8.4	Missouri	
Cairo	8.5			Columbia	9.9
Chicago	10.3	Maine		Kansas City	10.8
Moline	10.0	Caribou	11.2	Saint Louis	9.7
Peoria	10.0	Portland	8.8	Springfield	10.7
Rockford	10.0				
Springfield	11.2	Maryland		Montana	
		Baltimore	9.2	Billings	11.2
Indiana				Glasgow	10.8
Evansville	8.1	Massachusetts		Great Falls	12.8
Fort Wayne	10.0	Blue Hill Observatory	15.4	Helena	7.8
Indianapolis	9.6	Boston	12.4	Kalispell	6.6
South Bend	10.3	Worcester	10.2	Missoula	6.2
Iowa		Michigan		Nebraska	
Des Moines	10.9	Alpena	8.1	Grand Island	11.9
Sioux City	11.0	Detroit	10.2	Lincoln	10.4
Waterloo	10.7	Flint	10.2	Norfolk	11.7
		Grand Rapids	9.8	North Platte	10.2
Kansas		Houghton Lake	8.9	Omaha	10.6
Concordia	12.3	Lansing	10.0	Scottsbuff	10.6
Dodge City	14.0	Muskegon	10.7	Valentine	9.7
Goodland	12.6	Sault Sainte Marie	9.3		
Topeka	10.2			Nevada	
Wichita	12.3	Minnesota		Elko	6.0
		Duluth	11.1	Ely	10.3
Kentucky		International Falls	8.9	Las Vegas	9.3
Cincinnati Airport	9.1	Minneapolis-Saint Paul	10.6	Reno	6.6
Jackson	7.2	Rochester	13.1	Winnemucca	8.0
Lexington	9.3	Saint Cloud	8.0		
Louisville	8.4				

Table 7.1-9 (cont.).

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
New Hampshire		Ohio		Rhode Island	
Concord	6.7	Akron	9.8	Providence	10.6
Mount Washington	35.3	Cleveland	10.6		
		Columbus	8.5	South Carolina	
New Jersey		Dayton	9.9	Charleston	8.6
Atlantic City	10.1	Mansfield	11.0	Columbia	6.9
Newark	10.2	Toledo	9.4	Greenville-Spartanburg	6.9
		Youngstown	9.9		
New Mexico				South Dakota	
Albuquerque	9.1	Oklahoma		Aberdeen	11.2
Roswell	8.6	Oklahoma City	12.4	Huron	11.5
		Tulsa	10.3	Rapid City	11.3
New York				Sioux Falls	11.1
Albany	8.9	Oregon			
Birmingham	10.3	Astoria	12.4	Tennessee	
Buffalo	12.0	Eugene	7.6	Bristol-Johnson City	5.5
New York (Central Park)	9.4	Medford	4.8	Chattanooga	6.1
New York (JFK Airport)	12.0	Pendleton	8.7	Knoxville	7.0
New York (La Guarida Airport)	12.2	Portland	7.9	Memphis	8.9
Rochester	9.7	Salem	7.1	Nashville	8.0
Syracuse	9.5	Sexton Summit	11.8	Oak Ridge	4.4
North Carolina		Pennsylvania		Texas	
Asheville	7.6	Allentown	9.2	Abilene	12.0
Cape Hatteras	11.1	Avoca	8.3	Amarillo	13.6
Charlotte	7.5	Erie	11.3	Austin	9.2
Greensboro-High Point	7.5	Harrisburg	7.6	Brownsville	11.5
Raleigh	7.8	Philadelphia	9.5	Corpus Christi	12.0
Wilmington	8.8	Pittsburgh Int'l Airport	9.1	Dallas-Fort Worth	10.8
		Williamsport	7.8	Del Rio	9.9
North Dakota				El Paso	8.9
Bismark	10.2	Puerto Rico		Galveston	11.0
Fargo	12.3	San Juan	8.4	Houston	7.9
Williston	10.1			Lubbock	12.4

Table 7.1-9 (cont.).

Location	Wind Speed (mph)	Location	Wind Speed (mph)	Location	Wind Speed (mph)
Texas (continued)		Wisconsin			
Midland-Odessa	11.1	Green Bay	10.0		
Port Arthur	9.8	La Crosse	8.8		
San Angelo	10.4	Madison	9.9		
San Antonio	9.3	Milwaukee	11.6		
Victoria	10.1				
Waco	11.3	Wyoming			
Wichita Falls	11.7	Casper	12.9		
		Cheyenne	13.0		
Utah		Lander	6.8		
Salt Lake City	8.9	Sheridan	8.0		
Vermont					
Burlington	8.9				
Virginia					
Lynchburg	7.7				
Norfolk	10.7				
Richmond	7.7				
Roanoke	8.1				
Washington					
Olympia	6.7				
Quillayute	6.1				
Seattle Int'l. Airport	9.0				
Spokane	8.9				
Walla Walla	5.3				
Yakima	7.1				
West Virginia					
Belkley	9.1				
Charleston	6.4				
Elkins	6.2				
Huntington	6.6				

[a] Reference 11.

Table 7.1-10 (English Units). AVERAGE CLINGAGE FACTORS, C[a]
($bbl/10^3\ ft^2$)

Product Stored	Shell Condition		
	Light Rust	Dense Rust	Gunite Lining
Gasoline	0.0015	0.0075	0.15
Single-component stocks	0.0015	0.0075	0.15
Crude oil	0.0060	0.030	0.60

[a] Reference 3. If no specific information is available, the values in this table can be assumed to represent the most common or typical condition of tanks currently in use.

Table 7.1-11 (English Units). EXTERNAL FLOATING ROOF-FITTING LOSS FACTORS, K_{Fa}, K_{Fb}, AND m, AND TYPICAL NUMBER OF ROOF FITTINGS, N_F[a]

Fitting Type And Construction Details	Loss Factors			Typical Number Of Fittings, N_F
	K_{Fa} (lb-mole/yr)	K_{Fb} (lb-mole/(mph)^m-yr)	m (dimensionless)	
Access hatch (24-inch diameter well)				1
Bolted cover, gasketed	0	0	0[b]	
Unbolted cover, ungasketed	2.7	7.1	1.0	
Unbolted cover, gasketed	2.9	0.41	1.0	
Unslotted guidepole well (8-inch diameter unslotted pole, 21-inch diameter well)				1
Ungasketed sliding cover	0	67	0.98[b]	
Gasketed sliding cover	0	3.0	1.4	
Slotted guide-pole/sample well (8 inch diameter slotted pole, 21-inch diameter well)				c
Ungasketed sliding cover, without float	0	310	1.2	
Ungasketed sliding cover, with float	0	29	2.0	
Gasketed sliding cover, without float	0	260	1.2	
Gasketed sliding cover, with float	0	8.5	2.4	
Gauge-float well (20-inch diameter)				1
Unbolted cover, ungasketed	2.3	5.9	1.0[b]	
Unbolted cover, gasketed	2.4	0.34	1.0	
Bolted cover, gasketed	0	0	0	
Gauge-hatch/sample well (8-inch diameter)				1
Weighted mechanical actuation, gasketed	0.95	0.14	1.0[b]	
Weighted mechanical actuation, ungasketed	0.91	2.4	1.0	
Vacuum breaker (10-inch diameter well)				N_{F6} (Table 7.1.-12)
Weighted mechanical actuation, gasketed	1.2	0.17	1.0[b]	
Weighted mechanical actuation, ungasketed	1.1	3.0	1.0	
Roof drain (3-inch diameter)				N_{F7} (Table 7.1.-12)
Open	0	7.0	1.4[d]	
90% closed	0.51	0.81	1.0	
Roof leg (3-inch diameter)				N_{F8} (Table 7.1-13)[e]
Adjustable, pontoon area	1.5	0.20	1.0[b]	
Adjustable, center area	0.25	0.067	1.0[b]	
Adjustable, double-deck roofs	0.25	0.067	1.0	
Fixed	0	0	0	
Roof leg (2-1/2 inch diameter)				N_{F8} (Table 7.1-13)[e]
Adjustable, pontoon area	1.7	0	0	
Adjustable, center area	0.41	0	0	
Adjustable, double-deck roofs	0.41	0	0	
Fixed	0	0	0	

Table 7.1-11 (cont.).

Fitting Type And Construction Details	Loss Factors			Typical Number Of Fittings, N_F
	K_{Fa} (lb-mole/yr)	K_{Fb} (lb-mole/(mph)^m-yr)	m (dimensionless)	
Rim vent (6-inch diameter)				1^f
Weighted mechanical actuation, gasketed	0.71	0.10	1.0^b	
Weighted mechanical actuation, ungasketed	0.68	1.8	1.0	

[a] Reference 3. The roof-fitting loss factors, K_{Fa}, K_{Fb}, and m, may be used only for wind speeds from 2 to 15 miles per hour.

[b] If no specific information is available, this value can be assumed to represent the most common or typical roof fitting currently in use.

[c] A slotted guide-pole/sample well is an optional fitting and is not typically used.

[d] Roof drains that drain excess rainwater into the product are not used on pontoon floating roofs. They are, however, used on double-deck floating roofs and are typically left open.

[e] The most common roof leg diameter is 3 in. The loss factors for 2.5-in. diameter roof legs are provided for use if this smaller size roof leg is used on a particular floating roof.

[f] Rim vents are used only with mechanical-shoe primary seals.

Table 7.1-12. EXTERNAL FLOATING ROOF TANKS: TYPICAL NUMBER OF VACUUM BREAKERS, N_{F6}, AND ROOF DRAINS, N_{F7}[a]

Tank Diameter D (feet)[b]	Number Of Vacuum Breakers, N_{F6}		Number Of Roof Drains, N_{F7} (double-deck roof)[c]
	Pontoon Roof	Double-Deck Roof	
50	1	1	1
100	1	1	1
150	2	2	2
200	3	2	3
250	4	3	5
300	5	3	7
350	6	4	ND
400	7	4	ND

[a] Reference 3. This table was derived from a survey of users and manufacturers. The actual number of vacuum breakers may vary greatly, depending on throughput and manufacturing prerogatives. The actual number of roof drains may also vary greatly, depending on the design rainfall and manufacturing prerogatives. For tanks more than 350 ft in diameter, actual tank data or the manufacturer's recommendations may be needed for the number of roof drains. This table should not be used when actual tank data are available. ND = no data.

[b] If the actual diameter is between the diameters listed, the closest diameter listed should be used. If the actual diameter is midway between the diameters listed, the next larger diameter should be used.

[c] Roof drains that drain excess rainwater into the product are not used on pontoon floating roofs. They are, however, used on double-deck floating roofs and are typically left open.

Table 7.1-13. EXTERNAL FLOATING ROOF TANKS: TYPICAL NUMBER OF ROOF LEGS, N_{F8}[a]

Tank Diameter, D (feet)[b]	Pontoon Roof		Number Of Legs On Double-Deck Roof
	Number Of Pontoon Legs	Number Of Center Legs	
30	4	2	6
40	4	4	7
50	6	6	8
60	9	7	10
70	13	9	13
80	15	10	16
90	16	12	20
100	17	16	25
110	18	20	29
120	19	24	34
130	20	28	40
140	21	33	46
150	23	38	52
160	26	42	58
170	27	49	66
180	28	56	74
190	29	62	82
200	30	69	90
210	31	77	98
220	32	83	107
230	33	92	115
240	34	101	127
250	35	109	138
260	36	118	149
270	36	128	162
280	37	138	173
290	38	148	186
300	38	156	200
310	39	168	213
320	39	179	226
330	40	190	240
340	41	202	255
350	42	213	270
360	44	226	285
370	45	238	300
380	46	252	315
390	47	266	330
400	48	281	345

[a] Reference 3. This table was derived from a survey of users and manufacturers. The actual number of roof legs may vary greatly depending on age, style of floating roof, loading specifications, and manufacturing prerogatives. This table should not be used when actual tank data are available.

[b] If the actual diameter is between the diameters listed, the closest diameter listed should be used. If the actual diameter is midway between the diameters listed, the next larger diameter should be used.

Table 7.1-14. INTERNAL FLOATING ROOF RIM SEAL LOSS FACTORS (K_R)[a]

Rim Seal System Description	K_R (lb-mole/ft • yr)
	Average
Vapor-mounted primary seal only	6.7[b]
Liquid-mounted primary seal only	3.0
Vapor-mounted primary seal plus secondary seal	2.5
Liquid-mounted primary seal plus secondary seal	1.6

[a] Reference 4.

[b] If no specific information is available, this value can be assumed to represent the most common/typical rim seal system currently in use.

Table 7.1-15. TYPICAL NUMBER OF COLUMNS AS A FUNCTION OF TANK DIAMETER FOR INTERNAL FLOATING ROOF TANKS WITH COLUMN-SUPPORTED FIXED ROOFS[a]

Tank Diameter Range, D (ft)	Typical Number of Columns, N_C
$0 < D \leq 85$	1
$85 < D \leq 100$	6
$100 < D \leq 120$	7
$120 < D \leq 135$	8
$135 < D \leq 150$	9
$150 < D \leq 170$	16
$170 < D \leq 190$	19
$190 < D \leq 220$	22
$220 < D \leq 235$	31
$235 < D \leq 270$	37
$270 < D \leq 275$	43
$275 < D \leq 290$	49
$290 < D \leq 330$	61
$330 < D \leq 360$	71
$360 < D \leq 400$	81

[a] Reference 4. This table was derived from a survey of users and manufacturers. The actual number of columns in a particular tank may vary greatly with age, fixed roof style, loading specifications, and manufacturing prerogatives. This table should not be used when actual tank data are available.

Table 7.1-16. SUMMARY OF INTERNAL FLOATING DECK FITTING LOSS FACTORS (K_F) AND TYPICAL NUMBER OF FITTINGS (N_F)[a]

Deck Fitting Type	Deck Fitting Loss Factor, K_F (lb-mole/yr)	Typical Number Of Fittings, N_F
Access hatch (24-inch diameter)		1
Bolted cover, gasketed	1.6	
Unbolted cover, gasketed	11	
Unbolted cover, ungasketed	25[b]	
Automatic gauge float well		1
Bolted cover, gasketed	5.1	
Unbolted cover, gasketed	15	
Unbolted cover, ungasketed	28[b]	
Column well (24-inch diameter)[c]		(see Table 7.1-15)
Builtup column-sliding cover, gasketed	33	
Builtup column-sliding cover, ungasketed	47[b]	
Pipe column-flexible fabric sleeve seal	10	
Pipe column-sliding cover, gasketed	19	
Pipe column-sliding cover, ungasketed	32	
Ladder well (36-inch diameter)[c]		1[f]
Sliding cover, gasketed	56	
Sliding cover, ungasketed	76[b]	
Roof leg or hanger well[c,d]		
Adjustable	7.9[b]	$(5+\frac{D}{10}+\frac{D^2}{600})$
Fixed	0	
Sample pipe or well (24-inch diameter)		
Slotted pipe-sliding cover, gasketed	44	1
Slotted pipe-sliding cover, ungasketed	57	
Sample well-slit fabric seal 10% open area	12[b]	
Stub drain (1-inch diameter)[d,e]	1.2	$(\frac{D^2}{125})$
Vacuum breaker (10-inch diameter)		1
Weighted mechanical actuation, gasketed	0.7[b]	
Weighted mechanical actuation, ungasketed	0.9	

[a] Reference 4.

[b] If no specific information is available, this value can be assumed to represent the most common/typical deck fittings currently used.

[c] Column wells and ladder wells are not typically used with self-supported roofs.

[d] D = tank diameter (ft).

[e] Not used on welded contact internal floating decks.

[f] Not typically used on tanks with self-supporting fixed roofs.

Table 7.1-17 (English Units). DECK SEAM LENGTH FACTORS (S_D) FOR TYPICAL DECK CONSTRUCTIONS FOR INTERNAL FLOATING ROOF TANKS[a]

Deck Construction	Typical Deck Seam Length Factor, S_D (ft/ft^2)
Continuous sheet construction[b]	
5 ft wide	0.20[c]
6 ft wide	0.17
7 ft wide	0.14
Panel construction[d]	
5 x 7.5 ft rectangular	0.33
5 x 12 ft rectangular	0.28

[a] Reference 4. Deck seam loss applies to bolted decks only.

[b] S_D = 1/W, where W = sheet width (ft).

[c] If no specific information is available, this factor can be assumed to represent the most common bolted decks currently in use.

[d] S_D = (L+W)/LW, where W = panel width (ft) and L = panel length (ft).

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8. INORGANIC CHEMICAL INDUSTRY

Possible emissions from the manufacture and use of inorganic chemicals and chemical products are high but, because of economic necessity, they are usually recovered. In some cases, the manufacturing operation is run as a closed system, allowing little or no emissions to escape to the atmosphere. Emission sources from chemical processes include heaters and boilers; valves, flanges, pumps, and compressors; storage and transfer of products and intermediates; waste water handling; and emergency vents.

The emissions that do reach the atmosphere from the inorganic chemical industry generally are gaseous and are controlled by adsorption or absorption. Particulate emissions also could be a problem, since the particulate emitted is usually extremely small, requiring very efficient treatment for removal.

Emissions data from chemical processes are sparse. It has been frequently necessary, therefore, to make estimates of emission factors on the basis of material balances, yields, or process similarities.

8.1 Synthetic Ammonia

8.1.1 General[1-2]

Synthetic ammonia (NH_3) refers to ammonia that has been synthesized (Standard Industrial Classification 2873) from natural gas. Natural gas molecules are reduced to carbon and hydrogen. The hydrogen is then purified and reacted with nitrogen to produce ammonia. Approximately 75 percent of the ammonia produced is used as fertilizer, either directly as ammonia or indirectly after synthesis as urea, ammonium nitrate, and monoammonium or diammonium phosphates. The remainder is used as raw material in the manufacture of polymeric resins, explosives, nitric acid, and other products.

Synthetic ammonia plants are located throughout the U. S. and Canada. Synthetic ammonia is produced in 25 states by 60 plants which have an estimated combined annual production capacity of 15.9 million megagrams (Mg) (17.5 million tons) in 1991. Ammonia plants are concentrated in areas with abundant supplies of natural gas. Seventy percent of U. S. capacity is located in Louisiana, Texas, Oklahoma, Iowa, and Nebraska.

8.1.2 Process Description[1,3-4]

Anhydrous ammonia is synthesized by reacting hydrogen with nitrogen at a molar ratio of 3 to 1, then compressing the gas and cooling it to -33°C (-27°F). Nitrogen is obtained from the air, while hydrogen is obtained from either the catalytic steam reforming of natural gas (methane [CH_4]) or naphtha, or the electrolysis of brine at chlorine plants. In the U. S., about 98 percent of synthetic ammonia is produced by catalytic steam reforming of natural gas. Figure 8.1-1 shows a general process flow diagram of a typical ammonia plant.

Six process steps are required to produce synthetic ammonia using the catalytic steam reforming method: (1) natural gas desulfurization, (2) catalytic steam reforming, (3) carbon monoxide (CO) shift, (4) carbon dioxide (CO_2) removal, (5) methanation, and (6) ammonia synthesis. The first, third, fourth, and fifth steps remove impurities such as sulfur, CO, CO_2 and water (H_2O) from the feedstock, hydrogen, and synthesis gas streams. In the second step, hydrogen is manufactured and nitrogen (air) is introduced into this 2-stage process. The sixth step produces anhydrous ammonia from the synthetic gas. While all ammonia plants use this basic process, details such as operating pressures, temperatures, and quantities of feedstock vary from plant to plant.

8.1.2.1 Natural Gas Desulfurization -

In this step, the sulfur content (as hydrogen sulfide [H_2S]) in natural gas is reduced to below 280 micrograms per cubic meter ($\mu g/m^3$) (122 grams per cubic feet) to prevent poisoning of the nickel catalyst in the primary reformer. Desulfurization can be accomplished by using either activated carbon or zinc oxide. Over 95 percent of the ammonia plants in the U. S. use activated carbon fortified with metallic oxide additives for feedstock desulfurization. The remaining plants use a tank filled with zinc oxide for desulfurization. Heavy hydrocarbons can decrease the effectiveness of an activated carbon bed. This carbon bed also has another disadvantage in that it cannot remove carbonyl sulfide. Regeneration of carbon is accomplished by passing superheated steam through the carbon bed. A zinc oxide bed offers several advantages over the activated carbon bed. Steam regeneration to use as energy is not required when using a zinc oxide bed. No air emissions are created by the zinc oxide bed, and

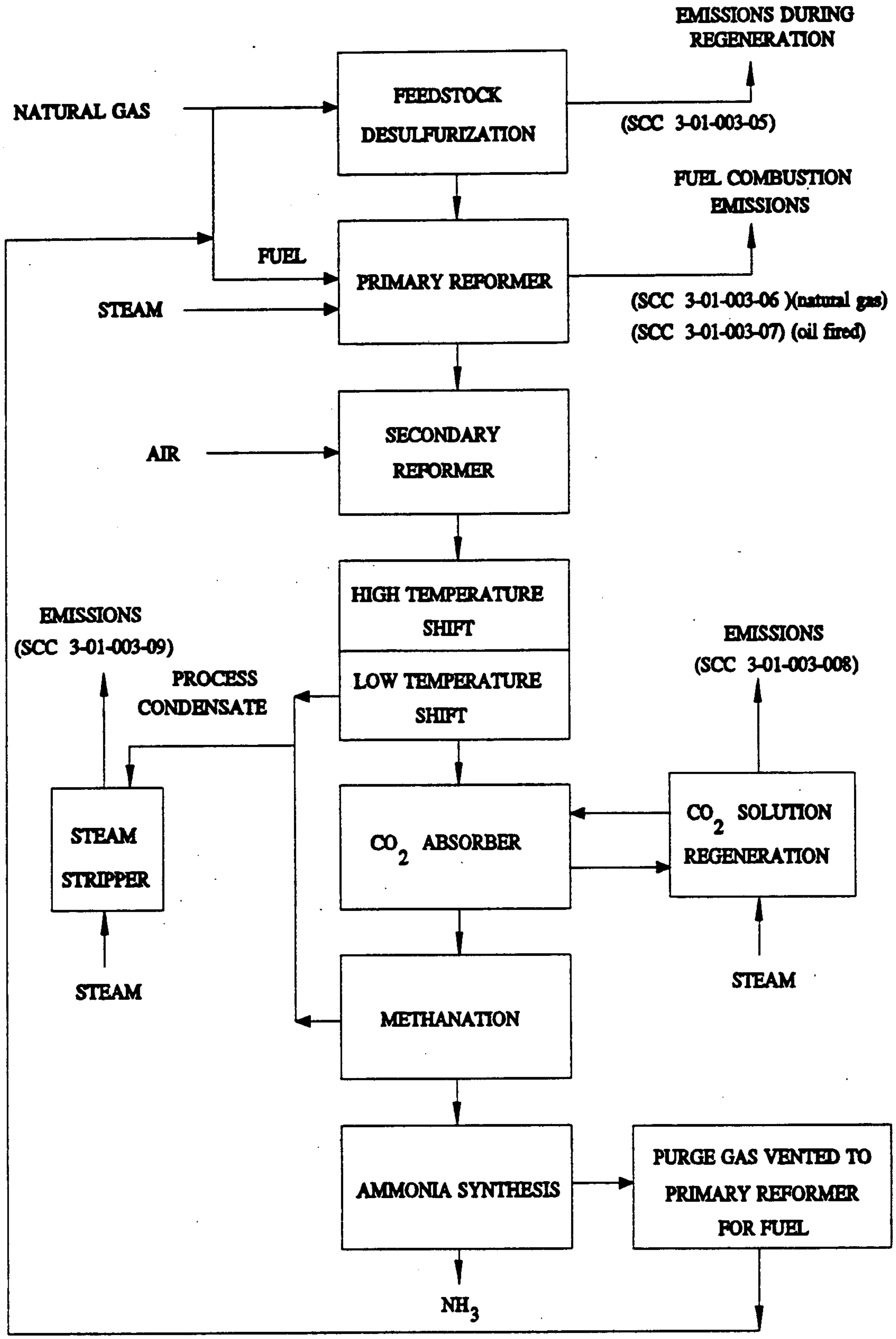

Figure 8.1-1. General flow diagram of a typical ammonia plant.
(Source Classification Codes in parentheses.)

the higher molecular weight hydrocarbons are not removed. Therefore, the heating value of the natural gas is not reduced.

8.1.2.2 Catalytic Steam Reforming -

Natural gas leaving the desulfurization tank is mixed with process steam and preheated to 540°C (1004°F). The mixture of steam and gas enters the primary reformer (natural gas fired primary reformer) and oil fired primary reformer tubes, which are filled with a nickel-based reforming catalyst. Approximately 70 percent of the CH_4 is converted to hydrogen and CO_2. An additional amount of CH_4 is converted to CO. This process gas is then sent to the secondary reformer, where it is mixed with compressed air that has been preheated to about 540°C (1004°F). Sufficient air is added to produce a final synthesis gas having a hydrogen-to-nitrogen mole ratio of 3 to 1. The gas leaving the secondary reformer is then cooled to 360°C (680°F) in a waste heat boiler.

8.1.2.3 Carbon Monoxide Shift -

After cooling, the secondary reformer effluent gas enters a high temperature CO shift converter which is filled with chromium oxide initiator and iron oxide catalyst. The following reaction takes place in the carbon monoxide converter:

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{1}$$

The exit gas is then cooled in a heat exchanger. In some plants, the gas is passed through a bed of zinc oxide to remove any residual sulfur contaminants that would poison the low-temperature shift catalyst. In other plants, excess low-temperature shift catalyst is added to ensure that the unit will operate as expected. The low-temperature shift converter is filled with a copper oxide/zinc oxide catalyst. Final shift gas from this converter is cooled from 210 to 110°C (410 to 230°F) and enters the bottom of the carbon dioxide absorption system. Unreacted steam is condensed and separated from the gas in a knockout drum. This condensed steam (process condensate) contains ammonium carbonate ($[(NH_4)_2 CO_3 \bullet H_2O]$) from the high-temperature shift converter, methanol (CH_3OH) from the low-temperature shift converter, and small amounts of sodium, iron, copper, zinc, aluminum and calcium.

Process condensate is sent to the stripper to remove volatile gases such as ammonia, methanol, and carbon dioxide. Trace metals remaining in the process condensate are removed by the ion exchange unit.

8.1.2.4 Carbon Dioxide Removal -

In this step, CO_2 in the final shift gas is removed. CO_2 removal can be done by using 2 methods: monoethanolamine ($C_2H_4NH_2OH$) scrubbing and hot potassium scrubbing. Approximately 80 percent of the ammonia plants use monoethanolamine (MEA) to aid in removing CO_2. The CO_2 gas is passed upward through an adsorption tower countercurrent to a 15 to 30 percent solution of MEA in water fortified with effective corrosion inhibitors. After absorbing the CO_2, the amine solution is preheated and regenerated (carbon dioxide regenerator) in a reactivating tower. This reacting tower removes CO_2 by steam stripping and then by heating. The CO_2 gas (98.5 percent CO_2) is either vented to the atmosphere or used for chemical feedstock in other parts of the plant complex. The regenerated MEA is pumped back to the absorber tower after being cooled in a heat exchanger and solution cooler.

8.1.2.5 Methanation -

Residual CO_2 in the synthesis gas is removed by catalytic methanation which is conducted over a nickel catalyst at temperatures of 400 to 600°C (752 to 1112°F) and pressures up to 3,000 kilopascals (kPa) (435 pounds per square inch absolute [psia]) according to the following reactions:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{2}$$

$$CO_2 + H_2 \rightarrow CO + H_2O \tag{3}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{4}$$

Exit gas from the methanator, which has a 3:1 mole ratio of hydrogen and nitrogen, is then cooled to 38°C (100°F).

8.1.2.6 Ammonia Synthesis -

In the synthesis step, the synthesis gas from the methanator is compressed at pressures ranging from 13,800 to 34,500 kPa (2000 to 5000 psia), mixed with recycled synthesis gas, and cooled to 0°C (32°F). Condensed ammonia is separated from the unconverted synthesis gas in a liquid-vapor separator and sent to a let-down separator. The unconverted synthesis is compressed and preheated to 180°C (356°F) before entering the synthesis converter which contains iron oxide catalyst. Ammonia from the exit gas is condensed and separated, then sent to the let-down separator. A small portion of the overhead gas is purged to prevent the buildup of inert gases such as argon in the circulating gas system.

Ammonia in the let-down separator is flashed to 100 kPa (14.5 psia) at -33°C (-27°F) to remove impurities from the liquid. The flash vapor is condensed in the let-down chiller where anhydrous ammonia is drawn off and stored at low temperature.

8.1.3 Emissions And Controls[1,3]

Pollutants from the manufacture of synthetic anhydrous ammonia are emitted from 4 process steps: (1) regeneration of the desulfurization bed, (2) heating of the catalytic steam, (3) regeneration of carbon dioxide scrubbing solution, and (4) steam stripping of process condensate.

More than 95 percent of the ammonia plants in the U. S. use activated carbon fortified with metallic oxide additives for feedstock desulfurization. The desulfurization bed must be regenerated about once every 30 days for an average period of 8 to 10 hours. Vented regeneration steam contains sulfur oxides (SO_x) and H_2S, depending on the amount of oxygen in the steam. Regeneration also emits hydrocarbons and CO. The reformer, heated with natural gas or fuel oil, emits combustion products such as oxides of nitrogen, CO, CO_2, SO_x, hydrocarbons, and particulates. Emission factors for the reformer may be estimated using factors presented in the appropriate section in Chapter 1, "External Combustion Source". Table 8.1-1 presents uncontrolled emission factors for a typical ammonia plant.

CO_2 is removed from the synthesis gas by scrubbing with MEA or hot potassium carbonate solution. Regeneration of this CO_2 scrubbing solution with steam produces emission of water, NH_3, CO, CO_2, and MEA.

Cooling the synthesis gas after low temperature shift conversion forms a condensate containing NH_3, CO_2, CH_3OH, and trace metals. Condensate steam strippers are used to remove NH_3 and methanol from the water, and steam from this is vented to the atmosphere, emitting NH_3, CO_2, and CH_3OH.

Table 8.1-1 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR A TYPICAL AMMONIA PLANT[a]

EMISSION FACTOR RATING: E

Emission Point	CO		SO_2		Total Organic Compounds		NH_3		CO_2	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Desulfurization unit regeneration[b] (SCC 3-01-003-05)	6.9	13.8	0.0288[c,d]	0.0576[c,d]	3.6	7.2	NA	NA	ND	ND
Carbon dioxide regenerator (SCC 3-01-003-008)	1.0[e]	2.0[e]	NA	NA	0.52[f]	1.04	1.0	2.0	1220	2440
Condensate steam stripper (SCC 3-01-003-09)	NA	NA	NA	NA	0.6[g]	1.2	1.1	2.2	3.4[h]	6.8[h]

[a] References 1,3. SCC = Source Classification Code. NA = not applicable. ND = no data.

[b] Intermittent emissions. Desulfurization tank is regenerated for a 10-hour period on average once every 30 days.

[c] Assumed worst case, that all sulfur entering tank is emitted during regeneration.

[d] Normalized to a 24-hour emission factor. Total sulfur is 0.0096 kg/Mg (0.019 lb/ton).

[e] Mostly CO.

[f] 0.05 kg/Mg (0.1 lb/ton) is monoethanolamine.

[g] Mostly methanol, which is classified as Non Methane Organic Compound and a hazardous air pollutant.

[h] ±60%.

Some processes have been modified to reduce emissions and to improve utility of raw materials and energy. One such technique is the injection of the overheads into the reformer stack along with the combustion gases to eliminate emissions from the condensate steam stripper.

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8.2 Urea

8.2.1 General[1-13]

Urea [$CO(NH_2)_2$], also known as carbamide or carbonyl diamide, is marketed as a solution or in solid form. Most urea solution produced is used in fertilizer mixtures, with a small amount going to animal feed supplements. Most solids are produced as prills or granules, for use as fertilizer or protein supplement in animal feed, and in plastics manufacturing. Five U. S. plants produce solid urea in crystalline form. About 7.3 million megagrams (Mg) (8 million tons) of urea were produced in the U. S. in 1991. About 85 percent was used in fertilizers (both solid and solution forms), 3 percent in animal feed supplements, and the remaining 12 percent in plastics and other uses.

8.2.2 Process Description[1-2]

The process for manufacturing urea involves a combination of up to 7 major unit operations. These operations, illustrated by the flow diagram in Figure 8.2-1, are solution synthesis, solution concentration, solids formation, solids cooling, solids screening, solids coating and bagging, and/or bulk shipping.

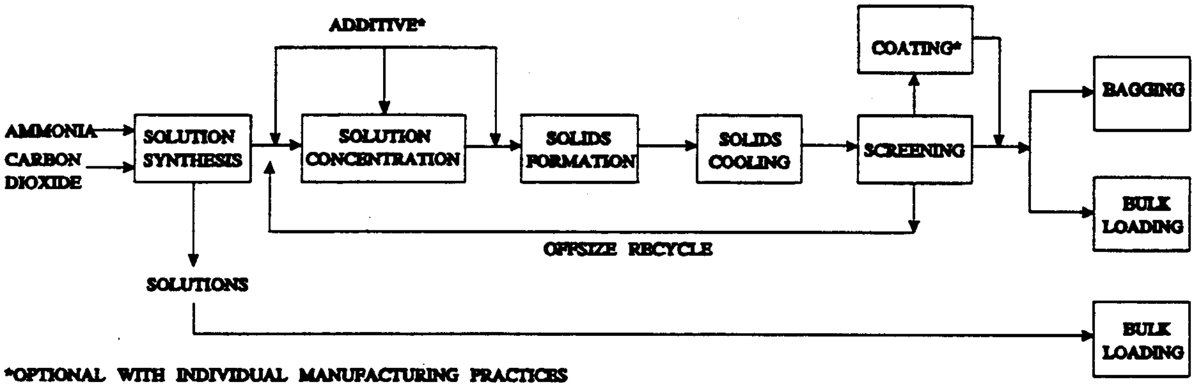

Figure 8.2-1. Major area manufacturing operations.

The combination of processing steps is determined by the desired end products. For example, plants producing urea solution use only the solution formulation and bulk shipping operations. Facilities producing solid urea employ these 2 operations and various combinations of the remaining 5 operations, depending upon the specific end product being produced.

In the solution synthesis operation, ammonia (NH_3) and carbon dioxide (CO_2) are reacted to form ammonium carbamate ($NH_2CO_2NH_4$). Typical operating conditions include temperatures from 180 to 200°C (356 to 392°F), pressures from 140 to 250 atmospheres (14,185 to 25,331 kilopascals) NH_3:CO_2 molar ratios from 3:1 to 4:1, and a retention time of 20 to 30 minutes. The carbamate is then dehydrated to yield 70 to 77 percent aqueous urea solution. These reactions are as follows:

$$2NH_3 + CO_2 \rightarrow NH_2CO_2NH_4 \qquad (1)$$

$$NH_2CO_2NH_4 \rightarrow NH_2CONH_2 + H_2O \qquad (2)$$

The urea solution can be used as an ingredient of nitrogen solution fertilizers, or it can be concentrated further to produce solid urea.

The 3 methods of concentrating the urea solution are vacuum concentration, crystallization, and atmospheric evaporation. The method chosen depends upon the level of biuret ($NH_2CONHCONH_2$) impurity allowable in the end product. Aqueous urea solution begins to decompose at 60°C (140°F) to biuret and ammonia. The most common method of solution concentration is evaporation.

The concentration process furnishes urea "melt" for solids formation. Urea solids are produced from the urea melt by 2 basic methods: prilling and granulation. Prilling is a process by which solid particles are produced from molten urea. Molten urea is sprayed from the top of a prill tower. As the droplets fall through a countercurrent air flow, they cool and solidify into nearly spherical particles. There are 2 types of prill towers: fluidized bed and nonfluidized bed. The major difference is that a separate solids cooling operation may be required to produce agricultural grade prills in a nonfluidized bed prill tower.

Granulation is used more frequently than prilling in producing solid urea for fertilizer. Granular urea is generally stronger than prilled urea, both in crushing strength and abrasion resistance. There are 2 granulation methods: drum granulation and pan granulation. In drum granulation, solids are built up in layers on seed granules placed in a rotating drum granulator/cooler approximately 4.3 meters (14 feet) in diameter. Pan granulators also form the product in a layering process, but different equipment is used and pan granulators are not commonly used in the U. S.

The solids cooling operation is generally accomplished during solids formation, but for pan granulation processes and for some agricultural grade prills, some supplementary cooling is provided by auxiliary rotary drums.

The solids screening operation removes offsize product from solid urea. The offsize material may be returned to the process in the solid phase or be redissolved in water and returned to the solution concentration process.

Clay coatings are used in the urea industry to reduce product caking and urea dust formation. The coating also reduces the nitrogen content of the product. The use of clay coating has diminished considerably, being replaced by injection of formaldehyde additives into the liquid or molten urea before solids formation. Formaldehyde reacts with urea to from methylenediurea, which is the conditioning agent. Additives reduce solids caking during storage and urea dust formation during transport and handling.

The majority of solid urea product is bulk shipped in trucks, enclosed railroad cars, or barges, but approximately 10 percent is bagged.

8.2.3 Emissions And Controls[1,3-7]

Emissions from urea manufacture are mainly ammonia and particulate matter. Formaldehyde and methanol, hazardous air pollutants, may be emitted if additives are used. Formalin™, used as a formaldehyde additive, may contain up to 15 percent methanol. Ammonia is emitted during the solution synthesis and solids production processes. Particulate matter is emitted during all urea processes. There have been no reliable measurements of free gaseous formaldehyde emissions. The chromotropic acid procedure that has been used to measure formaldehyde is not capable of distinguishing between gaseous formaldehyde and methylenediurea, the principle compound formed when the formaldehyde additive reacts with hot urea.

Table 8.2-1 summarizes the uncontrolled and controlled emission factors, by processes, for urea manufacture. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton). Table 8.2-2 summarizes particle sizes for these emissions. Units are expressed in terms of micrometers (μm).

In the synthesis process, some emission control is inherent in the recycle process where carbamate gases and/or liquids are recovered and recycled. Typical emission sources from the solution synthesis process are noncondensable vent streams from ammonium carbamate decomposers and separators. Emissions from synthesis processes are generally combined with emissions from the solution concentration process and are vented through a common stack. Combined particulate emissions from urea synthesis and concentration operations are small compared to particulate emissions from a typical solids-producing urea plant. The synthesis and concentration operations are usually uncontrolled except for recycle provisions to recover ammonia. For these reasons, no factor for controlled emissions from synthesis and concentration processes is given in this section.

Uncontrolled emission rates from prill towers may be affected by the following factors: (1) product grade being produced, (2) air flow rate through the tower, (3) type of tower bed, and (4) ambient temperature and humidity.

The total of mass emissions per unit is usually lower for feed grade prill production than for agricultural grade prills, due to lower airflows. Uncontrolled particulate emission rates for fluidized bed prill towers are higher than those for nonfluidized bed prill towers making agricultural grade prills, and are approximately equal to those for nonfluidized bed feed grade prills. Ambient air conditions can affect prill tower emissions. Available data indicate that colder temperatures promote the formation of smaller particles in the prill tower exhaust. Since smaller particles are more difficult to remove, the efficiency of prill tower control devices tends to decrease with ambient temperatures. This can lead to higher emission levels for prill towers operated during cold weather. Ambient humidity can also affect prill tower emissions. Air flow rates must be increased with high humidity, and higher air flow rates usually cause higher emissions.

The design parameters of drum granulators and rotary drum coolers may affect emissions. Drum granulators have an advantage over prill towers in that they are capable of producing very large particles without difficulty. Granulators also require less air for operation than do prill towers. A disadvantage of granulators is their inability to produce the smaller feed grade granules economically. To produce smaller granules, the drum must be operated at a higher seed particle recycle rate. It has been reported that, although the increase in seed material results in a lower bed temperature, the corresponding increase in fines in the granulator causes a higher emission rate. Cooling air passing through the drum granulator entrains approximately 10 to 20 percent of the product. This air stream is controlled with a wet scrubber which is standard process equipment on drum granulators.

In the solids screening process, dust is generated by abrasion of urea particles and the vibration of the screening mechanisms. Therefore, almost all screening operations used in the urea manufacturing industry are enclosed or are covered over the uppermost screen. This operation is a small emission source; therefore particulate emission factors from solids screening are not presented.

Emissions attributable to coating include entrained clay dust from loading, inplant transfer, and leaks from the seals of the coater. No emissions data are available to quantify this fugitive dust source.

Table 8.2-1 (Metric And English Units). EMISSION FACTORS FOR UREA PRODUCTION

EMISSON FACTOR RATING: A (except as noted)

	Particulate[a]				Ammonia			
	Uncontrolled		Controlled		Uncontrolled		Controlled[b]	
Type Of Operation	kg/Mg Of Product	lb/ton Of Product	kg/Mg Of Product	lb/ton Of Product	kg/Mg Of Product	lb/ton Of Product	kg/Mg Of Product	lb/ton Of Product
Solution formation and concentration[c]	0.0105[d]	0.021[d]	ND	ND	9.23[e]	18.46[e]	ND	ND
Nonfluidized bed prilling								
Agricultural grade[f]	1.9	3.8	0.032[g]	0.063[g]	0.43	0.87	ND	ND
Feed grade[h]	1.8	3.6	ND	ND	ND	ND	ND	ND
Fluidized bed prilling								
Agricultural grade[h]	3.1	6.2	0.39	0.78	1.46	2.91	ND	ND
Feed grade[h]	1.8	3.6	0.24	0.48	2.07	4.14	1.04	2.08
Drum granulation[j]	120	241	0.115	0.234	1.07[k]	2.15[k]	ND	ND
Rotary drum cooler	3.89[m]	7.78[m]	0.10[n]	0.20[n]	0.0256[m]	0.051[m]	ND	ND
Bagging	0.095[n]	0.19[n]	ND	ND	NA	NA	NA	NA

[a] Particulate test data were collected using a modification of EPA Reference Method 3. Reference 1, Appendix B explains these modifications. ND = no data. NA = not applicable.

[b] No ammonia control demonstrated by scrubbers installed for particulate control. Some increase in ammonia emissions exiting the control device was noted.

[c] References 9,11. Emissions from the synthesis process are generally combined with emissions from the solution concentration process and vented through a common stack. In the synthesis process, some emission control is inherent in the recycle process where carbamate gases and/or liquids are recovered and recycled.

[d] EPA test data indicated a range of 0.005 to 0.016 kg/Mg (0.010 to 0.032 lb/ton).

[e] EPA test data indicated a range of 4.01 to 14.45 kg/Mg (8.02 to 28.90 lb/ton).

[f] Reference 12. These factors were determined at an ambient temperature of 14 to 21°C (57 to 69°F). The controlled emission factors are based on ducting exhaust through a downcomer and then a wetted fiber filter scrubber achieving a 98.3% efficiency. This represents a higher degree of control than is typical in this industry.

[g] Only runs 2 and 3 were used (test Series A).

[h] Reference 11. Feed grade factors were determined at an ambient temperature of 29°C (85°F) and agricultural grade factors at an ambient temperature of 27°C (80°F). For fluidized bed prilling, controlled emission factors are based on use of an entrainment scrubber.

[j] References 8-9. Controlled emission factors are based on use of a wet entrainment scrubber. Wet scrubbers are standard process equipment on drum granulators. Uncontrolled emissions were measured at the scrubber inlet.

[k] EPA test data indicated a range of 0.955 to 1.20 kg/Mg (1.90 to 2.45 lb/ton).

[m] Reference 10.

[n] Reference 1. EMISSION FACTOR RATING: E. Data were provided by industry.

Table 8.2-2 (Metric Units). UNCONTROLLED PARTICLE SIZE DATA FOR UREA PRODUCTION

Type Of Operation	Particle Size (cumulative weight %)		
	≤ 10 μm	≤ 5 μm	≤ 2.5 μm
Solid Formation			
Nonfluidized bed prilling			
Agricultural grade	90	84	79
Feed grade	85	74	50
Fluidized bed prilling			
Agricultural grade	60	52	43
Feed grade	24	18	14
Drum granulation	—[a]	—[a]	—[a]
Rotary drum cooler	0.70	0.15	0.04

[a] All particulate matter ≥ 5.7 μm was collected in the cyclone precollector sampling equipment.

Bagging operations are sources of particulate emissions. Dust is emitted from each bagging method during the final stages of filling, when dust-laden air is displaced from the bag by urea. Bagging operations are conducted inside warehouses and are usually vented to keep dust out of the workroom area, as mandated by Occupational Safety and Health Administration (OSHA) regulations. Most vents are controlled with baghouses. Nationwide, approximately 90 percent of urea produced is bulk loaded. Few plants control their bulk loading operations. Generation of visible fugitive particles is negligible.

Urea manufacturers presently control particulate matter emissions from prill towers, coolers, granulators, and bagging operations. With the exception of bagging operations, urea emission sources are usually controlled with wet scrubbers. Scrubber systems are preferred over dry collection systems primarily for the easy recycling of dissolved urea collected in the device. Scrubber liquors are recycled to the solution concentration process to eliminate waste disposal problems and to recover the urea collected.

Fabric filters (baghouses) are used to control fugitive dust from bagging operations, where humidities are low and binding of the bags is not a problem. However, many bagging operations are uncontrolled.

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8.3 Ammonium Nitrate

8.3.1 General[1-3]

Ammonium nitrate (NH_4NO_3) is produced by neutralizing nitric acid (HNO_3) with ammonia (NH_3). In 1991, there were 58 U. S. ammonium nitrate plants located in 22 states producing about 8.2 million megagrams (Mg) (9 million tons) of ammonium nitrate. Approximately 15 to 20 percent of this amount was used for explosives and the balance for fertilizer.

Ammonium nitrate is marketed in several forms, depending upon its use. Liquid ammonium nitrate may be sold as a fertilizer, generally in combination with urea. Liquid ammonium nitrate may be concentrated to form an ammonium nitrate "melt" for use in solids formation processes. Solid ammonium nitrate may be produced in the form of prills, grains, granules, or crystals. Prills can be produced in either high or low density form, depending on the concentration of the melt. High density prills, granules, and crystals are used as fertilizer, grains are used solely in explosives, and low density prills can be used as either.

8.3.2 Process Description[1,2]

The manufacture of ammonium nitrate involves several major unit operations including solution formation and concentration; solids formation, finishing, screening, and coating; and product bagging and/or bulk shipping. In some cases, solutions may be blended for marketing as liquid fertilizers. These operations are shown schematically in Figure 8.3-1.

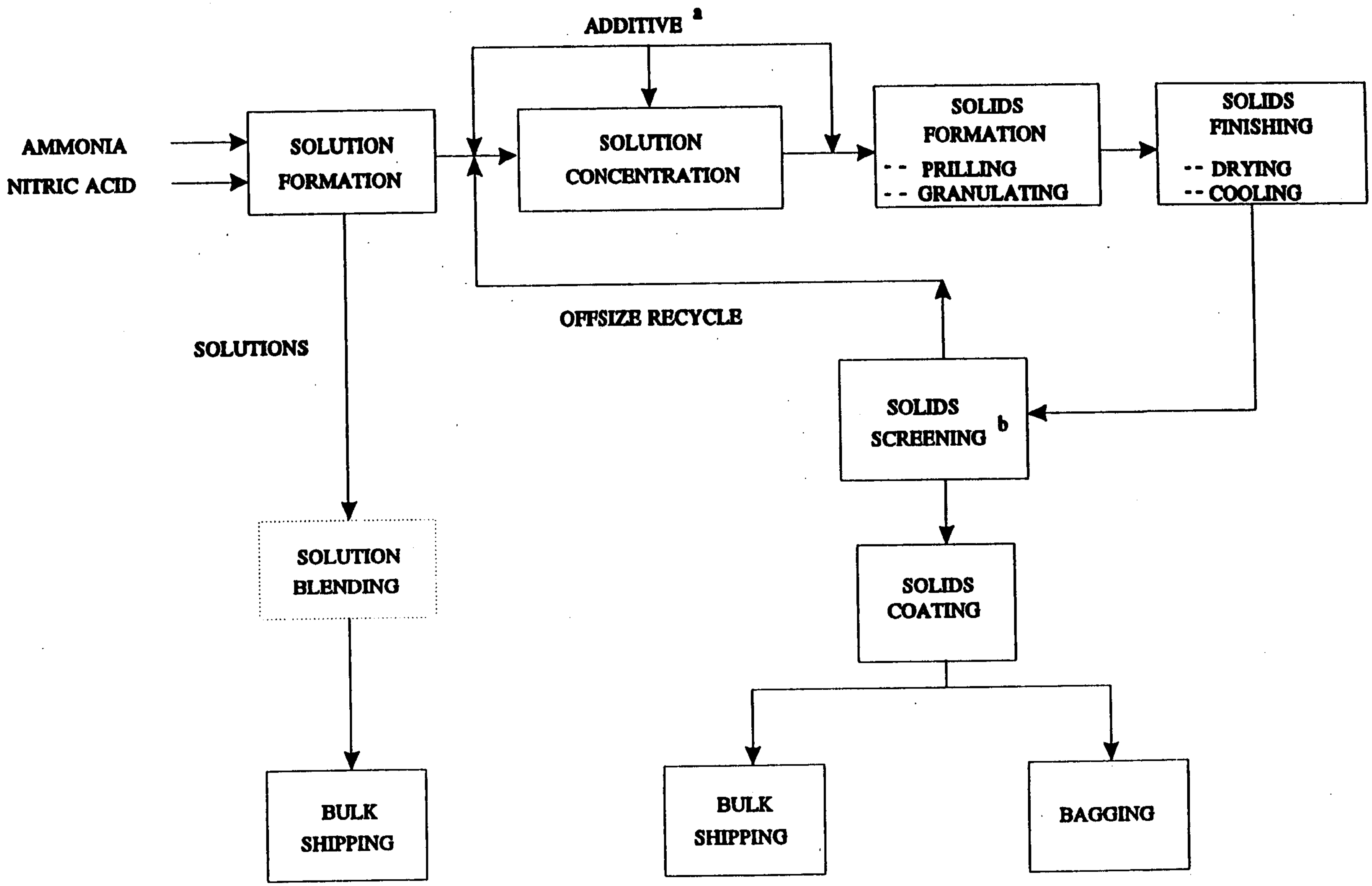
The number of operating steps employed depends on the end product desired. For example, plants producing ammonium nitrate solutions alone use only the solution formation, solution blending, and bulk shipping operations. Plants producing a solid ammonium nitrate product may employ all of the operations.

All ammonium nitrate plants produce an aqueous ammonium nitrate solution through the reaction of ammonia and nitric acid in a neutralizer as follows:

$$NH_3 + HNO_3 \rightarrow NH_4NO_3$$

Approximately 60 percent of the ammonium nitrate produced in the U. S. is sold as a solid product. To produce a solid product, the ammonium nitrate solution is concentrated in an evaporator or concentrator. The resulting "melt" contains about 95 to 99.8 percent ammonium nitrate at approximately 149°C (300°F). This melt is then used to make solid ammonium nitrate products.

Prilling and granulation are the most common processes used to produce solid ammonium nitrate. To produce prills, concentrated melt is sprayed into the top of a prill tower. In the tower, ammonium nitrate droplets fall countercurrent to a rising air stream that cools and solidifies the falling droplets into spherical prills. Prill density can be varied by using different concentrations of ammonium nitrate melt. Low density prills, in the range of 1.29 specific gravity, are formed from a 95 to 97.5 percent ammonium nitrate melt, and high density prills, in the range of 1.65 specific gravity, are formed from a 99.5 to 99.8 percent melt. Low density prills are more porous than high density prills. Therefore, low density prills are used for making blasting agents because they will absorb oil. Most high density prills are used as fertilizers.



[a] ADDITIVE MAY BE ADDED BEFORE, DURING, OR AFTER CONCENTRATION

[b] SCREENING MAY BE PERFORMED BEFORE OR AFTER SOLIDS FINISHING

Figure 8.3-1. Ammonium nitrate manufacturing operations.

Rotary drum granulators produce granules by spraying a concentrated ammonium nitrate melt (99.0 to 99.8 percent) onto small seed particles of ammonium nitrate in a long rotating cylindrical drum. As the seed particles rotate in the drum, successive layers of ammonium nitrate are added to the particles, forming granules. Granules are removed from the granulator and screened. Offsize granules are crushed and recycled to the granulator to supply additional seed particles or are dissolved and returned to the solution process. Pan granulators operate on the same principle as drum granulators, except the solids are formed in a large, rotating circular pan. Pan granulators produce a solid product with physical characteristics similar to those of drum granules.

Although not widely used, an additive such as magnesium nitrate or magnesium oxide may be injected directly into the melt stream. This additive serves 3 purposes: to raise the crystalline transition temperature of the final solid product; to act as a desiccant, drawing water into the final product to reduce caking; and to allow solidification to occur at a low temperature by reducing the freezing point of molten ammonium nitrate.

The temperature of the ammonium nitrate product exiting the solids formation process is approximately 66 to 124°C (150 to 255°F). Rotary drum or fluidized bed cooling prevents deterioration and agglomeration of solids before storage and shipping. Low density prills have a high moisture content because of the lower melt concentration, and therefore require drying in rotary drums or fluidized beds before cooling.

Since the solids are produced in a wide variety of sizes, they must be screened for consistently sized prills or granules. Cooled prills are screened and offsize prills are dissolved and recycled to the solution concentration process. Granules are screened before cooling. Undersize particles are returned directly to the granulator and oversize granules may be either crushed and returned to the granulator or sent to the solution concentration process.

Following screening, products can be coated in a rotary drum to prevent agglomeration during storage and shipment. The most common coating materials are clays and diatomaceous earth. However, the use of additives in the ammonium nitrate melt before solidification, as described above, may preclude the use of coatings.

Solid ammonium nitrate is stored and shipped in either bulk or bags. Approximately 10 percent of solid ammonium nitrate produced in the U. S. is bagged.

8.3.3 Emissions And Controls

Emissions from ammonium nitrate production plants are particulate matter (ammonium nitrate and coating materials), ammonia, and nitric acid. Ammonia and nitric acid are emitted primarily from solution formation and granulators. Particulate matter (largely as ammonium nitrate) is emitted from most of the process operations and is the primary emission addressed here.

The emission sources in solution formation and concentration processes are neutralizers and evaporators, primarily emitting nitric acid and ammonia. The vapor stream off the top of the neutralization reactor is primarily steam with some ammonia and NH_4NO_3 particulates present. Specific plant operating characteristics, however, make these emissions vary depending upon use of excess ammonia or acid in the neutralizer. Since the neutralization operation can dictate the quantity of these emissions, a range of emission factors is presented in Tables 8.3-1 and 8.3-2. Units are expressed in terms of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton). Particulate emissions from these operations tend to be smaller in size than those from solids production and handling processes and generally are recycled back to the process.

Table 8.3-1 (Metric Units). EMISSION FACTORS FOR PROCESSES IN AMMONIUM NITRATE MANUFACTURING PLANTS[a]

EMISSION FACTOR RATING: A (except as noted)

Process	Particulate Matter		Ammonia	Nitric Acid
	Uncontrolled (kg/Mg Of Product)	Controlled[b] (kg/Mg Of Product)	Uncontrolled[c] (kg/Mg Of Product)	Controlled[d] (kg/Mg Of Product)
Neutralizer	0.045 - 4.3[e]	0.002 - 0.22[e]	0.43 - 18.0[d]	0.042 - 1[e]
Evaporation/concentration operations	0.26	ND	0.27 - 16.7	ND
Solids formation operations				
High density prill towers	1.59	0.60	28.6	ND
Low density prill towers	0.46	0.26	0.13	ND
Rotary drum granulators	146	0.22	29.7	ND
Pan granulators	1.34	0.02	0.07	ND
Coolers and dryers[f]				
High density prill coolers	0.8	0.01	0.02	ND
Low density prill coolers	25.8	0.26	0.15	ND
Low density prill dryers	57.2	0.57	0 - 1.59	ND
Rotary drum granulator coolers	8.1	0.08	ND	ND
Pan granulator coolers	18.3	0.18[d]	ND	ND
Coating operations[g]	≤ 2.0[d]	≤ 0.02[d]	NA	NA
Bulk loading operations[g]	≤ 0.01[d]	ND	NA	NA

[a] Some ammonium nitrate emission factors are based on data gathered using a modification of EPA Method 5 (See Reference 1). ND = no data. NA = not applicable.

[b] Based on the following control efficiencies for wet scrubbers, applied to uncontrolled emissions: neutralizers, 95%; high density prill towers, 62%; low density prill towers, 43%; rotary drum granulators, 99.9%; pan granulators, 98.5%; coolers, dryers, and coaters, 99%.

[c] Given as ranges because of variation in data and plant operations. Factors for controlled emissions not presented due to conflicting results on control efficiency.

[d] Based on 95% recovery in a granulator recycle scrubber.

[e] EMISSION FACTOR RATING: B.

[f] Factors for coolers represent combined precooler and cooler emissions, and factors for dryers represent combined predryer and dryer emissions.

[g] Fugitive particulate emissions arise from coating and bulk loading operations.

Table 8.3-2 (English Units). EMISSION FACTORS FOR PROCESSES IN AMMONIUM NITRATE MANUFACTURING PLANTS[a]

EMISSION FACTOR RATING: A (except as noted)

Process	Particulate Matter		Ammonia	Nitric Acid
	Uncontrolled (lb/ton Of Product)	Controlled[b] (lb/ton Of Product)	Uncontrolled[c] (lb/ton Of Product)	Controlled[d] (lb/ton Of Product)
Neutralizer	0.09 - 8.6[e]	0.004 - 0.43[d]	0.86 - 36.02[d]	0.084 - 2[d,e]
Evaporation/concentration operations	0.52	ND	0.54 - 33.4	ND
Solids formation operations				
High density prill towers	3.18	1.20	57.2	ND
Low density prill towers	0.92	0.52	0.26	ND
Rotary drum granulators	392	0.44	59.4	ND
Pan granulators	2.68	0.04	0.14	ND
Coolers and dryers[f]				
High density prill coolers	1.6	0.02	0.04	ND
Low density prill coolers	51.6	0.52	0.30	ND
Low density prill dryers	114.4	1.14	0 - 3.18	ND
Rotary drum granulator coolers	16.2	0.16	ND	ND
Pan granulator coolers	36.6	0.36[d]	ND	ND
Coating operations[g]	≤ 4.0[d]	≤ 0.04[d]	NA	NA
Bulk loading operations[g]	≤ 0.02[d]	ND	NA	NA

[a] Some ammonium nitrate emission factors are based on data gathered using a modification of EPA Method 5 (See Reference 1). ND = no data. NA = not applicable.

[b] Based on the following control efficiencies for wet scrubbers, applied to uncontrolled emissions: neutralizers, 95%; high density prill towers, 62%; low density prill towers, 43%; rotary drum granulators, 99.9%; pan granulators, 98.5%; coolers, dryers, and coaters, 99%.

[c] Given as ranges because of variation in data and plant operations. Factors for controlled emissions not presented due to conflicting results on control efficiency.

[d] Based on 95% recovery in a granulator recycle scrubber.

[e] EMISSION FACTOR RATING: B.

[f] Factors for coolers represent combined precooler and cooler emissions, and factors for dryers represent combined predryer and dryer emissions.

[g] Fugitive particulate emissions arise from coating and bulk loading operations.

Emissions from solids formation processes are ammonium nitrate particulate matter and ammonia. The sources of primary importance are prill towers (for high density and low density prills) and granulators (rotary drum and pan). Emissions from prill towers result from carryover of fine particles and fume by the prill cooling air flowing through the tower. These fine particles are from microprill formation, from attrition of prills colliding with the tower or with one another, and from rapid transition of the ammonia nitrate between crystal states. The uncontrolled particulate emissions from prill towers, therefore, are affected by tower airflow, spray melt temperature, condition and type of melt spray device, air temperature, and crystal state changes of the solid prills. The amount of microprill mass that can be entrained in the prill tower exhaust is determined by the tower air velocity. Increasing spray melt temperature causes an increase in the amount of gas-phase ammonium nitrate generated. Thus, gaseous emissions from high density prilling are greater than from low density towers.

Microprill formation resulting from partially plugged orifices of melt spray devices can increase fine dust loading and emissions. Certain designs (spinning buckets) and practices (vibration of spray plates) help reduce microprill formation. High ambient air temperatures can cause increased emissions because of entrainment as a result of higher air flow required to cool prills and because of increased fume formation at the higher temperatures.

The granulation process in general provides a larger degree of control in product formation than does prilling. Granulation produces a solid ammonium nitrate product that, relative to prills, is larger and has greater abrasion resistance and crushing strength. The air flow in granulation processes is lower than that in prilling operations. Granulators, however, cannot produce low density ammonium nitrate economically with current technology. The design and operating parameters of granulators may affect emission rates. For example, the recycle rate of seed ammonium nitrate particles affects the bed temperature in the granulator. An increase in bed temperature resulting from decreased recycle of seed particles may cause an increase in dust emissions from granule disintegration.

Cooling and drying are usually conducted in rotary drums. As with granulators, the design and operating parameters of the rotary drums may affect the quantity of emissions. In addition to design parameters, prill and granule temperature control is necessary to control emissions from disintegration of solids caused by changes in crystal state.

Emissions from screening operations are generated by the attrition of the ammonium nitrate solids against the screens and against one another. Almost all screening operations used in the ammonium nitrate manufacturing industry are enclosed or have a cover over the uppermost screen. Screening equipment is located inside a building and emissions are ducted from the process for recovery or reuse.

Prills and granules are typically coated in a rotary drum. The rotating action produces a uniformly coated product. The mixing action also causes some of the coating material to be suspended, creating particulate emissions. Rotary drums used to coat solid product are typically kept at a slight negative pressure and emissions are vented to a particulate control device. Any dust captured is usually recycled to the coating storage bins.

Bagging and bulk loading operations are a source of particulate emissions. Dust is emitted from each type of bagging process during final filling when dust-laden air is displaced from the bag by the ammonium nitrate. The potential for emissions during bagging is greater for coated than for uncoated material. It is expected that emissions from bagging operations are primarily the kaolin, talc, or diatomaceous earth coating matter. About 90 percent of solid ammonium nitrate produced domestically is bulk loaded. While particulate emissions from bulk loading are not generally controlled, visible emissions are within typical state regulatory requirements (below 20 percent opacity).

Tables 8.3-1 and 8.3-2 summarize emission factors for various processes involved in the manufacture of ammonium nitrate. Uncontrolled emissions of particulate matter, ammonia, and nitric acid are also given in Tables 8.3-1 and 8.3-2. Emissions of ammonia and nitric acid depend upon specific operating practices, so ranges of factors are given for some emission sources.

Emission factors for controlled particulate emissions are also in Tables 8.3-1 and 8.3-2, reflecting wet scrubbing particulate control techniques. The particle size distribution data presented in Table 8.3-3 indicate the emissions. In addition, wet scrubbing is used as a control technique because the solution containing the recovered ammonium nitrate can be sent to the solution concentration process for reuse in production of ammonium nitrate, rather than to waste disposal facilities.

Table 8.3-3 (Metric Units). PARTICLE SIZE DISTRIBUTION DATA FOR UNCONTROLLED EMISSIONS FROM AMMONIUM NITRATE MANUFACTURING FACILITIES[a]

Operation	Cumulative Weight %		
	$\leq 2.5\ \mu m$	$\leq 5\ \mu m$	$\leq 10\ \mu m$
Solids Formation Operations			
Low density prill tower	56	73	83
Rotary drum granulator	0.07	0.3	2
Coolers and Dryers			
Low density prill cooler	0.03	0.09	0.4
Low density prill predryer	0.03	0.06	0.2
Low density prill dryer	0.04	0.04	0.15
Rotary drum granulator cooler	0.06	0.5	3
Pan granulator precooler	0.3	0.3	1.5

[a] References 5,12-13,23-24. Particle size determinations were not done in strict accordance with EPA Method 5. A modification was used to handle the high concentrations of soluble nitrogenous compounds.[1] Particle size distributions were not determined for controlled particulate emissions.

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8.4 Ammonium Sulfate

8.4.1 General[1-2]

Ammonium sulfate ($[NH_4]_2SO_4$) is commonly used as a fertilizer. In 1991, U. S. facilities produced about 2.7 million megagrams (Mg) (3 million tons) of ammonium sulfate in about 35 plants. Production rates at these plants range from 1.8 to 360 Mg (2 to 400 tons) per year.

8.4.2 Process Description[1]

About 90 percent of ammonium sulfate is produced by 3 different processes: (1) as a byproduct of caprolactam [$(CH_2)_5COHN$] production, (2) from synthetic manufacture, and (3) as a coke oven byproduct. The remainder is produced as a byproduct of either nickel or methyl methacrylate manufacture, or from ammonia (NH_3) scrubbing of tailgas at sulfuric acid (H_2SO_4) plants. These minor sources are not discussed here.

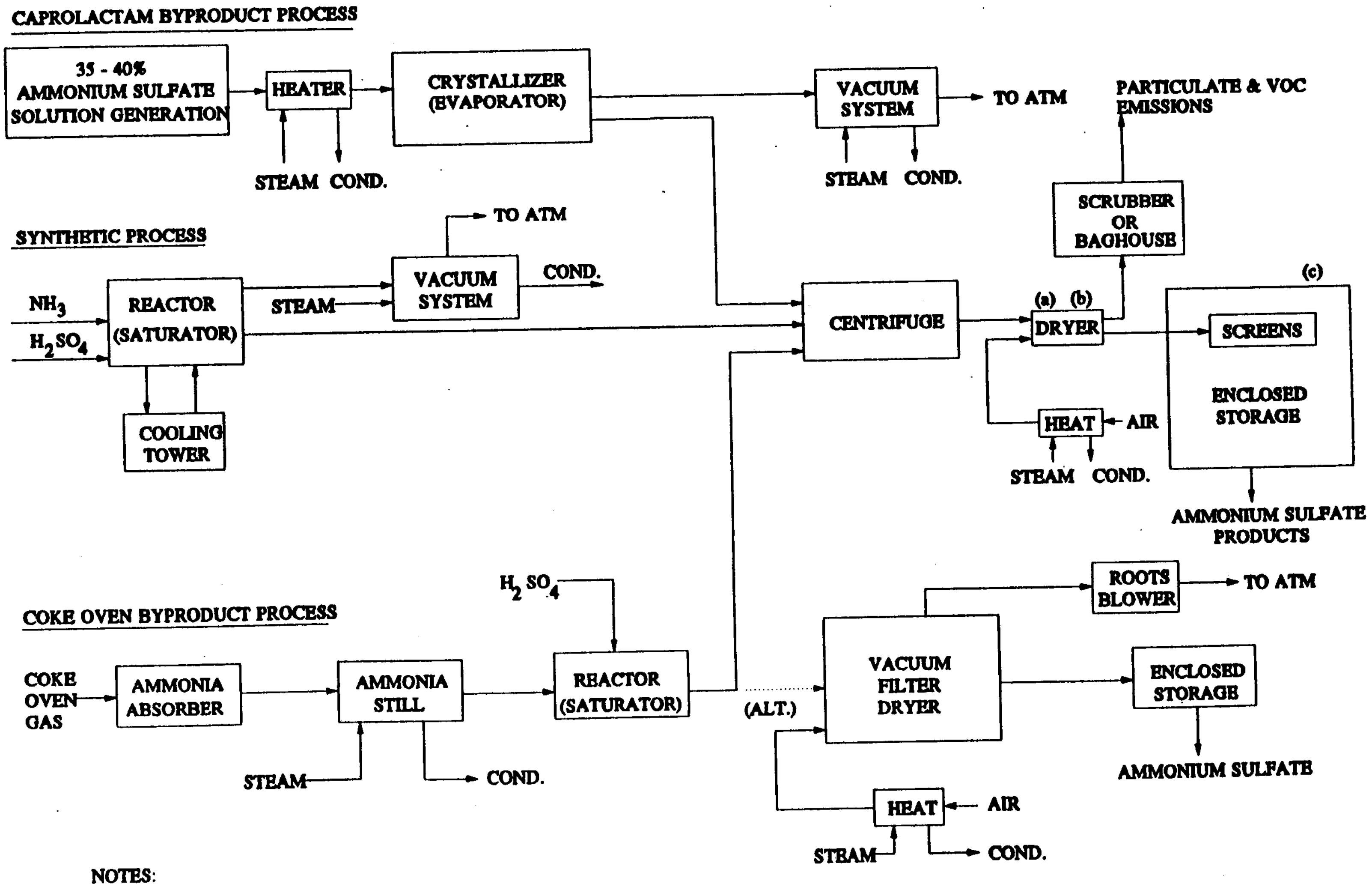
Ammonium sulfate is produced as a byproduct from the caprolactam oxidation process stream and the rearrangement reaction stream. Synthetic ammonium sulfate is produced by combining anhydrous ammonia and sulfuric acid in a reactor. Coke oven byproduct ammonium sulfate is produced by reacting the ammonia recovered from coke oven offgas with sulfuric acid. Figure 8.4-1 is a diagram of typical ammonium sulfate manufacturing for each of the 3 primary commercial processes.

After formation of the ammonium sulfate solution, manufacturing operations of each process are similar. Ammonium sulfate crystals are formed by circulating the ammonium sulfate liquor through a water evaporator, which thickens the solution. Ammonium sulfate crystals are separated from the liquor in a centrifuge. In the caprolactam byproduct process, the product is first transferred to a settling tank to reduce the liquid load on the centrifuge. The saturated liquor is returned to the dilute ammonium sulfate brine of the evaporator. The crystals, which contain about 1 to 2.5 percent moisture by weight after the centrifuge, are fed to either a fluidized-bed or a rotary drum dryer. Fluidized-bed dryers are continuously steam heated, while the rotary dryers are fired directly with either oil or natural gas or may use steam-heated air.

At coke oven byproduct plants, rotary vacuum filters may be used in place of a centrifuge and dryer. The crystal layer is deposited on the filter and is removed as product. These crystals are generally not screened, although they contain a wide range of particle sizes. They are then carried by conveyors to bulk storage.

At synthetic plants, a small quantity (about 0.05 percent) of a heavy organic (i. e., high molecular weight organic) is added to the product after drying to reduce caking.

Dryer exhaust gases pass through a particulate collection device, such as a wet scrubber. This collection controls emissions and reclaims residual product. After being dried, the ammonium sulfate crystals are screened into coarse and fine crystals. This screening is done in an enclosed area to restrict fugitive dust in the building.



NOTES:

(a) Dryer may be rotary or fluidized bed type.
(b) Coke oven plant may integrate centrifuge and drying or centrifuging only.
(c) Coke oven plant product not screened.
ATM = atmosphere. ALT. = alternate. COND. = condensate

Figure 8.4-1. Typical diagram of ammonium sulfate processes.

8.4.3 Emissions And Controls[1]

Ammonium sulfate particulate is the principal emission from ammonium sulfate manufacturing plants. The gaseous exhaust of the dryers contains nearly all the emitted ammonium sulfate. Other plant processes, such as evaporation, screening and materials handling, are not significant sources of emissions.

The particulate emission rate of a dryer is dependent on gas velocity and particle size distribution. Gas velocity, and thus emission rates, varies according to the dryer type. Generally, the gas velocity of fluidized-bed dryers is higher than for most rotary drum dryers. Therefore, the particulate emission rates are higher for fluidized-bed dryers. At caprolactam byproduct plants, relatively small amounts of volatile organic compounds (VOC) are emitted from the dryers.

Some plants use baghouses for emission control, but wet scrubbers, such as venturi and centrifugal scrubbers, are more suitable for reducing particulate emissions from the dryers. Wet scrubbers use the process streams as the scrubbing liquid so that the collected particulate can be easily recycled to the production system.

Table 8.4-1 shows uncontrolled and controlled particulate and VOC emission factors for various dryer types. Emission factors are in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton). The VOC emissions shown apply only to caprolactam byproduct plants.

Table 8.4-1 (Metric And English Units). EMISSION FACTORS FOR AMMONIUM SULFATE MANUFACTURE[a]

EMISSION FACTOR RATING: C (except as noted)

Dryer Type	Particulate		VOC[b]	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Rotary dryers				
Uncontrolled	23	46	0.74	1.48
Wet scrubber	0.02[c]	0.04[c]	0.11	0.22
Fluidized-bed dryers				
Uncontrolled	109	218	0.74	1.48
Wet scrubber	0.14	0.28	0.11	0.22

[a] Reference 3. Units are kg of pollutant/Mg of ammonium sulfate produced (lb of pollutant/ton of ammonium sulfate produced).

[b] VOC emissions occur only at caprolactam plants. The emissions are caprolactam vapor.

[c] Reference 4. EMISSION FACTOR RATING: A.

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8.5 Phosphate Fertilizers

Phosphate fertilizers are classified into 3 groups of chemical compounds. Two of these groups are known as superphosphates and are defined by the percentage of phosphorus as phosphorus pentoxide (P_2O_5). Normal superphosphate contains between 15 and 21 percent phosphorus as P_2O_5 whereas triple superphosphate contains over 40 percent phosphorus. The remaining group is ammonium phosphate ($NH_4H_2PO_4$).

8.5.1 Normal Superphosphates

8.5.1.1 General[1-3]

Normal superphosphate refers to fertilizer material containing 15 to 21 percent phosphorus as phosphorus pentoxide (P_2O_5). As defined by the Census Bureau, normal superphosphate contains not more than 22 percent of available P_2O_5. There are currently about 8 fertilizer facilities producing normal superphosphates in the U. S. with an estimated total production of about 273,000 megagrams (Mg) (300,000 tons) per year.

8.5.1.2 Process Description[1]

Normal superphosphates are prepared by reacting ground phosphate rock with 65 to 75 percent sulfuric acid. An important factor in the production of normal superphosphates is the amount of iron and aluminum in the phosphate rock. Aluminum (as Al_2O_3) and iron (as Fe_2O_3) above 5 percent imparts an extreme stickiness to the superphosphate and makes it difficult to handle.

The 2 general types of sulfuric acid used in superphosphate manufacture are virgin and spent acid. Virgin acid is produced from elemental sulfur, pyrites, and industrial gases and is relatively pure. Spent acid is a recycled waste product from various industries that use large quantities of sulfuric acid. Problems encountered with using spent acid include unusual color, unfamiliar odor, and toxicity.

A generalized flow diagram of normal superphosphate production is shown in Figure 8.5.1-1. Ground phosphate rock and acid are mixed in a reaction vessel, held in an enclosed area for about 30 minutes until the reaction is partially completed, and then transferred, using an enclosed conveyer known as the den, to a storage pile for curing (the completion of the reaction). Following curing, the product is most often used as a high-phosphate additive in the production of granular fertilizers. It can also be granulated for sale as granulated superphosphate or granular mixed fertilizer. To produce granulated normal superphosphate, cured superphosphate is fed through a clod breaker and sent to a rotary drum granulator where steam, water, and acid may be added to aid in granulation. Material is processed through a rotary drum granulator, a rotary dryer, and a rotary cooler, and is then screened to specification. Finally, it is stored in bagged or bulk form prior to being sold.

8.5.1.3 Emissions And Controls[1-6]

Sources of emissions at a normal superphosphate plant include rock unloading and feeding, mixing operations (in the reactor), storage (in the curing building), and fertilizer handling operations. Rock unloading, handling, and feeding generate particulate emissions of phosphate rock dust. The mixer, den, and curing building emit gases in the form of silicon tetrafluoride (SiF_4), hydrogen fluoride (HF), and particulates composed of fluoride and phosphate material. Fertilizer handling operations release fertilizer dust. Emission factors for the production of normal superphosphate are presented in Table 8.5.1-1. Units are expressed in terms of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton).

At a typical normal superphosphate plant, emissions from the rock unloading, handling, and feeding operations are controlled by a baghouse. Baghouse cloth filters have reported efficiencies of den are controlled by a wet scrubber. The curing building and fertilizer handling operations over

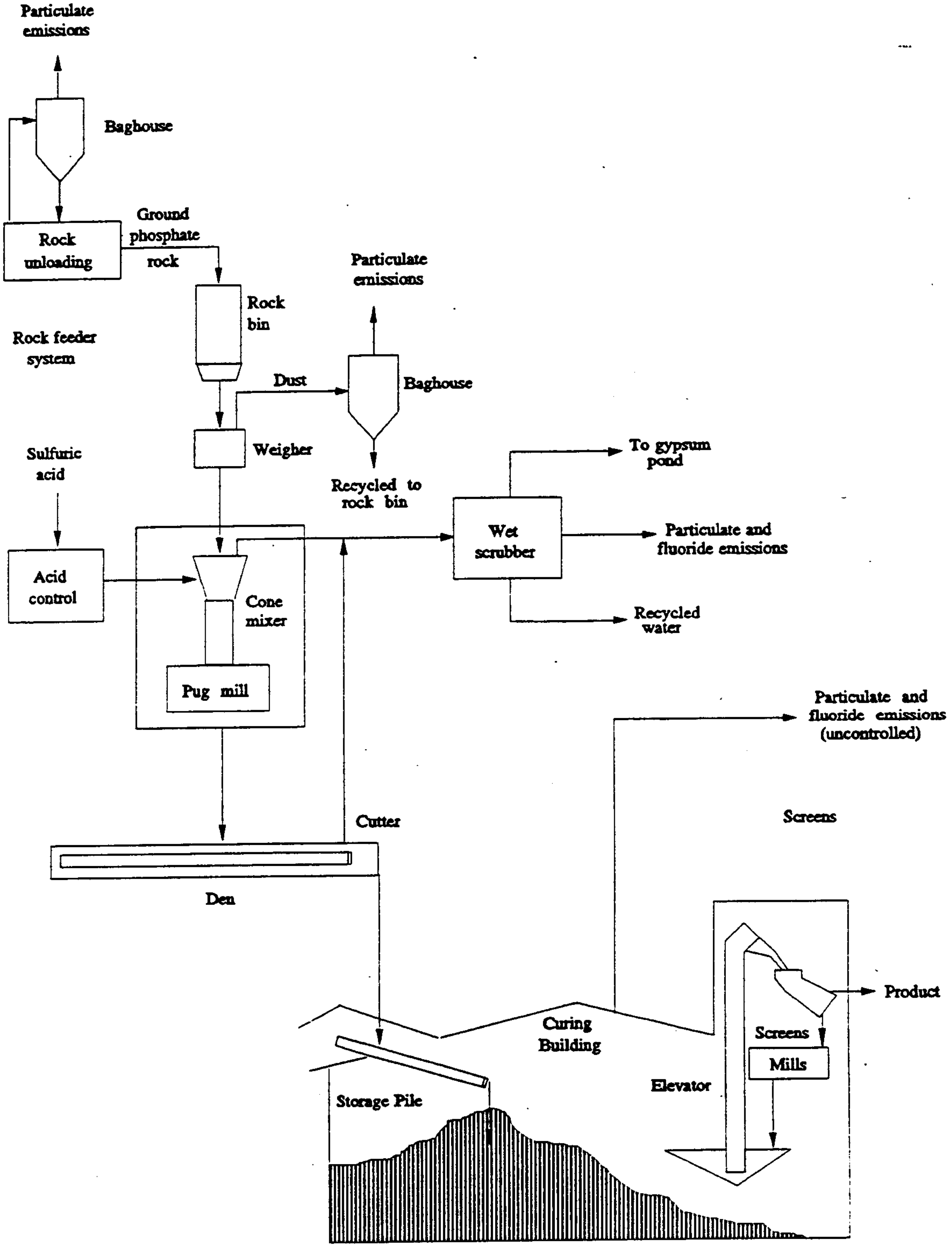

Figure 8.5.1-1. Normal superphosphate process flow diagram.[1]

Table 8.5.1-1 (Metric And English Units). EMISSION FACTORS FOR THE PRODUCTION OF NORMAL SUPERPHOSPHATE

EMISSION FACTOR RATING: E

Emission Point	Pollutant	Emission Factor	
		kg/Mg Of P_2O_5 Produced	lb/ton Of P_2O_5 Produced
Rock unloading[a]	Particulate[b]	0.28	0.56
	PM-10[c]	0.15	0.29
Rock feeding[a]	Particulate[b]	0.06	0.11
	PM-10[c]	0.03	0.06
Mixer and den[d]	Particulate[b]	0.26	0.52
	Fluoride[b]	0.10	0.2
	PM-10[c]	0.22	0.44
Curing building[e]	Particulate[b]	3.60	7.20
	Fluoride[b]	1.90	3.80
	PM-10[c]	3.0	6.1

[a] Factors are for emissions from baghouse with an estimated collection efficiency of 99%. PM-10 = particulate matter no greater than 10 micrometers.

[b] Reference 1, pp. 74-77, 169.

[c] Taken from Aerometric Information Retrieval System (AIRS) Listing for Criteria Air Pollutants.

[d] Factors are for emissions from wet scrubbers with a reported 97% control efficiency.

[e] Uncontrolled.

99 percent under ideal conditions. Collected dust is recycled. Emissions from the mixer and den are controlled by a wet scrubber. The curing building and fertilizer handling operations normally are not controlled.

SiF_4 and HF emissions, and particulate from the mixer, den, and curing building are controlled by scrubbing the offgases with recycled water. Gaseous SiF_4 in the presence of moisture reacts to form gelatinous silica, which has a tendency to plug scrubber packings. The use of conventional packed-countercurrent scrubbers and other contacting devices with small gas passages for emissions control is therefore limited. Scrubbers that can be used are cyclones, venturi, impingement, jet ejector, and spray-crossflow packed scrubbers. Spray towers are also used as precontactors for fluorine removal at relatively high concentration levels of greater than 4.67 grams per cubic meter (3000 parts per million).

Air pollution control techniques vary with particular plant designs. The effectiveness of abatement systems in removing fluoride and particulate also varies from plant to plant, depending on a number of factors. The effectiveness of fluorine abatement is determined by the inlet fluorine concentration, outlet or saturated gas temperature, composition and temperature of the scrubbing liquid, scrubber type and transfer units, and the effectiveness of entrainment separation. Control efficiency is enhanced by increasing the number of scrubbing stages in series and by using a fresh water scrub in the final stage. Reported efficiencies for fluoride control range from less than 90 percent to over 99 percent, depending on inlet fluoride concentrations and the system employed. An efficiency of 98 percent for particulate control is achievable.

The emission factors have not been adjusted by this revision, but they have been downgraded to an "E" quality rating based on the absence of supporting source tests. The PM-10 (particulate matter with a diameter of less than 10 micrometers) emission factors have been added to the table, but were taken from the AIRS Listing for Criteria Air Pollutants, which is also rated "E". No additional or recent data were found concerning fluoride emissions from gypsum ponds. A number of hazardous air pollutants (HAPs) have been identified by SPECIATE as being present in the phosphate manufacturing process. Some HAPs identified include hexane, methyl alcohol, formaldehyde, methyl ethyl ketone, benzene, toluene, and styrene. Heavy metals such as lead and mercury are present in the phosphate rock. The phosphate rock is mildly radioactive due to the presence of some radionuclides. No emission factors are included for these HAPs, heavy metals, or radionuclides due to the lack of sufficient data.

References For Section 8.5.1

1. J. M. Nyers, *et al.*, *Source Assessment: Phosphate Fertilizer Industry*, EPA-600/2-79-019c, U. S. Environmental Protection Agency, Cinncinnati, OH, May 1979.

2. H. C. Mann, *Normal Superphosphate*, National Fertilizer & Environmental Research Center, Tennessee Valley Authority, Muscle Shoals, AL, February 1992.

3. North American Fertilizer Capacity Data (including supplement), Tennessee Valley Authority, Muscle Shoals, AL, December 1991.

4. *Background Information For Standards Of Performance: Phosphate Fertilizer Industry: Volume 1: Proposed Standards*, EPA-450/2-74-019a, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1974.

5. *Background Information For Standards Of Performance: Phosphate Fertilizer Industry: Volume 2: Test Data Summary*, EPA-450/2-74-019b, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1974.

6. *Final Guideline Document: Control Of Fluoride Emissions From Existing Phosphate Fertilizer Plants*, EPA-450/2-77-005, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1977.

8.5.2 Triple Superphosphates

8.5.2.1 General[2-3]

Triple superphosphate, also known as double, treble, or concentrated superphosphate, is a fertilizer material with a phosphorus content of over 40 percent, measured as phosphorus pentoxide (P_2O_5). Triple superphosphate is produced in only 6 fertilizer facilities in the U. S. In 1989, there were an estimated 3.2 million megagrams (Mg) (3.5 million tons) of triple superphosphate produced. Production rates from the various facilities range from 23 to 92 Mg (25 to 100 tons) per hour.

8.5.2.2 Process Description[1-2]

Two processes have been used to produce triple superphosphate: run-of-the-pile (ROP-TSP) and granular (GTSP). At this time, no facilities in the U. S. are currently producing ROP-TSP, but a process description is given.

The ROP-TSP material is essentially a pulverized mass of variable particle size produced in a manner similar to normal superphosphate. Wet-process phosphoric acid (50 to 55 percent P_2O_5) is reacted with ground phosphate rock in a cone mixer. The resultant slurry begins to solidify on a slow moving conveyer en route to the curing area. At the point of discharge from the den, the material passes through a rotary mechanical cutter that breaks up the solid mass. Coarse ROP-TSP product is sent to a storage pile and cured for 3 to 5 weeks. The product is then mined from the storage pile to be crushed, screened, and shipped in bulk.

GTSP yields larger, more uniform particles with improved storage and handling properties. Most of this material is made with the Dorr-Oliver slurry granulation process, illustrated in Figure 8.5.2-1. In this process, ground phosphate rock or limestone is reacted with phosphoric acid in 1 or 2 reactors in series. The phosphoric acid used in this process is appreciably lower in concentration (40 percent P_2O_5) than that used to manufacture ROP-TSP product. The lower strength acid maintains the slurry in a fluid state during a mixing period of 1 to 2 hours. A small sidestream of slurry is continuously removed and distributed onto dried, recycled fines, where it coats the granule surfaces and builds up its size.

Pugmills and rotating drum granulators have been used in the granulation process. Only 1 pugmill is currently operating in the U. S. A pugmill is composed of a U-shaped trough carrying twin counter-rotating shafts, upon which are mounted strong blades or paddles. The blades agitate, shear, and knead the liquified mix and transport the material along the trough. The basic rotary drum granulator consists of an open-ended, slightly inclined rotary cylinder, with retaining rings at each end and a scraper or cutter mounted inside the drum shell. A rolling bed of dry material is maintained in the unit while the slurry is introduced through distributor pipes set lengthwise in the drum under the bed. Slurry-wetted granules are then discharged onto a rotary dryer, where excess water is evaporated and the chemical reaction is accelerated to completion by the dryer heat. Dried granules are then sized on vibrating screens. Oversize particles are crushed and recirculated to the screen, and undersize particles are recycled to the granulator. Product-size granules are cooled in a countercurrent rotary drum, then sent to a storage pile for curing. After a curing period of 3 to 5 days, granules are removed from storage, screened, bagged, and shipped.

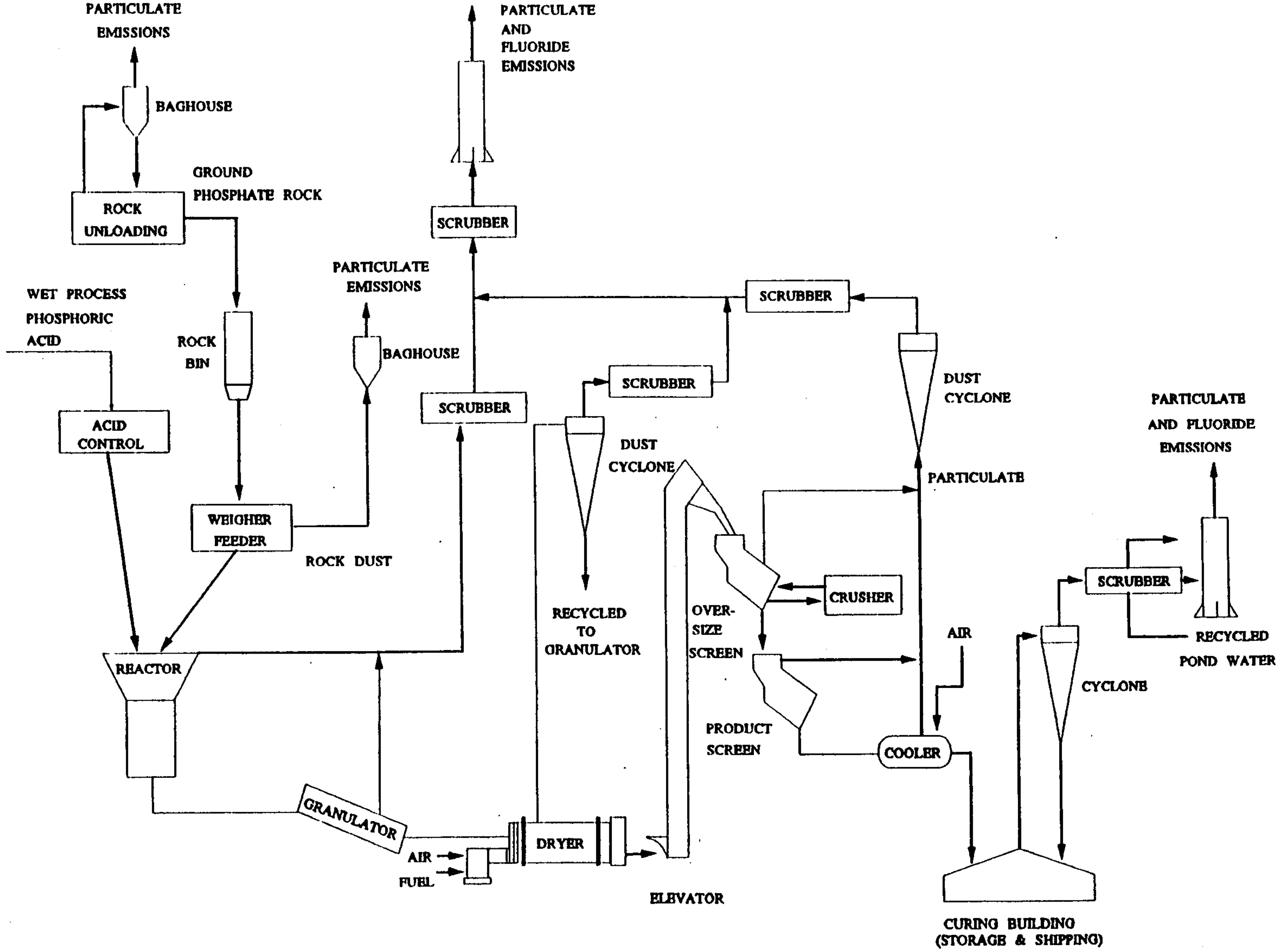

Figure 8.5.2-1. Dorr-Oliver process for granular triple superphosphate production.[1]

8.5.2.3 Emissions And Controls[1-6]

Controlled emission factors for the production of GTSP are given in Table 8.5.2-1. Units are expressed in terms of kilograms per megagrams (kg/Mg) and pounds per ton (lb/ton). Emission factors for ROP-TSP are not given since it is not being produced currently in the U. S.

Table 8.5.2-1 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR THE PRODUCTION OF TRIPLE SUPERPHOSPHATES

EMISSION FACTOR RATING: E

Granular Triple Superphosphate Process	Pollutant	Controlled Emission Factor	
		kg/Mg Of Product	lb/ton Of Product
Rock unloading[a]	Particulate[b]	0.09	0.18
	PM-10[c]	0.04	0.08
Rock feeding[a]	Particulate[b]	0.02	0.04
	PM-10[c]	0.01	0.02
Reactor, granulator, dryer, cooler, and screens[d]	Particulate[b]	0.05	0.10
	Fluoride[b]	0.12	0.24
	PM-10[c]	0.04	0.08
Curing building[d]	Particulate[b]	0.10	0.20
	Fluoride[b]	0.02	0.04
	PM-10[c]	0.08	0.17

[a] Factors are for emissions from baghouses with an estimated collection efficiency of 99%. PM-10 = particulate matter with a diameter of less than 10 micrometers.

[b] Reference 1, pp. 77-80, 168, 170-171.

[c] Based on Aerometic Information Retrieval System (AIRS) Listing For Criteria Air Pollutants.

[d] Factors are for emissions from wet scrubbers with an estimated 97% control efficiency.

Sources of particulate emissions include the reactor, granulator, dryer, screens, cooler, mills, and transfer conveyors. Additional emissions of particulate result from the unloading, grinding, storage, and transfer of ground phosphate rock. One facility uses limestone, which is received in granulated form and does not require additional milling.

Emissions of fluorine compounds and dust particles occur during the production of GTSP triple superphosphate. Silicon tetrafluoride (SiF_4) and hydrogen fluoride (HF) are released by the acidulation reaction and they evolve from the reactors, den, granulator, and dryer. Evolution of fluoride is essentially finished in the dryer and there is little fluoride evolved from the storage pile in the curing building.

At a typical plant, baghouses are used to control the fine rock particles generated by the rock grinding and handling activities. Emissions from the reactor, den, and granulator are controlled by scrubbing the effluent gas with recycled gypsum pond water in cyclonic scrubbers. Emissions from the dryer, cooler, screens, mills, product transfer systems, and storage building are sent to a cyclone separator for removal of a portion of the dust before going to wet scrubbers to remove fluorides.

Particulate emissions from ground rock unloading, storage, and transfer systems are controlled by baghouse collectors. These baghouse cloth filters have reported efficiencies of over 99 percent. Collected solids are recycled to the process. Emissions of SiF_4, HF, and particulate from the production area and curing building are controlled by scrubbing the offgases with recycled water. Exhausts from the dryer, cooler, screens, mills, and curing building are sent first to a cyclone separator and then to a wet scrubber. Tailgas wet scrubbers perform final cleanup of the plant offgases.

Gaseous SiF_4 in the presence of moisture reacts to form gelatinous silica, which has the tendency to plug scrubber packings. Therefore, the use of conventional packed countercurrent scrubbers and other contacting devices with small gas passages for emissions control is not feasible. Scrubber types that can be used are: (1) spray tower, (2) cyclone, (3) venturi, (4) impingement, (5) jet ejector, and (6) spray-crossflow packed.

The effectiveness of abatement systems for the removal of fluoride and particulate varies from plant to plant, depending on a number of factors. The effectiveness of fluorine abatement is determined by: (1) inlet fluorine concentration, (2) outlet or saturated gas temperature, (3) composition and temperature of the scrubbing liquid, (4) scrubber type and transfer units, and (5) effectiveness of entrainment separation. Control efficiency is enhanced by increasing the number of scrubbing stages in series and by using a fresh water scrub in the final stage. Reported efficiencies for fluoride control range from less than 90 percent to over 99 percent, depending on inlet fluoride concentrations and the system employed. An efficiency of 98 percent for particulate control is achievable.

The particulate and fluoride emission factors are identical to the previous revisions, but have been downgraded to "E" quality because no documented, up-to-date source tests were available and previous emission factors could not be validated from the references which were given. The PM-10 emission factors have been added to the table, but were derived from the AIRS data base, which also has an "E" rating. No additional or recent data were found concerning fluoride emissions from gypsum ponds. A number of hazardous air pollutants (HAP) have been identified by SPECIATE as being present in the phosphate fertilizer manufacturing process. Some HAPs identified include hexane, methyl alcohol, formaldehyde, methyl ethyl ketone, benzene, toluene, and styrene. Heavy metals such as lead and mercury are present in the phosphate rock. The phosphate rock is mildly radioactive due to the presence of some radionuclides. No emission factors are included for these HAPs, heavy metals, or radionuclides due to the lack of sufficient data.

References For Section 8.5.2

1. J. M. Nyers, *et al.*, *Source Assessment: Phosphate Fertilizer Industry*, EPA-600/2-79-019c, U. S. Environmental Protection Agency, Cinncinnati, OH, May 1979.

2. H. C. Mann, *Triple Superphosphate*, National Fertilizer & Environmental Research Center, Tennessee Valley Authority, Muscle Shoals, AL, February 1992.

3. *North American Fertilizer Capacity Data* (including supplement), Tennessee Valley Authority, Muscle Shoals, AL, December 1991.

4. *Background Information For Standards Of Performance: Phosphate Fertilizer Industry: Volume 1: Proposed Standards*, EPA-450/2-74-019a, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1974.

5. *Background Information For Standards Of Performance: Phosphate Fertilizer Industry: Volume 2: Test Data Summary*, EPA-450/2-74-019b, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1974.

6. *Final Guideline Document: Control Of Fluoride Emissions From Existing Phosphate Fertilizer Plants*, EPA-450/2-77-005, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1977.

8.5.3 Ammonium Phosphate

8.5.3.1 General[1]

Ammonium phosphate ($NH_4H_2PO_4$) is produced by reacting phosphoric acid (H_3PO_4) with anhydrous ammonia (NH_3). Ammoniated superphosphates are produced by adding normal superphosphate or triple superphosphate to the mixture. The production of liquid ammonium phosphate and ammoniated superphosphates in fertilizer mixing plants is considered a separate process. Both solid and liquid ammonium phosphate fertilizers are produced in the U. S. This discussion covers only the granulation of phosphoric acid with anhydrous ammonia to produce granular fertilizer. Total ammonium phosphate production in the U. S. in 1992 was estimated to be 7.7 million megagrams (Mg) (8.5 million tons).[2]

8.5.3.2 Process Description[1]

Two basic mixer designs are used by ammoniation-granulation plants: the pugmill ammoniator and the rotary drum ammoniator. Approximately 95 percent of ammoniation-granulation plants in the U. S. use a rotary drum mixer developed and patented by the Tennessee Valley Authority (TVA). The basic rotary drum ammoniator-granulator consists of a slightly inclined open-end rotary cylinder with retaining rings at each end, and a scrapper or cutter mounted inside the drum shell. A rolling bed of recycled solids is maintained in the unit.

Ammonia-rich offgases pass through a wet scrubber before exhausting to the atmosphere. Primary scrubbers use raw materials mixed with acids (such as scrubbing liquor), and secondary scrubbers use gypsum pond water.

In the TVA process, phosphoric acid is mixed in an acid surge tank with 93 percent sulfuric acid (H_2SO_4), which is used for product analysis control, and with recycled acid from wet scrubbers. (A schematic diagram of the ammonium phosphate process flow diagram is shown in Figure 8.5.3-1.) Mixed acids are then partially neutralized with liquid or gaseous anhydrous ammonia in a brick-lined acid reactor. All of the phosphoric acid and approximately 70 percent of the ammonia are introduced into this vessel. A slurry of ammonium phosphate and 22 percent water are produced and sent through steam-traced lines to the ammoniator-granulator. Slurry from the reactor is distributed on the bed; the remaining ammonia (approximately 30 percent) is sparged underneath. Granulation, by agglomeration and by coating particulate with slurry, takes place in the rotating drum and is completed in the dryer. Ammonia-rich offgases pass through a wet scrubber before exhausting to the atmosphere. Primary scrubbers use raw materials mixed with acid (such as scrubbing liquor), and secondary scrubbers use pond water.

Moist ammonium phosphate granules are transferred to a rotary concurrent dryer and then to a cooler. Before being exhausted to the atmosphere, these offgases pass through cyclones and wet scrubbers. Cooled granules pass to a double-deck screen, in which oversize and undersize particles are separated from product particles. The product ranges in granule size from 1 to 4 millimeters. The oversized granules are crushed, mixed with the undersized, and recycled back to the ammoniator-granulator.

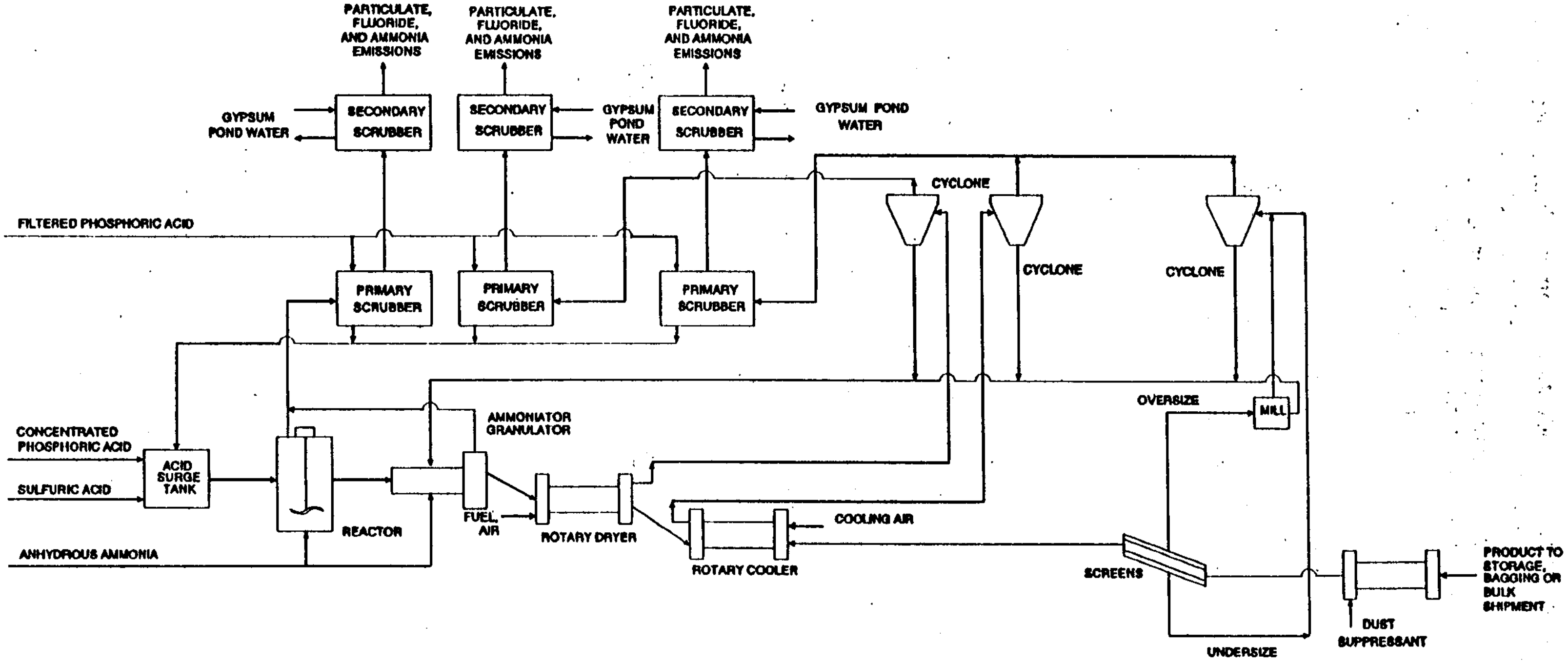

Figure 8.5.3-1. Ammonium phosphate process flow diagram.

8.5.3.3 Emissions And Controls[1]

Sources of air emissions from the production of ammonium phosphate fertilizers include the reactor, the ammoniator-granulator, the dryer and cooler, product sizing and material transfer, and the gypsum pond. The reactor and ammoniator-granulator produce emissions of gaseous ammonia, gaseous fluorides such as hydrogen fluoride (HF) and silicon tetrafluoride (SiF_4), and particulate ammonium phosphates. These 2 exhaust streams are generally combined and passed through primary and secondary scrubbers.

Exhaust gases from the dryer and cooler also contain ammonia, fluorides, and particulates and these streams are commonly combined and passed through cyclones and primary and secondary scrubbers. Particulate emissions and low levels of ammonia and fluorides from product sizing and material transfer operations are controlled the same way.

Emissions factors for ammonium phosphate production are summarized in Table 8.5.3-1. Units are expressed in terms of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton) of product. These emission factors are averaged based on recent source test data from controlled phosphate fertilizer plants in Tampa, Florida.

Table 8.5.3-1 (Metric And English Units). AVERAGE CONTROLLED EMISSION FACTORS FOR THE PRODUCTION OF AMMONIUM PHOSPHATES[a]

EMISSION FACTOR RATING: E (except as noted)

	Fluoride as F		Particulate		Ammonia		SO_2	
Emission Point	kg/Mg Of Product	lb/ton Of Product	kg/Mg Of Product	lb/ton Of Product	kg/Mg Of Product	lb/ton Of Product	kg/Mg Of Product	lb/ton Of Product
Reactor/ ammoniator - granulator	0.02	0.05	0.76	1.52	ND	ND	NA	NA
Dryer/cooler	0.02	0.04	0.75	1.50	NA	NA	NA	NA
Product sizing and material transfer[b]	0.001	0.002	0.03	0.06	NA	NA	NA	NA
Total plant emissions	0.02[c]	0.04[c]	0.34[d]	0.68[d]	0.07	0.14	0.04[e]	0.08[e]

[a] Reference 1, pp. 80-83, 173. ND = no data. NA = not applicable.
[b] Represents only 1 sample.
[c] References 7-8,10-11,13-15. EMISSION FACTOR RATING: A. EPA has promulgated a fluoride emission guideline of 0.03 kg/Mg (0.06 lb/ton) P_2O_5 input.
[d] References 7-9,10,13-15. EMISSION FACTOR RATING: A.
[e] Based on limited data from only one plant, Reference 9.

Exhaust streams from the reactor and ammoniator-granulator pass through a primary scrubber, in which phosphoric acid is used to recover ammonia and particulate. Exhaust gases from the dryer, cooler, and screen first go to cyclones for particulate recovery, and then to primary scrubbers. Materials collected in the cyclone and primary scrubbers are returned to the process. The exhaust is sent to secondary scrubbers, where recycled gypsum pond water is used as a scrubbing liquid to control fluoride emissions. The scrubber effluent is returned to the gypsum pond.

Primary scrubbing equipment commonly includes venturi and cyclonic spray towers. Impingement scrubbers and spray-crossflow packed bed scrubbers are used as secondary controls. Primary scrubbers generally use phosphoric acid of 20 to 30 percent as scrubbing liquor, principally to recover ammonia. Secondary scrubbers generally use gypsum and pond water for fluoride control.

Throughout the industry, however, there are many combinations and variations. Some plants use reactor-feed concentration phosphoric acid (40 percent phosphorous pentoxide [P_2O_5]) in both primary and secondary scrubbers, and some use phosphoric acid near the dilute end of the 20 to 30 percent P_2O_5 range in only a single scrubber. Existing plants are equipped with ammonia recovery scrubbers on the reactor, ammoniator-granulator and dryer, and particulate controls on the dryer and cooler. Additional scrubbers for fluoride removal exist, but they are not typical. Only 15 to 20 percent of installations contacted in an EPA survey were equipped with spray-crossflow packed bed scrubbers or their equivalent for fluoride removal.

Emission control efficiencies for ammonium phosphate plant control equipment are reported as 94 to 99 percent for ammonium, 75 to 99.8 percent for particulates, and 74 to 94 percent for fluorides.

References For Section 8.5.3

1. J. M. Nyers, *et al.*, *Source Assessment: Phosphate Fertilizer Industry*, EPA-600/2-79-019c, U. S. Environmental Protection Agency, Cinncinnati, OH, May 1979.

2. North American Fertilizer Capacity Data, Tennessee Valley Authority, Muscle Shoals, AL, December 1991.

3. *Compliance Source Test Report: Texasgulf Inc., Granular Triple Super Phosphate Plant*, Aurora, NC, May 1987.

4. *Compliance Source Test Report: Texasgulf Inc., Diammonium Phosphate Plant No.2*, Aurora, NC, August 1989.

5. *Compliance Source Test Report: Texasgulf Inc., Diammonium Phosphate Plant #2*, Aurora, NC, December 1991.

6. *Compliance Source Test Report: Texasgulf, Inc., Diammonium Phosphate #1*, Aurora, NC, September 1990.

7. *Compliance Source Test Report: Texasgulf Inc., Ammonium Phosphate Plant #2*, Aurora, NC, November 1990.

8. *Compliance Source Test Report: Texasgulf Inc., Diammonium Phosphate Plant #2*, Aurora, NC, November 1991.

9. *Compliance Source Test Report: IMC Fertilizer, Inc., #1 DAP Plant*, Western Polk County, FL, October 1991.

10. *Compliance Source Test Report: IMC Fertilizer, Inc., #2 DAP Plant*, Western Polk County, FL, June 1991.

11. *Compliance Source Test Report: IMC Fertilizer, Inc.*, Western Polk County, FL, April 1991.

8.6 Hydrochloric Acid

8.6.1 General[1]

Hydrochloric acid (HCl) is listed as a Title III Hazardous Air Pollutant. Hydrochloric acid is a versatile chemical used in a variety of chemical processes, including hydrometallurgical processing (e. g., production of alumina and/or titanium dioxide), chlorine dioxide synthesis, hydrogen production, activation of petroleum wells, and miscellaneous cleaning/etching operations including metal cleaning (e. g., steel pickling). Also known as muriatic acid, HCl is used by masons to clean finished brick work, is also a common ingredient in many reactions, and is the preferred acid for catalyzing organic processes. One example is a carbohydrate reaction promoted by hydrochloric acid, analogous to those in the digestive tracts of mammals.

Hydrochloric acid may be manufactured by several different processes, although over 90 percent of the HCl produced in the U. S. is a byproduct of the chlorination reaction. Currently, U. S. facilities produce approximately 2.3 million megagrams (Mg) (2.5 million tons) of HCl annually, a slight decrease from the 2.5 million Mg (2.8 million tons) produced in 1985.

8.6.2 Process Description[1-4]

Hydrochloric acid can be produced by 1 of the 5 following processes:

1. Synthesis from elements:

$$H_2 + Cl_2 \rightarrow 2HCl \qquad (1)$$

2. Reaction of metallic chlorides, particularly sodium chloride (NaCl), with sulfuric acid (H_2SO_4) or a hydrogen sulfate:

$$NaCl + H_2SO_4 \rightarrow NaHSO_4 + HCl \qquad (2)$$

$$NaCl + NaHSO_4 \rightarrow Na_2SO_4 + HCl \qquad (3)$$

$$2NaCl + H_2SO_4 \rightarrow Na_2SO_4 + 2HCl \qquad (4)$$

3. As a byproduct of chlorination, e. g., in the production of dichloromethane, trichloroethylene, perchloroethylene, or vinyl chloride:

$$C_2H_4 + Cl_2 \rightarrow C_2H_4Cl_2 \qquad (5)$$

$$C_2H_4Cl_2 \rightarrow C_2H_3Cl + HCl \qquad (6)$$

4. By thermal decomposition of the hydrated heavy-metal chlorides from spent pickle liquor in metal treatment:

$$2FeCl_3 + 6H_2O \rightarrow Fe_2O_3 + 3H_2O + 6HCl \qquad (7)$$

5. From incineration of chlorinated organic waste:

$$C_4H_6Cl_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O + 2HCl \tag{8}$$

Figure 8.6-1 is a simplified diagram of the steps used for the production of byproduct HCl from the chlorination process.

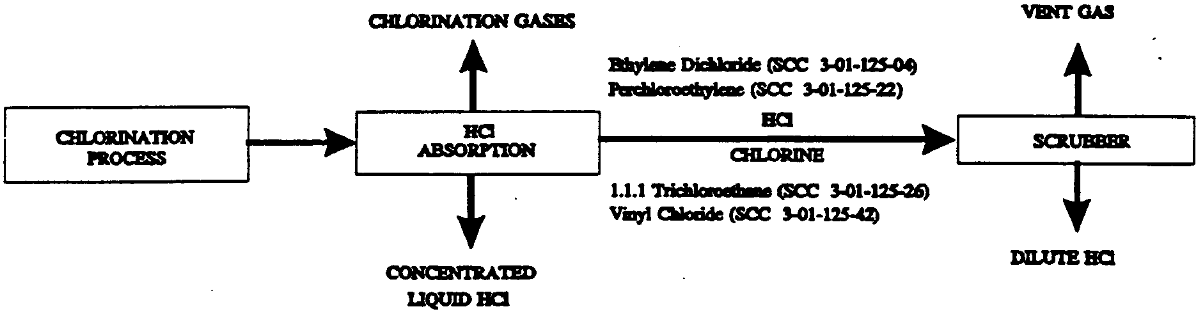

Figure 8.6-1. HCl production from chlorination process.
(SCC = Source Classification Code.)

After leaving the chlorination process, the HCl-containing gas stream proceeds to the absorption column, where concentrated liquid HCl is produced by absorption of HCl vapors into a weak solution of hydrochloric acid. The HCl-free chlorination gases are removed for further processing. The liquid acid is then either sold or used elsewhere in the plant. The final gas stream is sent to a scrubber to remove the remaining HCl prior to venting.

8.6.3 Emissions[4,5]

According to a 1985 emission inventory, over 89 percent of all HCl emitted to the atmosphere resulted from the combustion of coal. Less than 1 percent of the HCl emissions came from the direct production of HCl. Emissions from HCl production result primarily from gas exiting the HCl purification system. The contaminants are HCl gas, chlorine, and chlorinated organic compounds. Emissions data are only available for HCl gas. Table 8.6-1 lists estimated emission factors for systems with and without final scrubbers. Units are expressed in terms of kilograms per megagram (kg/Mg) and pounds per ton.

Table 8.6-1 (Metric And English Units). EMISSION FACTORS FOR HYDROCHLORIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: E

Byproduct Hydrochloric Acid Process	HCl Emissions	
	kg/Mg HCl Produced	lb/ton HCl Produced
With final scrubber (SCC 3-01-011-99)[b]	0.08	0.15
Without final scrubber (SCC 3-01-011-99)[b]	0.90	1.8

[a] Reference 5. SCC = Source Classification Code.

[b] This SCC is appropriate only when no other SCC is more appropriate. If HCl is produced as a byproduct of another process such as the production of dichloromethane, trichloroethane, perchloroethylene, or vinyl chloride then the emission factor and SCC appropriate for that process vent should be used.

References For Section 8.6

1. *Encyclopedia Of Chemical Technology, Third Edition*, Volume 12, John Wiley and Sons, New York, 1978.

2. *Ullmann's Encyclopedia Of Industrial Chemistry, Volume A*, VCH Publishers, New York, 1989.

3. *Encyclopedia Of Chemical Processing And Design*, Marcel Dekker, Inc., New York, 1987.

4. *Hydrogen Chloride And Hydrogen Fluoride Emission Factors For The NAPAP (National Acid Precipitation Assessment Program) Emission Inventory*, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1985.

5. *Atmospheric Emissions From Hydrochloric Acid Manufacturing Processes*, AP-54, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1969.

8.7 Hydrofluoric Acid

8.7.1 General[5-6]

Hydrogen fluoride (HF) is listed as a Title III Hazardous Air Pollutant. Hydrogen fluoride is produced in 2 forms, as anhydrous hydrogen fluoride and as aqueous hydrofluoric acid. The predominant form manufactured is hydrogen fluoride, a colorless liquid or gas that fumes on contact with air and is water soluble.

Traditionally, hydrofluoric acid has been used to etch and polish glass. Currently, the largest use for HF is in aluminum production. Other HF uses include uranium processing, petroleum alkylation, and stainless steel pickling. Hydrofluoric acid is also used to produce fluorocarbons used in aerosol sprays and in refrigerants. Although fluorocarbons are heavily regulated due to environmental concerns, other applications for fluorocarbons include manufacturing of resins, solvents, stain removers, surfactants, and pharmaceuticals.

8.7.2 Process Description[1-3,6]

Hydrofluoric acid is manufactured by the reaction of acid-grade fluorspar (CaF_2) with sulfuric acid (H_2SO_4) as shown below:

$$CaF_2 + H_2SO_4 \rightarrow CaSO_4 + 2HF$$

A typical HF plant is shown schematically in Figure 8.7-1. The endothermic reaction requires 30 to 60 minutes in horizontal rotary kilns externally heated to 200 to 250°C (390 to 480°F). Dry fluorspar ("spar") and a slight excess of sulfuric acid are fed continuously to the front end of a stationary prereactor or directly to the kiln by a screw conveyor. The prereactor mixes the components prior to charging to the rotary kiln. Calcium sulfate ($CaSO_4$) is removed through an air lock at the opposite end of the kiln. The gaseous reaction products—hydrogen fluoride and excess H_2SO_4 from the primary reaction and silicon tetrafluoride (SiF_4), sulfur dioxide (SO_2), carbon dioxide (CO_2), and water produced in secondary reactions—are removed from the front end of the kiln along with entrained particulate. The particulates are removed from the gas stream by a dust separator and returned to the kiln. Sulfuric acid and water are removed by a precondenser. Hydrogen fluoride vapors are then condensed in refrigerant condensers forming "crude HF", which is removed to intermediate storage tanks. The remaining gas stream passes through a sulfuric acid absorption tower or acid scrubber, removing most of the remaining hydrogen fluoride and some residual sulfuric acid, which are also placed in intermediate storage. The gases exiting the scrubber then pass through water scrubbers, where the SiF_4 and remaining HF are recovered as fluosilicic acid (H_2SiF_6). The water scrubber tailgases are passed through a caustic scrubber before being released to the atmosphere. The hydrogen fluoride and sulfuric acid are delivered from intermediate storage tanks to distillation columns, where the hydrofluoric acid is extracted at 99.98 percent purity. Weaker concentrations (typically 70 to 80 percent) are prepared by dilution with water.

8.7.3 Emissions And Controls[1-2,4]

Emission factors for various HF process operations are shown in Tables 8.7-1 and 8.7-2. Units are expressed in terms of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton) Emissions are suppressed to a great extent by the condensing, scrubbing, and absorption equipment used in the recovery and purification of the hydrofluoric and fluosilicic acid products. Particulate

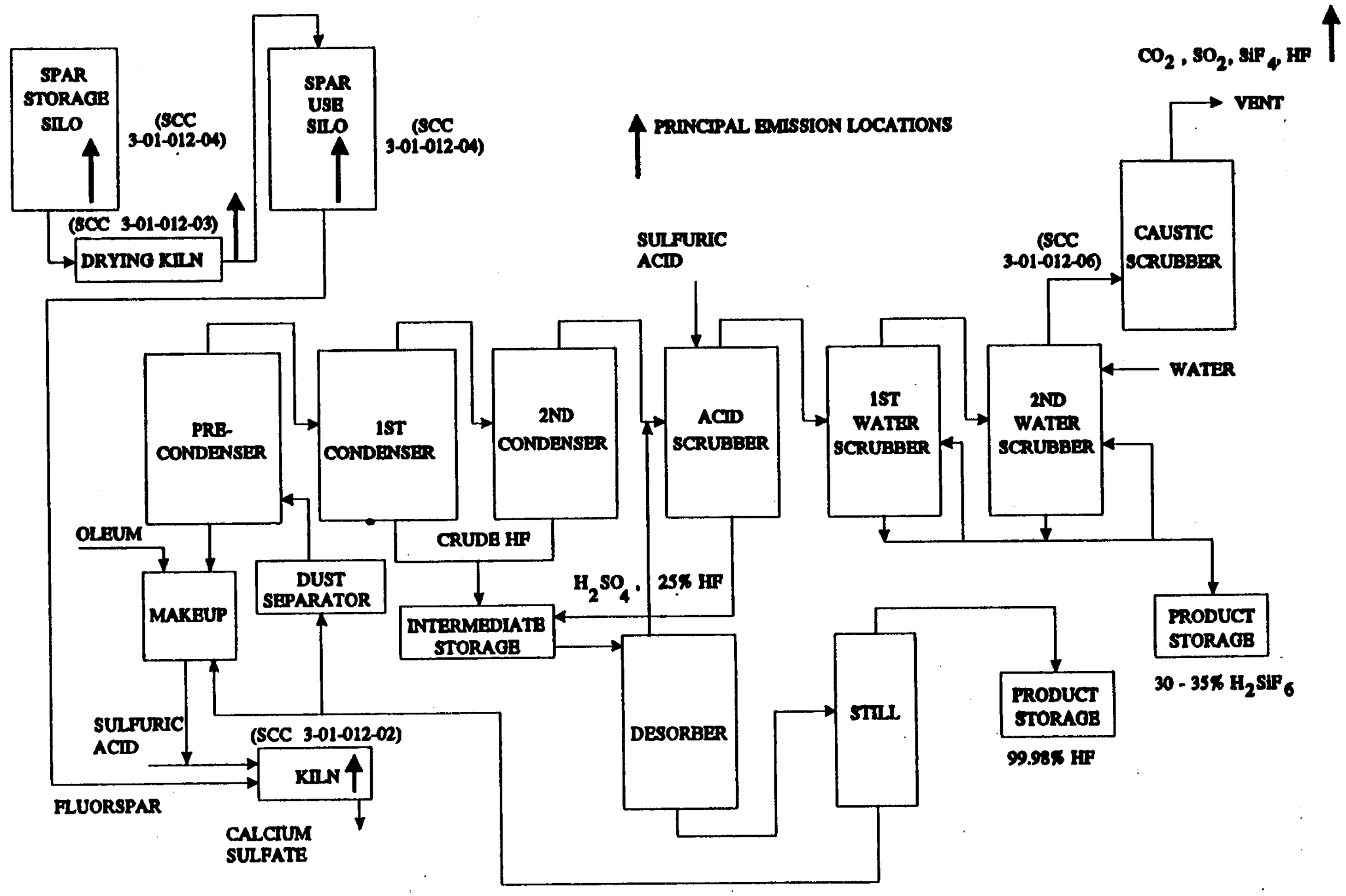

Figure 8.7-1. Hydrofluoric acid process flow diagram.
(Source Classification Codes in parentheses.)

Table 8.7-1 (Metric Units). EMISSION FACTORS FOR HYDROFLUORIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: E

Operation And Controls	Control Efficiency (%)	Emissions	
		Gases	Particulate (Spar)
		kg/Mg Acid Produced	kg/Mg Fluorspar Produced
Spar drying[b] (SCC 3-01-012-03)			
Uncontrolled	0	ND	37.5
Fabric filter	99	ND	0.4
Spar handling silos[c] (SCC 3-01-012-04)			
Uncontrolled	0	NA	30.0
Fabric filter	99	NA	0.3
Transfer operations (SCC 3-01-012-05)			
Uncontrolled	0	NA	
Covers, additives	80	NA	3.0
			0.6
Tailgas[d] (SCC 3-01-012-06)			
Uncontrolled	0	12.5 (HF)	ND
		15.0 (SiF_4)	ND
		22.5 (SO_2)	ND
Caustic scrubber	99	0.1 (HF)	ND
		0.2 (SiF_4)	ND
		0.3 (SO_2)	ND

[a] SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 1. Averaged from information provided by 4 plants. Hourly fluorspar input calculated from reported 1975 year capacity, assuming stoichiometric amount of calcium fluoride and 97.5% content in fluorspar. Hourly emission rates calculated from reported baghouse controlled rates. Values averaged are as follows:

Plant	1975 HF Capacity (Mg)	Emissions Fluorspar (kg/Mg)
1	13,600	53
2	18,100	65
3	45,400	21
4	10,000	15

[c] Reference 1. Four plants averaged for silo emissions, 2 plants for transfer operations emissions.

[d] Three plants averaged from Reference 1. Hydrogen fluoride and SiF_4 factors from Reference 4.

Table 8.7-2 (English Units). EMISSION FACTORS FOR HYDROFLUORIC ACID MANUFACTURE[a]

EMISSION FACTOR RATING: E

Operation And Control	Control Efficiency (%)	Emissions	
		Gases	Particulate (Spar)
		lb/ton Acid Produced	lb/ton Fluorspar Produced
Spar drying[b] (SCC 3-01-012-03)			
Uncontrolled	0	ND	75.0
Fabric filter	99	ND	0.8
Spar handling silos[c] (SCC 3-01-012-04)			
Uncontrolled	0	NA	60.0
Fabric Filter	99	NA	0.6
Transfer operations (SCC 3-01-012-05)			
Uncontrolled	0	NA	6.0
Covers, additives	80	NA	1.2
Tailgas[d] (SCC 3-01-012-06)			
Uncontrolled	0	25.0 (HF)	ND
		30.0 (SiF_4)	ND
		45.0 (SO_2)	ND
Caustic scrubber	99	0.2 (HF)	ND
		0.3 (SiF_4)	ND
		0.5 (SO_2)	ND

[a] SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 1. Averaged from information provided by 4 plants. Hourly fluorspar input calculated from reported 1975 year capacity, assuming stoichiometric amount of calcium fluoride and 97.5% content in fluorspar. Hourly emission rates calculated from reported baghouse controlled rates. Values averaged are as follows:

Plant	1975 HF Capacity (tons)	Emissions Fluorspar (lb/ton)
1	15,000	106
2	20,000	130
3	50,000	42
4	11,000	30

[c] Reference 1. Four plants averaged for silo emissions, 2 plants for transfer operations emissions.

[d] Three plants averaged from Reference 1. Hydrogen fluoride and SiF_4 factors from Reference 4.

in the gas stream is controlled by a dust separator near the outlet of the kiln and is recycled to the kiln for further processing. The precondenser removes water vapor and sulfuric acid mist, and the condensers, acid scrubber, and water scrubbers remove all but small amounts of HF, SiF_4, SO_2, and CO_2 from the tailgas. A caustic scrubber is employed to further reduce the levels of these pollutants in the tailgas.

Particulates are emitted during handling and drying of the fluorspar. They are controlled with bag filters at the spar silos and drying kilns. Fugitive dust emissions from spar handling and storage are controlled with flexible coverings and chemical additives.

Hydrogen fluoride emissions are minimized by maintaining a slight negative pressure in the kiln during normal operations. Under upset conditions, a standby caustic scrubber or a bypass to the tail caustic scrubber are used to control HF emissions from the kiln.

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1. *Screening Study On Feasibility Of Standards Of Performance For Hydrofluoric Acid Manufacture*, EPA-450/3-78-109, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1978.

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8.8 Nitric Acid

8.8.1 General[1-2]

In 1991, there were approximately 65 nitric acid (HNO_3) manufacturing plants in the U. S. with a total capacity of 10 million megagrams (Mg) (11 million tons) of acid per year. The plants range in size from 5,400 to 635,000 Mg (6,000 to 700,000 tons) per year. About 70 percent of the nitric acid produced is consumed as an intermediate in the manufacture of ammonium nitrate (NH_4NO_3), which in turn is used in fertilizers. The majority of the nitric acid plants are located in agricultural regions such as the Midwest, South Central, and Gulf States in order to accommodate the high concentration of fertilizer use. Another 5 to 10 percent of the nitric acid produced is used for organic oxidation in adipic acid manufacturing. Nitric acid is also used in organic oxidation to manufacture terephthalic acid and other organic compounds. Explosive manufacturing utilizes nitric acid for organic nitrations. Nitric acid nitrations are used in producing nitrobenzene, dinitrotoluenes, and other chemical intermediates.[1] Other end uses of nitric acid are gold and silver separation, military munitions, steel and brass pickling, photoengraving, and acidulation of phosphate rock.

8.8.2 Process Description[1,3-4]

Nitric acid is produced by 2 methods. The first method utilizes oxidation, condensation, and absorption to produce a weak nitric acid. Weak nitric acid can have concentrations ranging from 30 to 70 percent nitric acid. The second method combines dehydrating, bleaching, condensing, and absorption to produce a high-strength nitric acid from a weak nitric acid. High-strength nitric acid generally contains more than 90 percent nitric acid. The following text provides more specific details for each of these processes.

8.8.2.1 Weak Nitric Acid Production[1,3-4] -

Nearly all the nitric acid produced in the U. S. is manufactured by the high-temperature catalytic oxidation of ammonia as shown schematically in Figure 8.8-1. This process typically consists of 3 steps: (1) ammonia oxidation, (2) nitric oxide oxidation, and (3) absorption. Each step corresponds to a distinct chemical reaction.

Ammonia Oxidation -

First, a 1:9 ammonia/air mixture is oxidized at a temperature of 750 to 800°C (1380 to 1470°F) as it passes through a catalytic convertor, according to the following reaction:

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O \qquad (1)$$

The most commonly used catalyst is made of 90 percent platinum and 10 percent rhodium gauze constructed from squares of fine wire. Under these conditions the oxidation of ammonia to nitric oxide (NO) proceeds in an exothermic reaction with a range of 93 to 98 percent yield. Oxidation temperatures can vary from 750 to 900°C (1380 to 1650°F). Higher catalyst temperatures increase reaction selectivity toward NO production. Lower catalyst temperatures tend to be more selective toward less useful products; nitrogen (N_2) and nitrous oxide (N_2O). Nitric oxide is considered to be a criteria pollutant and nitrous oxide is known to be a global warming gas. The nitrogen dioxide/dimer mixture then passes through a waste heat boiler and a platinum filter.

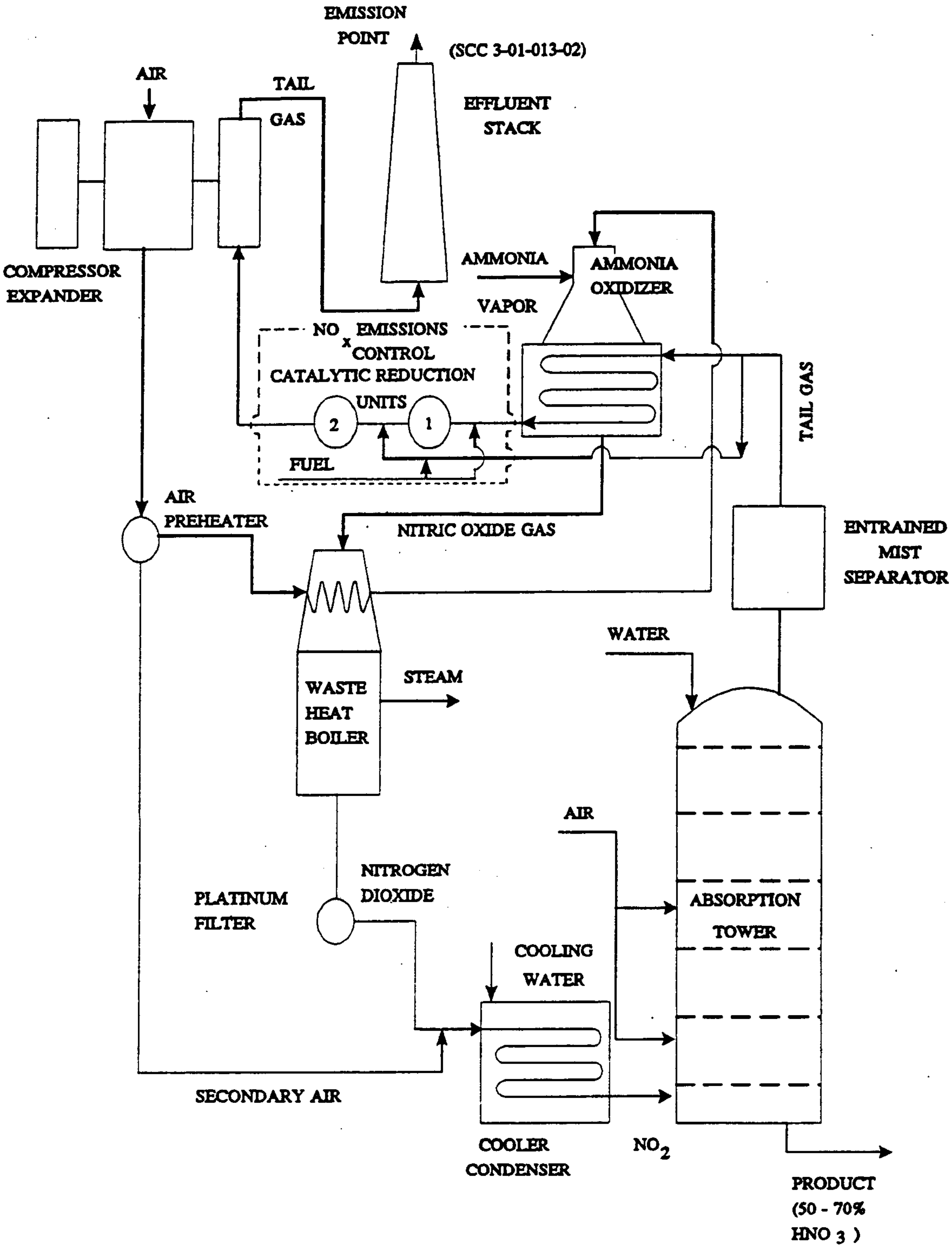

Figure 8.8-1. Flow diagram of typical nitric acid plant using single-pressure process (high-strength acid unit not shown).
(Source Classification Codes in parentheses.)

Nitric Oxide Oxidation -

The nitric oxide formed during the ammonia oxidation must be oxidized. The process stream is passed through a cooler/condenser and cooled to 38°C (100°F) or less at pressures up to 800 kilopascals (kPa) (116 pounds per square inch absolute [psia]). The nitric oxide reacts noncatalytically with residual oxygen to form nitrogen dioxide (NO_2) and its liquid dimer, nitrogen tetroxide:

$$2NO + O_2 \rightarrow 2NO_2 \leftrightharpoons N_2O_4 \qquad (2)$$

This slow, homogeneous reaction is highly temperature and pressure dependent. Operating at low temperatures and high pressures promotes maximum production of NO_2 within a minimum reaction time.

Absorption -

The final step introduces the nitrogen dioxide/dimer mixture into an absorption process after being cooled. The mixture is pumped into the bottom of the absorption tower, while liquid dinitrogen tetroxide is added at a higher point. Deionized process water enters the top of the column. Both liquids flow countercurrent to the nitrogen dioxide/dimer gas mixture. Oxidation takes place in the free space between the trays, while absorption occurs on the trays. The absorption trays are usually sieve or bubble cap trays. The exothermic reaction occurs as follows:

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO \qquad (3)$$

A secondary air stream is introduced into the column to re-oxidize the NO that is formed in Reaction 3. This secondary air also removes NO_2 from the product acid. An aqueous solution of 55 to 65 percent (typically) nitric acid is withdrawn from the bottom of the tower. The acid concentration can vary from 30 to 70 percent nitric acid. The acid concentration depends upon the temperature, pressure, number of absorption stages, and concentration of nitrogen oxides entering the absorber.

There are 2 basic types of systems used to produce weak nitric acid: (1) single-stage pressure process, and (2) dual-stage pressure process. In the past, nitric acid plants have been operated at a single pressure, ranging from atmospheric pressure to 1400 kPa (14.7 to 203 psia). However, since Reaction 1 is favored by low pressures and Reactions 2 and 3 are favored by higher pressures, newer plants tend to operate a dual-stage pressure system, incorporating a compressor between the ammonia oxidizer and the condenser. The oxidation reaction is carried out at pressures from slightly negative to about 400 kPa (58 psia), and the absorption reactions are carried out at 800 to 1,400 kPa (116 to 203 psia).

In the dual-stage pressure system, the nitric acid formed in the absorber (bottoms) is usually sent to an external bleacher where air is used to remove (bleach) any dissolved oxides of nitrogen. The bleacher gases are then compressed and passed through the absorber. The absorber tail gas (distillate) is sent to an entrainment separator for acid mist removal. Next, the tail gas is reheated in the ammonia oxidation heat exchanger to approximately 200°C (392°F). The final step expands the gas in the power-recovery turbine. The thermal energy produced in this turbine can be used to drive the compressor.

8.8.2.2 High-Strength Nitric Acid Production[1,3] -

A high-strength nitric acid (98 to 99 percent concentration) can be obtained by concentrating the weak nitric acid (30 to 70 percent concentration) using extractive distillation. The weak nitric acid cannot be concentrated by simple fractional distillation. The distillation must be carried out in the presence of a dehydrating agent. Concentrated sulfuric acid (typically 60 percent sulfuric acid) is most commonly used for this purpose. The nitric acid concentration process consists of feeding strong sulfuric acid and 55 to 65 percent nitric acid to the top of a packed dehydrating column at approximately atmospheric pressure. The acid mixture flows downward, countercurrent to ascending vapors. Concentrated nitric acid leaves the top of the column as 99 percent vapor, containing a small amount of NO_2 and oxygen (O_2) resulting from dissociation of nitric acid. The concentrated acid vapor leaves the column and goes to a bleacher and a countercurrent condenser system to effect the condensation of strong nitric acid and the separation of oxygen and oxides of nitrogen (NO_x) byproducts. These byproducts then flow to an absorption column where the nitric oxide mixes with auxiliary air to form NO_2, which is recovered as weak nitric acid. Inert and unreacted gases are vented to the atmosphere from the top of the absorption column. Emissions from this process are relatively minor. A small absorber can be used to recover NO_2. Figure 8.8-2 presents a flow diagram of high-strength nitric acid production from weak nitric acid.

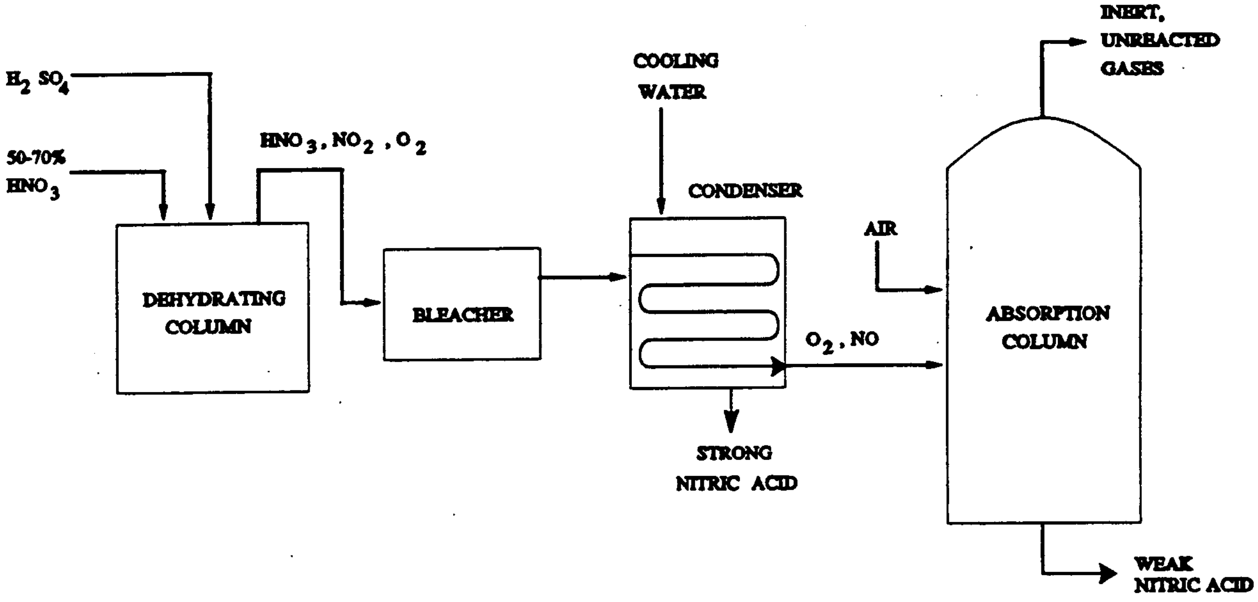

Figure 8.8-2. Flow diagram of high-strength nitric acid production from weak nitric acid.

8.8.3 Emissions And Controls[3-5]

Emissions from nitric acid manufacture consist primarily of NO, NO_2 (which account for visible emissions), trace amounts of HNO_3 mist, and ammonia (NH_3). By far, the major source of nitrogen oxides (NO_x) is the tailgas from the acid absorption tower. In general, the quantity of NO_x emissions is directly related to the kinetics of the nitric acid formation reaction and absorption tower design. NO_x emissions can increase when there is (1) insuffficient air supply to the oxidizer and absorber, (2) low pressure, especially in the absorber, (3) high temperatures in the cooler-condenser and absorber, (4) production of an excessively high-strength product acid, (5) operation at high throughput rates, and (6) faulty equipment such as compressors or pumps that lead to lower pressures and leaks, and decrease plant efficiency.

The 2 most common techniques used to control absorption tower tail gas emissions are extended absorption and catalytic reduction. Extended absorption reduces NO_x emissions by increasing the efficiency of the existing process absorption tower or incorporating an additional absorption tower. An efficiency increase is achieved by increasing the number of absorber trays, operating the absorber at higher pressures, or cooling the weak acid liquid in the absorber. The existing tower can also be replaced with a single tower of a larger diameter and/or additional trays. See Reference 5 for the relevant equations.

In the catalytic reduction process (often termed catalytic oxidation or incineration), tail gases from the absorption tower are heated to ignition temperature, mixed with fuel (natural gas, hydrogen, propane, butane, naphtha, carbon monoxide, or ammonia) and passed over a catalyst bed. In the presence of the catalyst, the fuels are oxidized and the NO_x are reduced to N_2. The extent of reduction of NO_2 and NO to N_2 is a function of plant design, fuel type, operating temperature and pressure, space velocity through the reduction catalytic reactor, type of catalyst, and reactant concentration. Catalytic reduction can be used in conjunction with other NO_x emission controls. Other advantages include the capability to operate at any pressure and the option of heat recovery to provide energy for process compression as well as extra steam. Catalytic reduction can achieve greater NO_x reduction than extended absorption. However, high fuel costs have caused a decline in its use.

Two seldom used alternative control devices for absorber tailgas are molecular sieves and wet scrubbers. In the molecular sieve adsorption technique, tailgas is contacted with an active molecular sieve that catalytically oxidizes NO to NO_2 and selectively adsorbs the NO_2. The NO_2 is then thermally stripped from the molecular sieve and returned to the absorber. Molecular sieve adsorption has successfully controlled NO_x emissions in existing plants. However, many new plants do not install this method of control. Its implementation incurs high capital and energy costs. Molecular sieve adsorption is a cyclic system, whereas most new nitric acid plants are continuous systems. Sieve bed fouling can also cause problems.

Wet scrubbers use an aqueous solution of alkali hydroxides or carbonates, ammonia, urea, potassium permanganate, or caustic chemicals to "scrub" NO_x from the absorber tailgas. The NO and NO_2 are absorbed and recovered as nitrate or nitrate salts. When caustic chemicals are used, the wet scrubber is referred to as a caustic scrubber. Some of the caustic chemicals used are solutions of sodium hydroxide, sodium carbonate, or other strong bases that will absorb NO_x in the form of nitrate or nitrate salts. Although caustic scrubbing can be an effective control device, it is often not used due to its incurred high costs and the necessity to treat its spent scrubbing solution.

Comparatively small amounts of nitrogen oxides are also lost from acid concentrating plants. These losses (mostly NO_2) are from the condenser system, but the emissions are small enough to be controlled easily by inexpensive absorbers.

Acid mist emissions do not occur from the tailgas of a properly operated plant. The small amounts that may be present in the absorber exit gas streams are removed by a separator or collector prior to entering the catalytic reduction unit or expander.

The acid production system and storage tanks are the only significant sources of visible emissions at most nitric acid plants. Emissions from acid storage tanks may occur during tank filling.

Nitrogen oxides emission factors shown in Table 8.8-1 vary considerably with the type of control employed and with process conditions. For comparison purposes, the New Source Performance Standard on nitrogen emissions expressed as NO_2 for both new and modified plants is 1.5 kilograms (kg) of NO_2 emitted per Mg (3.0 pounds/ton [lb/ton]) of 100 percent nitric acid produced.

Table 8.8-1 (Metric And English Units). NITROGEN OXIDE EMISSIONS FROM NITRIC ACID PLANTS[a]

EMISSION FACTOR RATING: E

Source	Control Efficiency %	NO_x kg/Mg Nitric Acid Produced	NO_x lb/ton Nitric Acid Produced
Weak acid plant tailgas			
Uncontrolled[b,c]	0	28	57
Catalytic reduction[c]			
Natural gas[d]	99.1	0.2	0.4
Hydrogen[e]	97 - 98.5	0.4	0.8
Natural gas/hydrogen (25%/75%)[f]	98 - 98.5	0.5	0.9
Extended absorption			
Single-stage process[g]	95.8	0.95	1.9
Dual-stage process[h]		1.1	2.1
Chilled absorption and caustic scrubber[j]	ND	1.1	2.2
High-strength acid plant[k]	ND	5	10

[a] Assumes 100% acid. Production rates are in terms of total weight of product (water and acid). A plant producing 454 Mg (500 tons) per day of 55 weight % nitric acid is calculated as producing 250 Mg (275 tons)/day of 100% acid. ND = no data.

[b] Reference 6. Based on a study of 12 plants, with average production rate of 207 Mg (100% HNO_3)/day (range 50 - 680 Mg) at average rated capacity of 97% (range 72 - 100%).

[c] Single-stage pressure process.

[d] Reference 4. Fuel is assumed to be natural gas. Based on data from 7 plants, with average production rate of 309 Mg (100% HNO_3)/day (range 50 - 977 Mg).

[e] Reference 6. Based on data from 2 plants, with average production rate of 145 Mg (100% HNO_3)/day (range 109 - 190 Mg) at average rated capacity of 98% (range 95 - 100%). Average absorber exit temperature is 29°C (85°F) (range 25 - 32°C [78 - 90°F]), and the average exit pressure is 586 kPa (85 pounds per square inch gauge [psig]) (range 552 - 648 kPa [80 - 94 psig]).

[f] Reference 6. Based on data from 2 plants, with average production rate of 208 Mg (100% HNO_3)/day (range 168 - 249 Mg) at average rated capacity of 110% (range 100 - 119%). Average absorber exit temperature is 33°C (91°F) (range 28 - 37°C [83 - 98°F]), and average exit pressure is 545 kPa (79 psig) (range 545 - 552 kPa [79 - 80 psig]).

[g] Reference 4. Based on data from 5 plants, with average production rate of 492 Mg (100%HNO_3)/day (range 190 - 952 Mg).

[h] Reference 4. Based of data from 3 plants, with average production rate of 532 Mg (100% HNO_3)/day (range 286 - 850 Mg).

[j] Reference 4. Based on data from 1 plant, with a production rate of 628 Mg (100% HNO_3)/day.

[k] Reference 2. Based on data from 1 plant, with a production rate of 1.4 Mg (100% HNO_3)/hour at 100% rated capacity, of 98% nitric acid.

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8.9 Phosphoric Acid

8.9.1 General[1-2]

Phosphoric acid (H_3PO_4) is produced by 2 commercial methods: wet process and thermal process. Wet process phosphoric acid is used in fertilizer production. Thermal process phosphoric acid is of a much higher purity and is used in the manufacture of high grade chemicals, pharmaceuticals, detergents, food products, beverages, and other nonfertilizer products. In 1987, over 9 million megagrams (Mg) (9.9 million tons) of wet process phosphoric acid was produced in the form of phosphorus pentoxide (P_2O_5). Only about 363,000 Mg (400,000 tons) of P_2O_5 was produced from the thermal process. Demand for phosphoric acid has increased approximately 2.3 to 2.5 percent per year.

The production of wet process phosphoric acid generates a considerable quantity of acidic cooling water with high concentrations of phosphorus and fluoride. This excess water is collected in cooling ponds that are used to temporarily store excess precipitation for subsequent evaporation and to allow recirculation of the process water to the plant for re-use. Leachate seeping is therefore a potential source of groundwater contamination. Excess rainfall also results in water overflows from settling ponds. However, cooling water can be treated to an acceptable level of phosphorus and fluoride if discharge is necessary.

8.9.2 Process Description[3-5]

8.9.2.1 Wet Process Acid Production -

In a wet process facility (see Figure 8.9-1A and Figure 8.9-1B), phosphoric acid is produced by reacting sulfuric acid (H_2SO_4) with naturally occurring phosphate rock. The phosphate rock is dried, crushed, and then continuously fed into the reactor along with sulfuric acid. The reaction combines calcium from the phosphate rock with sulfate, forming calcium sulfate ($CaSO_4$), commonly referred to as gypsum. Gypsum is separated from the reaction solution by filtration. Facilities in the U. S. generally use a dihydrate process that produces gypsum in the form of calcium sulfate with 2 molecules of water (H_2O) ($CaSO_4 \bullet 2\ H_2O$ or calcium sulfate dihydrate). Japanese facilities use a hemihydrate process that produces calcium sulfate with a half molecule of water ($CaSO_4 \bullet \frac{1}{2}\ H_2O$). This one-step hemihydrate process has the advantage of producing wet process phosphoric acid with a higher P_2O_5 concentration and less impurities than the dihydrate process. Due to these advantages, some U. S. companies have recently converted to the hemihydrate process. However, since most wet process phosphoric acid is still produced by the dihydrate process, the hemihydrate process will not be discussed in detail here. A simplified reaction for the dihydrate process is as follow:

$$Ca_3(PO_4)_2 + 3H_2SO_4 + 6H_2O \rightarrow 2H_3PO_4 + 3[CaSO_4 \bullet 2H_2O]\downarrow \qquad (1)$$

In order to make the strongest phosphoric acid possible and to decrease evaporation costs, 93 percent sulfuric acid is normally used. Because the proper ratio of acid to rock in the reactor is critical, precise automatic process control equipment is employed in the regulation of these 2 feed streams.

During the reaction, gypsum crystals are precipitated and separated from the acid by filtration. The separated crystals must be washed thoroughly to yield at least a 99 percent recovery of the filtered phosphoric acid. After washing, the slurried gypsum is pumped into a gypsum pond for

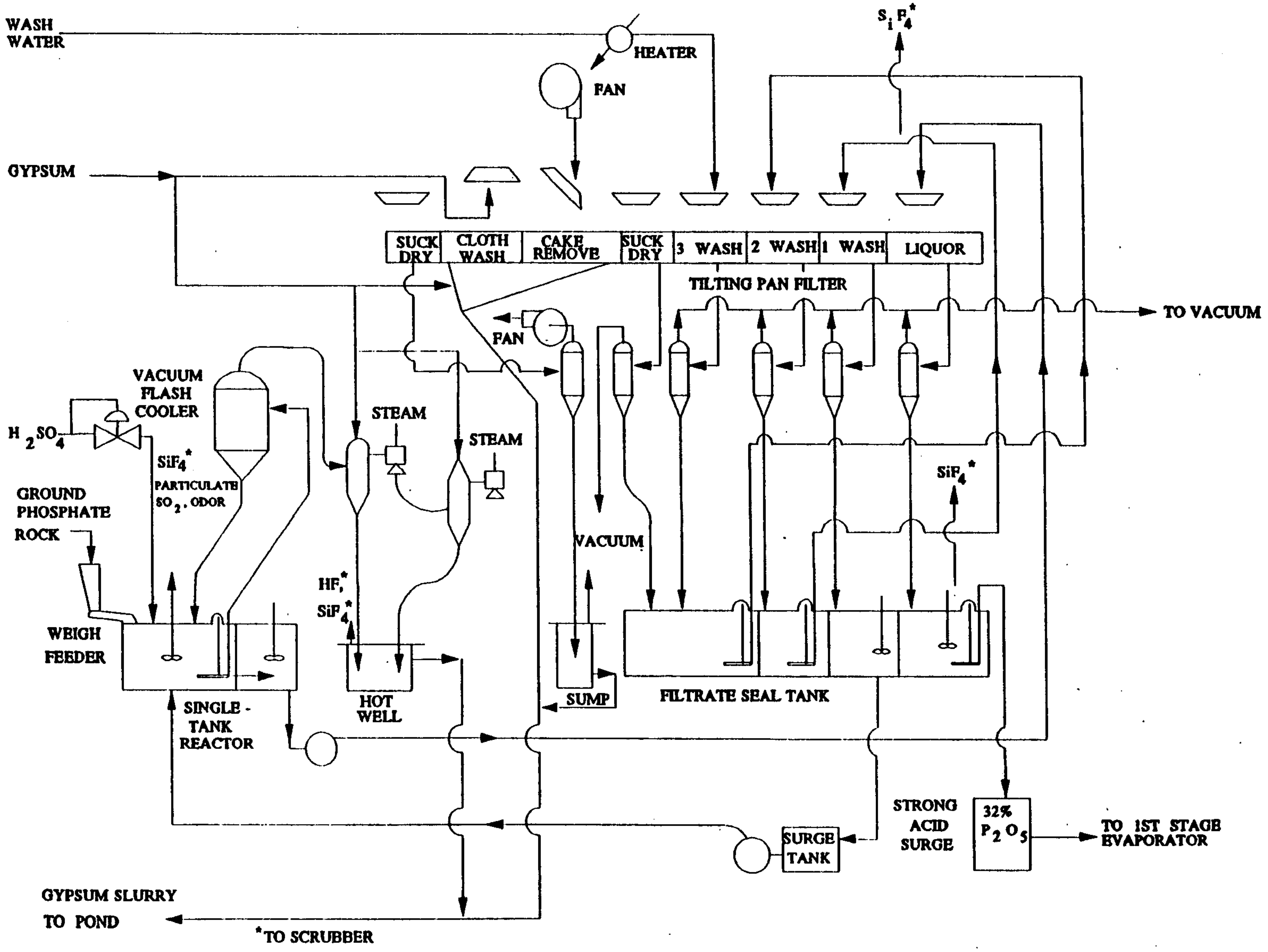

Figure 8.9-1A. Flow diagram of a wet process phosphoric acid plant.

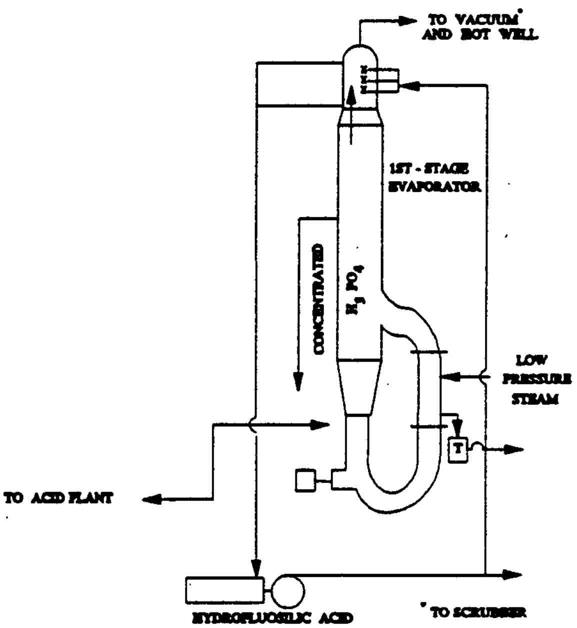

Figure 8.9-1B. Flow diagram of a wet process phosphoric acid plant (cont.).

storage. Water is syphoned off and recycled through a surge cooling pond to the phosphoric acid process. Approximately 0.3 hectares of cooling and settling pond area is required for every megagram of daily P_2O_5 capacity (0.7 acres of cooling and settling pond area for every ton of daily P_2O_5 capacity).

Considerable heat is generated in the reactor. In older plants, this heat was removed by blowing air over the hot slurry surface. Modern plants vacuum flash cool a portion of the slurry, and then recycle it back into the reactor.

Wet process phosphoric acid normally contains 26 to 30 percent P_2O_5. In most cases, the acid must be further concentrated to meet phosphate feed material specifications for fertilizer production. Depending on the types of fertilizer to be produced, phosphoric acid is usually concentrated to 40 to 55 percent P_2O_5 by using 2 or 3 vacuum evaporators.

8.9.2.2 Thermal Process Acid Production -

Raw materials for the production of phosphoric acid by the thermal process are elemental (yellow) phosphorus, air, and water. Thermal process phosphoric acid manufacture, as shown schematically in Figure 8.9-2, involves 3 major steps: (1) combustion, (2) hydration, and (3) demisting.

In combustion, the liquid elemental phosphorus is burned (oxidized) in ambient air in a combustion chamber at temperatures of 1650 to 2760°C (3000 to 5000°F) to form phosphorus pentoxide (Reaction 2). The phosphorus pentoxide is then hydrated with dilute H_3PO_4 or water to produce strong phosphoric acid liquid (Reaction 3). Demisting, the final step, removes the phosphoric acid mist from the combustion gas stream before release to the atmosphere. This is usually done with high-pressure drop demistors.

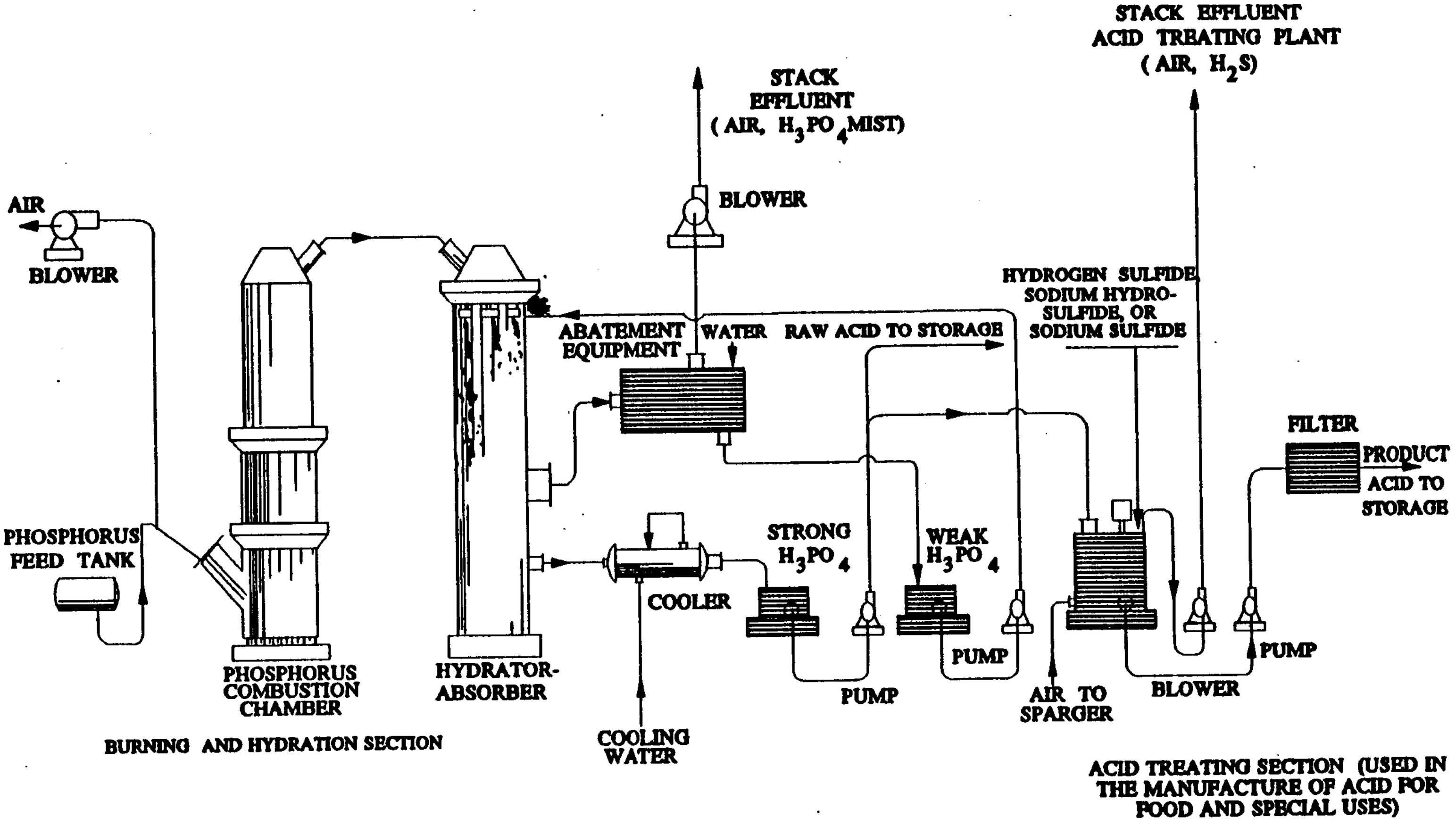

Figure 8.9-2. Flow diagram of a thermal process phosphoric acid plant.

$$P_4 + 5O_2 \rightarrow 2P_2O_5 \qquad (2)$$

$$2P_2O_5 + 6H_2O \rightarrow 4H_3PO_4 \qquad (3)$$

Concentration of H_3PO_4 produced from thermal process normally ranges from 75 to 85 percent. This high concentration is required for high grade chemical production and other nonfertilizer product manufacturing. Efficient plants recover about 99.9 percent of the elemental phosphorus burned as phosphoric acid.

8.9.3 Emissions And Controls[3-6]

Emission factors for controlled and uncontrolled wet phosphoric acid production are shown in Tables 8.9-1 and 8.9-2, respectively. Emission factors for controlled thermal phosphoric acid production are shown in Table 8.9-3.

8.9.3.1 Wet Process -

Major emissions from wet process acid production includes gaseous fluorides, mostly silicon tetrafluoride (SiF_4) and hydrogen fluoride (HF). Phosphate rock contains 3.5 to 4.0 percent fluorine. In general, part of the fluorine from the rock is precipitated out with the gypsum, another part is leached out with the phosphoric acid product, and the remaining portion is vaporized in the reactor or evaporator. The relative quantities of fluorides in the filter acid and gypsum depend on the type of rock and the operating conditions. Final disposition of the volatilized fluorine depends on the design and operation of the plant.

Scrubbers may be used to control fluorine emissions. Scrubbing systems used in phosphoric acid plants include venturi, wet cyclonic, and semi-cross-flow scrubbers. The leachate portion of the fluorine may be deposited in settling ponds. If the pond water becomes saturated with fluorides, fluorine gas may be emitted to the atmosphere.

The reactor in which phosphate rock is reacted with sulfuric acid is the main source of emissions. Fluoride emissions accompany the air used to cool the reactor slurry. Vacuum flash cooling has replaced the air cooling method to a large extent, since emissions are minimized in the closed system.

Acid concentration by evaporation is another source of fluoride emissions. Approximately 20 to 40 percent of the fluorine originally present in the rock vaporizes in this operation.

Total particulate emissions from process equipment were measured for 1 digester and for 1 filter. As much as 5.5 kilograms of particulate per megagram (kg/Mg) (11 pounds per ton [lb/ton]) of P_2O_5 were produced by the digester, and approximately 0.1 kg/Mg (0.2 lb/ton) of P_2O_5 were released by the filter. Of this particulate, 3 to 6 percent were fluorides.

Particulate emissions occurring from phosphate rock handling are discussed in Section 11.21, Phosphate Rock Processing.

8.9.3.2 Thermal Process -

The major source of emissions from the thermal process is H_3PO_4 mist contained in the gas stream from the hydrator. The particle size of the acid mist ranges from 1.4 to 2.6 micrometers. It is not uncommon for as much as half of the total P_2O_5 to be present as liquid phosphoric acid particles suspended in the gas stream. Efficient plants are economically motivated to control this potential loss

Table 8.9-1 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR WET PHOSPHORIC ACID PRODUCTION[a]

EMISSION FACTOR RATING: B (except as noted)

Source	Fluorine	
	kg/Mg P_2O_5 Produced	lb/ton P_2O_5 Produced
Reactor[b] (SCC 3-01-016-01)	1.9×10^{-3}	3.8×10^{-3}
Evaporator[c] (SCC 3-01-016-99)	0.022×10^{-3}	0.044×10^{-3}
Belt filter[c] (SCC 3-01-016-99)	0.32×10^{-3}	0.64×10^{-3}
Belt filter vacuum pump[c] (SCC 3-01-016-99)	0.073×10^{-3}	0.15×10^{-3}
Gypsum settling & cooling ponds[d,e] (SCC 3-01-016-02)	Site-specific	Site-specific

[a] SCC = Source Classification Code.
[b] References 8-13. EMISSION FACTOR RATING: A
[c] Reference 13.
[d] Reference 18. Site-specific. Acres of cooling pond required: ranges from 0.04 hectare per daily Mg (0.10 acre per daily ton) P_2O_5 produced in the summer in the southeastern U. S. to 0 in the colder locations in the winter months when the cooling ponds are frozen.
[e] Reference 19 states "Based on our findings concerning the emissions of fluoride from gypsum ponds, it was concluded than no investigator had as yet established experimentally the fluoride emission from gypsum ponds".

Table 8.9-2 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR WET PHOSPHORIC ACID PRODUCTION[a]

EMISSION FACTOR RATING: C (except as noted)

Source	Nominal Percent Control Efficiency	Fluoride	
		kg/Mg P_2O_5 Produced	lb/ton P_2O_5 Produced
Reactor[b] (SCC 3-01-016-01)	99	0.19	0.38
Evaporator[c] (SCC 3-01-016-99)	99	0.00217	0.0044
Belt filter[c] (SCC 3-01-016-99)	99	0.032	0.064
Belt filter vacuum pump[c] (SCC 3-01-016-99)	99	0.0073	0.015
Gypsum settling & cooling ponds[d,e] (SCC 3-01-016-02)	ND	Site-specific	Site-specific

[a] SCC = Source Classification Code. ND = No Data.
[b] References 8-13. EMISSION FACTOR RATING: B.
[c] Reference 13.
[d] Reference 18. Site specific. Acres of cooling pond required: ranges from 0.04 hectare per daily Mg (0.10 acre per daily ton) P_2O_5 produced in the summer in the southeastern U. S. to 0 in the colder locations in the winter months when the cooling ponds are frozen.
[e] Reference 19 states "Based on our findings concerning the emissions of fluoride from gypsum ponds, it was concluded than no investigator had as yet established experimentally the fluoride emission from gypsum ponds".

Table 8.9-3 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR THERMAL PHOSPHORIC ACID PRODUCTION[a]

EMISSION FACTOR RATING: E

Source	Nominal Percent Control Efficiency	Particulate[b]	
		kg/Mg P_2O_5 Produced	lb/ton P_2O_5 Produced
Packed tower (SCC 3-01-017-03)	95.5	1.07	2.14
Venturi scrubber (SCC 3-01-017-04)	97.5	1.27	2.53
Glass fiber mist eliminator (SCC 3-01-017-05)	96 - 99.9	0.35	0.69
Wire mesh mist eliminator (SCC 3-01-017-06)	95	2.73	5.46
High pressure drop mist (SCC 3-01-017-07)	99.9	0.06	0.11
Electrostatic precipitator (SCC 3-01-017-08)	98 - 99	0.83	1.66

[a] SCC = Source Classification Code.
[b] Reference 6.

with various control equipment. Control equipment commonly used in thermal process phosphoric acid plants includes venturi scrubbers, cyclonic separators with wire mesh mist eliminators, fiber mist eliminators, high energy wire mesh contractors, and electrostatic precipitators.

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8.10 Sulfuric Acid

8.10.1 General[1-2]

Sulfuric acid (H_2SO_4) is a basic raw material used in a wide range of industrial processes and manufacturing operations. Almost 70 percent of sulfuric acid manufactured is used in the production of phosphate fertilizers. Other uses include copper leaching, inorganic pigment production, petroleum refining, paper production, and industrial organic chemical production.

Sulfuric acid may be manufactured commercially by either the lead chamber process or the contact process. Because of economics, all of the sulfuric acid produced in the U. S. is now produced by the contact process. U. S. facilities produce approximately 42 million megagrams (Mg) (46.2 million tons) of H_2SO_4 annually. Growth in demand was about 1 percent per year from 1981 to 1991 and is projected to continue to increase at about 0.5 percent per year.

8.10.2 Process Description[3-5]

Since the contact process is the only process currently used, it will be the only one discussed in this section. Contact plants are classified according to the raw materials charged to them: elemental sulfur burning, spent sulfuric acid and hydrogen sulfide burning, and metal sulfide ores and smelter gas burning. The contributions from these plants to the total acid production are 81, 8, and 11 percent, respectively.

The contact process incorporates 3 basic operations, each of which corresponds to a distinct chemical reaction. First, the sulfur in the feedstock is oxidized (burned) to sulfur dioxide (SO_2):

$$S + O_2 \rightarrow SO_2 \qquad (1)$$

The resulting sulfur dioxide is fed to a process unit called a converter, where it is catalytically oxidized to sulfur trioxide (SO_3):

$$2SO_2 + O_2 \rightarrow 2SO_3 \qquad (2)$$

Finally, the sulfur trioxide is absorbed in a strong 98 percent sulfuric acid solution:

$$SO_3 + H_2O \rightarrow H_2SO_4 \qquad (3)$$

8.10.2.1 Elemental Sulfur Burning Plants -

Figure 8.10-1 is a schematic diagram of a dual absorption contact process sulfuric acid plant that burns elemental sulfur. In the Frasch process, elemental sulfur is melted, filtered to remove ash, and sprayed under pressure into a combustion chamber. The sulfur is burned in clean air that has been dried by scrubbing with 93 to 99 percent sulfuric acid. The gases from the combustion chamber cool by passing through a waste heat boiler and then enter the catalyst (vanadium pentoxide) converter. Usually, 95 to 98 percent of the sulfur dioxide from the combustion chamber is converted to sulfur trioxide, with an accompanying large evolution of heat. After being cooled, again by generating steam, the converter exit gas enters an absorption tower. The absorption tower is a packed column where acid is sprayed in the top and where the sulfur trioxide enters from the bottom. The

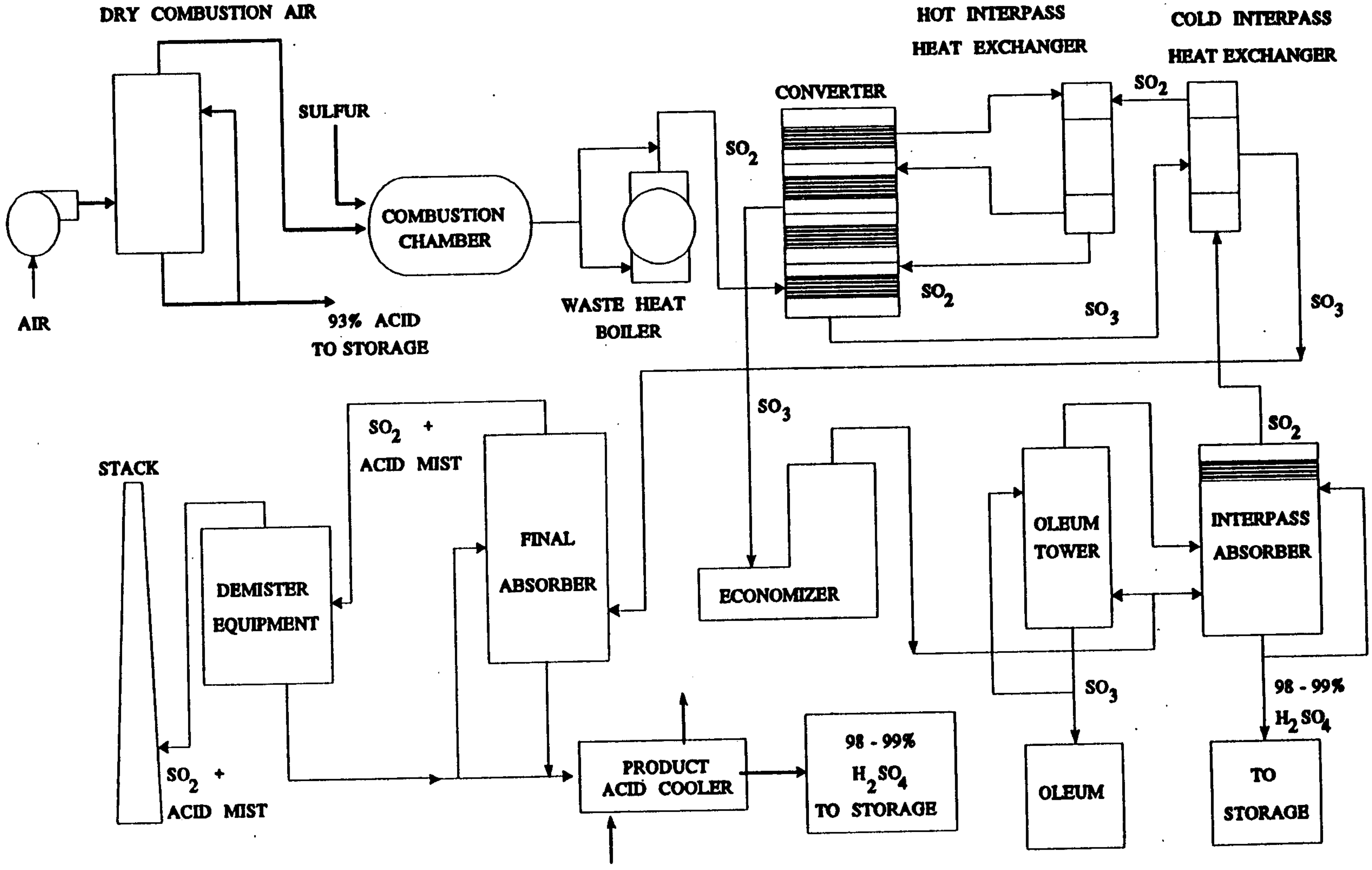

Figure 8.10-1. Typical contact process sulfuric acid plant burning elemental sulfur.

sulfur trioxide is absorbed in the 98 to 99 percent sulfuric acid. The sulfur trioxide combines with the water in the acid and forms more sulfuric acid.

If oleum (a solution of uncombined SO_3 dissolved in H_2SO_4) is produced, SO_3 from the converter is first passed to an oleum tower that is fed with 98 percent acid from the absorption system. The gases from the oleum tower are then pumped to the absorption column where the residual sulfur trioxide is removed.

In the dual absorption process shown in Figure 8.10-1, the SO_3 gas formed in the primary converter stages is sent to an interpass absorber where most of the SO_3 is removed to form H_2SO_4. The remaining unconverted sulfur dioxide is forwarded to the final stages in the converter to remove much of the remaining SO_2 by oxidation to SO_3, whence it is sent to the final absorber for removal of the remaining sulfur trioxide. The single absorption process uses only one absorber, as the name implies.

8.10.2.2 Spent Acid And Hydrogen Sulfide Burning Plants -

A schematic diagram of a contact process sulfuric acid plant that burns spent acid is shown in Figure 8.10-2. Two types of plants are used to process this type of sulfuric acid. In one, the sulfur dioxide and other products from the combustion of spent acid and/or hydrogen sulfide with undried atmospheric air are passed through gas cleaning and mist removal equipment. The gas stream next passes through a drying tower. A blower draws the gas from the drying tower and discharges the sulfur dioxide gas to the sulfur trioxide converter, then to the oleum tower and/or absorber.

In a "wet gas plant", the wet gases from the combustion chamber are charged directly to the converter, with no intermediate treatment. The gas from the converter flows to the absorber, through which 93 to 98 percent sulfuric acid is circulated.

8.10.2.3 Sulfide Ores And Smelter Gas Plants -

The configuration of this type of plant is essentially the same as that of a spent acid plant (Figure 8.10-2), with the primary exception that a roaster is used in place of the combustion furnace.

The feed used in these plants is smelter gas, available from such equipment as copper converters, reverberatory furnaces, roasters, and flash smelters. The sulfur dioxide in the gas is contaminated with dust, acid mist, and gaseous impurities. To remove the impurities, the gases must be cooled and passed through purification equipment consisting of cyclone dust collectors, electrostatic dust and mist precipitators, and scrubbing and gas cooling towers. After the gases are cleaned and the excess water vapor is removed, they are scrubbed with 98 percent acid in a drying tower. Beginning with the drying tower stage, these plants are nearly identical to the elemental sulfur plants shown in Figure 8.10-1.

8.10.3 Emissions[4,6-7]

8.10.3.1 Sulfur Dioxide -

Nearly all sulfur dioxide emissions from sulfuric acid plants are found in the exit stack gases. Extensive testing has shown that the mass of these SO_2 emissions is an inverse function of the sulfur conversion efficiency (SO_2 oxidized to SO_3). This conversion is always incomplete, and is affected by the number of stages in the catalytic converter, the amount of catalyst used, temperature and pressure, and the concentrations of the reactants (sulfur dioxide and oxygen). For example, if the inlet SO_2 concentration to the converter were 9 percent by volume (a representative value), and the conversion temperature was 430°C (806°F), the conversion efficiency would be 98 percent. At this conversion, Table 8.10-1 shows that the uncontrolled emission factor for SO_2 would be 13 kilograms

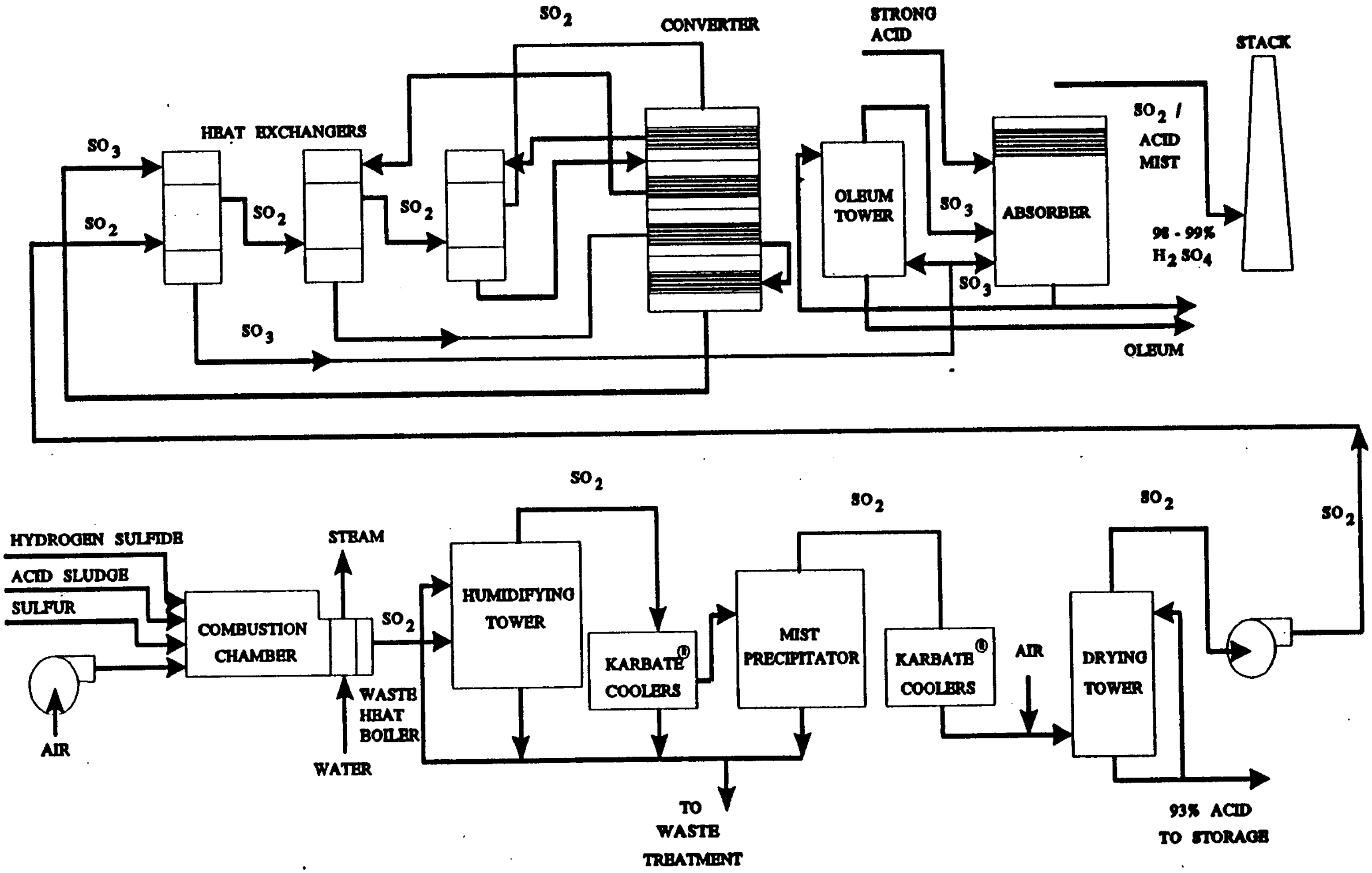

Figure 8.10-2. Basic flow diagram of contact process sulfuric acid plant burning spent acid.

per megagram (kg/Mg) (26 pounds per ton [lb/ton]) of 100 percent sulfuric acid produced. (For purposes of comparison, note that the Agency's new source performance standard [NSPS] for new and modified plants is 2 kg/Mg (4 lb/ton) of 100 percent acid produced, maximum 2 hour average.) As Table 8.10-1 and Figure 8.10-3 indicate, achieving this standard requires a conversion efficiency of 99.7 percent in an uncontrolled plant, or the equivalent SO_2 collection mechanism in a controlled facility.

Dual absorption, as discussed above, has generally been accepted as the best available control technology for meeting NSPS emission limits. There are no byproducts or waste scrubbing materials created, only additional sulfuric acid. Conversion efficiencies of 99.7 percent and higher are achievable, whereas most single absorption plants have SO_2 conversion efficiencies ranging only from 95 to 98 percent. Furthermore, dual absorption permits higher converter inlet sulfur dioxide concentrations than are used in single absorption plants, because the final conversion stages effectively remove any residual sulfur dioxide from the interpass absorber.

In addition to exit gases, small quantities of sulfur oxides are emitted from storage tank vents and tank car and tank truck vents during loading operations, from sulfuric acid concentrators, and through leaks in process equipment. Few data are available on the quantity of emissions from these sources.

Table 8.10-1 (Metric And English Units). SULFUR DIOXIDE EMISSION FACTORS FOR SULFURIC ACID PLANTS[a]

EMISSION FACTOR RATING: E

SO_2 To SO_3 Conversion Efficiency (%)	SO_2 Emissions[b]	
	kg/Mg Of Product	lb/ton Of Product
93 (SCC 3-01-023-18)	48.0	96
94 (SCC 3-01-023-16)	41.0	82
95 (SCC 3-01-023-14)	35.0	70
96 (SCC 3-01-023-12)	27.5	55
97 (SCC 3-01-023-10)	20.0	40
98 (SCC 3-01-023-08)	13.0	26
99 (SCC 3-01-023-06)	7.0	14
99.5 (SCC 3-01-023-04)	3.5	7
99.7 NA	2.0	4
100 (SCC 3-01-023-01)	0.0	0.0

[a] Reference 3. SCC = Source Classification Code. NA = not applicable.

[b] This linear interpolation formula can be used for calculating emission factors for conversion efficiencies between 93 and 100%: emission factor (kg/Mg of Product) = 682 - 6.82 (% conversion efficiency) (emission factor [lb/ton of Product] = 1365 - 13.65 [% conversion efficiency]).

8.10.3.2 Acid Mist -

Nearly all the acid mist emitted from sulfuric acid manufacturing can be traced to the absorber exit gases. Acid mist is created when sulfur trioxide combines with water vapor at a

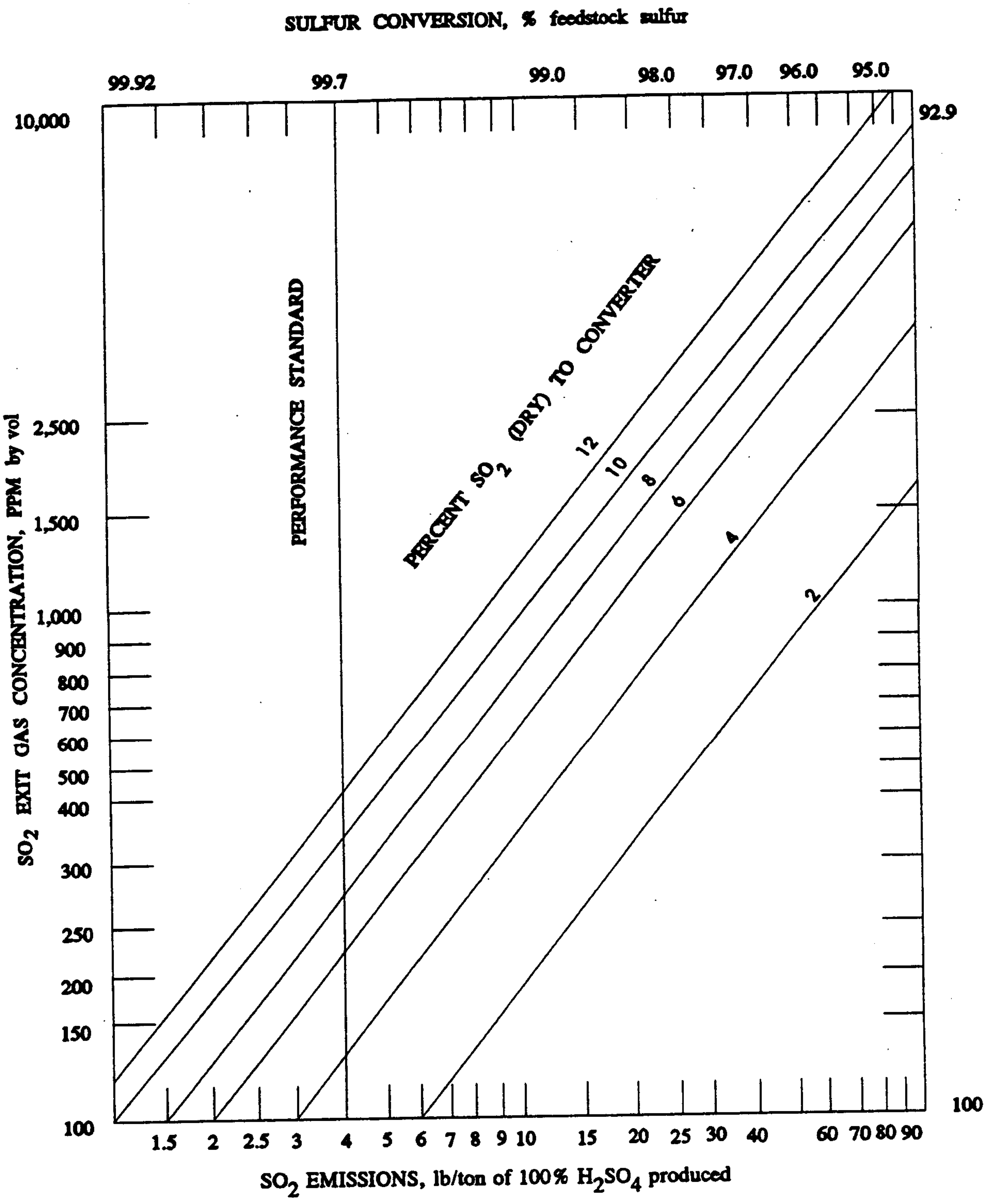

Figure 8.10-3. Sulfuric acid plant feedstock conversion versus volumetric and mass SO_2 emissions at various inlet SO_2 concentrations by volume.

temperature below the dew point of sulfur trioxide. Once formed within the process system, this mist is so stable that only a small quantity can be removed in the absorber.

In general, the quantity and particle size distribution of acid mist are dependent on the type of sulfur feedstock used, the strength of acid produced, and the conditions in the absorber. Because it contains virtually no water vapor, bright elemental sulfur produces little acid mist when burned. However, the hydrocarbon impurities in other feedstocks (i. e., dark sulfur, spent acid, and hydrogen sulfide) oxidize to water vapor during combustion. The water vapor, in turn, combines with sulfur trioxide as the gas cools in the system.

The strength of acid produced, whether oleum or 99 percent sulfuric acid, also affects mist emissions. Oleum plants produce greater quantities of finer, more stable mist. For example, an unpublished report found that uncontrolled mist emissions from oleum plants burning spent acid range from 0.5 to 5.0 kg/Mg (1.0 to 10.0 lb/ton), while those from 98 percent acid plants burning elemental sulfur range from 0.2 to 2.0 kg/Mg (0.4 to 4.0 lb/ton).[4] Furthermore, 85 to 95 weight percent of the mist particles from oleum plants are less than 2 micrometers (μm) in diameter, compared with only 30 weight percent that are less than 2 μm in diameter from 98 percent acid plants.

The operating temperature of the absorption column directly affects sulfur trioxide absorption and, accordingly, the quality of acid mist formed after exit gases leave the stack. The optimum absorber operating temperature depends on the strength of the acid produced, throughput rates, inlet sulfur trioxide concentrations, and other variables peculiar to each individual plant. Finally, it should be emphasized that the percentage conversion of sulfur trioxide has no direct effect on acid mist emissions.

Table 8.10-2 presents uncontrolled acid mist emission factors for various sulfuric acid plants. Table 8.10-3 shows emission factors for plants that use fiber mist eliminator control devices. The 3 most commonly used fiber mist eliminators are the vertical tube, vertical panel, and horizontal dual pad types. They differ from one another in the arrangement of the fiber elements, which are composed of either chemically resistant glass or fluorocarbon, and in the means employed to collect the trapped liquid. Data are available only with percent oleum ranges for 2 raw material categories.

8.10.3.3 Carbon Dioxide -

The 9 source tests mentioned above were also used to determine the amount of carbon dioxide (CO_2), a global warming gas, emitted by sulfuric acid production facilities. Based on the tests, a CO_2 emission factor of 4.05 kg emitted per Mg produced (8.10 lb/ton) was developed, with an emission factor rating of C.

Table 8.10-2 (Metric And English Units). UNCONTROLLED ACID MIST EMISSION FACTORS FOR SULFURIC ACID PLANTS[a]

EMISSION FACTOR RATING: E

Raw Material	Oleum Produced, % Total Output	Emissions[b]	
		kg/Mg Of Product	lb/ton Of Product
Recovered sulfur (SCC 3-01-023-22)	0 - 43	0.174 - 0.4	0.348 - 0.8
Bright virgin sulfur (SCC 3-01-023-22)	0	0.85	1.7
Dark virgin sulfur (SCC 3-01-023-22)	0 - 100	0.16 - 3.14	0.32 - 6.28
Spent acid (SCC 3-01-023-22)	0 - 77	1.1 - 1.2	2.2 - 2.4

[a] Reference 3. SCC = Source Classification Code.

[b] Emissions are proportional to the percentage of oleum in the total product. Use low end of ranges for low oleum percentage and high end of ranges for high oleum percentage.

Table 8.10-3 (Metric And English Units). CONTROLLED ACID MIST EMISSION FACTORS FOR SULFURIC ACID PLANTS

EMISSION FACTOR RATING: E (except as noted)

Raw Material	Oleum Produced, % Total Output	Emissions	
		kg/Mg Of Product	lb/ton Of Product
Elemental sulfur[a] (SCC 3-01-023-22)	—	0.064	0.128
Dark virgin sulfur[b] (SCC 3-01-023-22)	0 - 13	0.26 - 1.8	0.52 - 3.6
Spent acid (SCC 3-01-023-22)	0 - 56	0.014 - 0.20	0.28 - 0.40

[a] References 8-13,15-17. EMISSION FACTOR RATING: C. SCC = Source Classification Code.

[b] Reference 3.

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8.11 Chlor-Alkali

8.11.1 General[1-2]

The chlor-alkali electrolysis process is used in the manufacture of chlorine, hydrogen, and sodium hydroxide (caustic) solution. Of these 3, the primary product is chlorine.

Chlorine is 1 of the more abundant chemicals produced by industry and has a wide variety of industrial uses. Chlorine was first used to produce bleaching agents for the textile and paper industries and for general cleaning and disinfecting. Since 1950, chlorine has become increasingly important as a raw material for synthetic organic chemistry. Chlorine is an essential component of construction materials, solvents, and insecticides. Annual production from U. S. facilities was 9.9 million megagrams (Mg) (10.9 million tons) in 1990 after peaking at 10.4 million Mg (11.4 million tons) in 1989.

8.11.2 Process Description[1-3]

There are 3 types of electrolytic processes used in the production of chlorine: (1) the diaphragm cell process, (2) the mercury cell process, and (3) the membrane cell process. In each process, a salt solution is electrolyzed by the action of direct electric current that converts chloride ions to elemental chlorine. The overall process reaction is:

$$2NaCl + 2H_2O \rightarrow Cl_2 + H_2 + 2NaOH$$

In all 3 methods, the chlorine (Cl_2) is produced at the positive electrode (anode) and the caustic soda (NaOH) and hydrogen (H_2) are produced, directly or indirectly, at the negative electrode (cathode). The 3 processes differ in the method by which the anode products are kept separate from the cathode products.

Of the chlorine produced in the U. S. in 1989, 94 percent was produced either by the diaphragm cell or mercury cell process. Therefore, these will be the only 2 processes discussed in this section.

8.11.2.1 Diaphragm Cell -

Figure 8.11-1 shows a simplified block diagram of the diaphragm cell process. Water (H_2O) and sodium chloride (NaCl) are combined to create the starting brine solution. The brine undergoes precipitation and filtration to remove impurities. Heat is applied and more salt is added. Then the nearly saturated, purified brine is heated again before direct electric current is applied. The anode is separated from the cathode by a permeable asbestos-based diaphragm to prevent the caustic soda from reacting with the chlorine. The chlorine produced at the anode is removed, and the saturated brine flows through the diaphragm to the cathode chamber. The chlorine is then purified by liquefaction and evaporation to yield a pure liquified product.

The caustic brine produced at the cathode is separated from salt and concentrated in an elaborate evaporative process to produce commercial caustic soda. The salt is recycled to saturate the

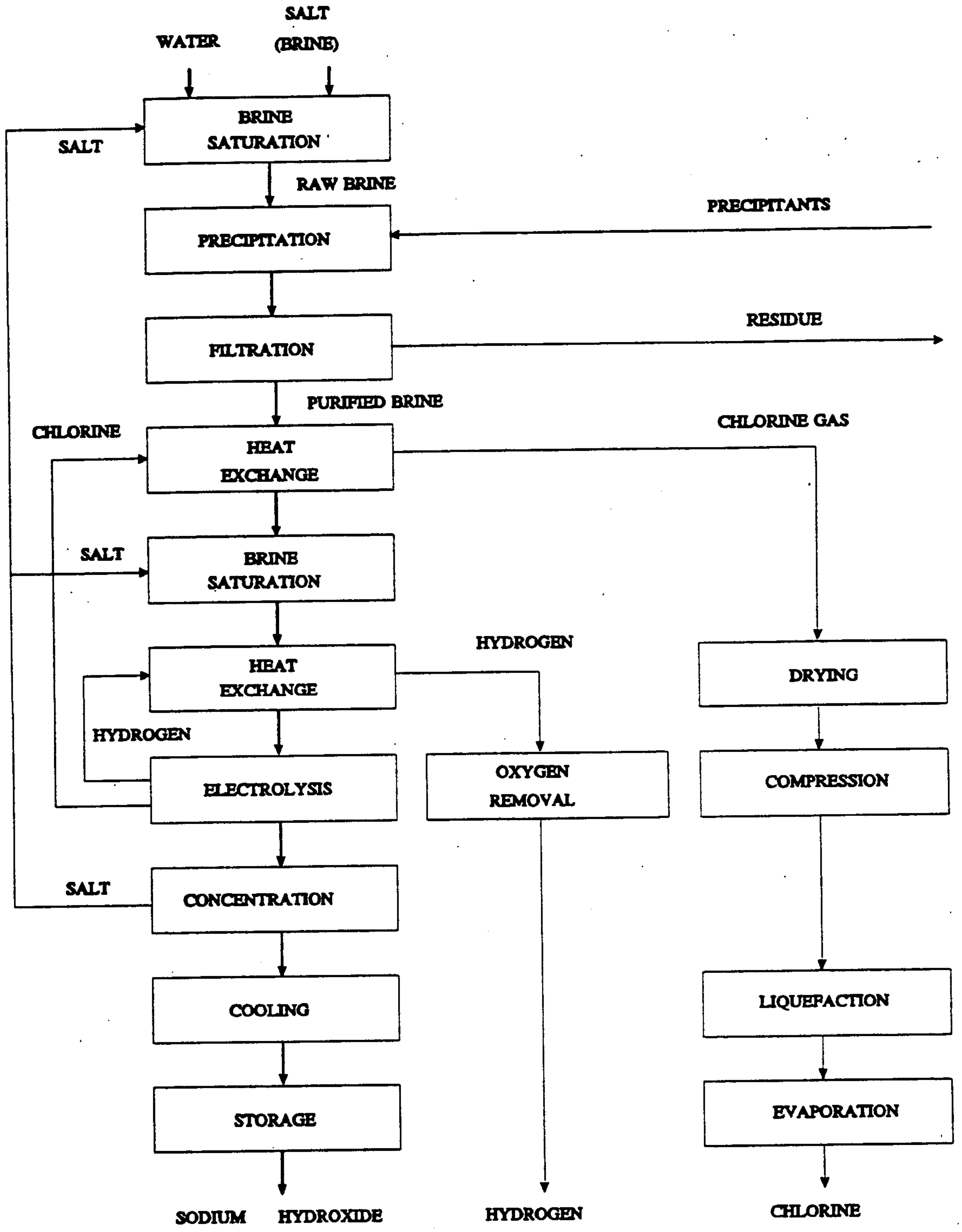

Figure 8.11-1. Simplified diagram of the diaphragm cell process.

dilute brine. The hydrogen removed in the cathode chamber is cooled and purified by removal of oxygen, then used in other plant processes or sold.

8.11.2.2 Mercury Cell -

Figure 8.11-2 shows a simplified block diagram for the mercury cell process. The recycled brine from the electrolysis process (anolyte) is dechlorinated and purified by a precipitation-filtration process. The liquid mercury cathode and the brine enter the cell flowing concurrently. The electrolysis process creates chlorine at the anode and elemental sodium at the cathode. The chlorine is removed from the anode, cooled, dried, and compressed. The sodium combines with mercury to form a sodium amalgam. The amalgam is further reacted with water in a separate reactor called the decomposer to produce hydrogen gas and caustic soda solution. The caustic and hydrogen are then separately cooled and the mercury is removed before proceeding to storage, sales, or other processes.

8.11.3 Emissions And Controls[4]

Tables 8.11-1 and 8.11-2 are is a summaries of chlorine emission factors for chlor-alkali plants. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton). Emissions from diaphragm and mercury cell plants include chlorine gas, carbon dioxide (CO_2), carbon monoxide (CO), and hydrogen. Gaseous chlorine is present in the blow gas from liquefaction, from vents in tank cars and tank containers during loading and unloading, and from storage tanks and process transfer tanks. Carbon dioxide emissions result from the decomposition of carbonates in the brine feed when contacted with acid. Carbon monoxide and hydrogen are created by side reactions within the production cell. Other emissions include mercury vapor from mercury cathode cells and chlorine from compressor seals, header seals, and the air blowing of depleted brine in mercury-cell plants. Emissions from these locations are, for the most part, controlled through the use of the gas in other parts of the plant, neutralization in alkaline scrubbers, or recovery of the chlorine from effluent gas streams.

Table 8.11-3 presents mercury emission factors based on 2 source tests used to substantiate the mercury national emission standard for hazardous air pollutants. Due to insufficient data, emission factors for CO, CO_2, and hydrogen are not presented here.

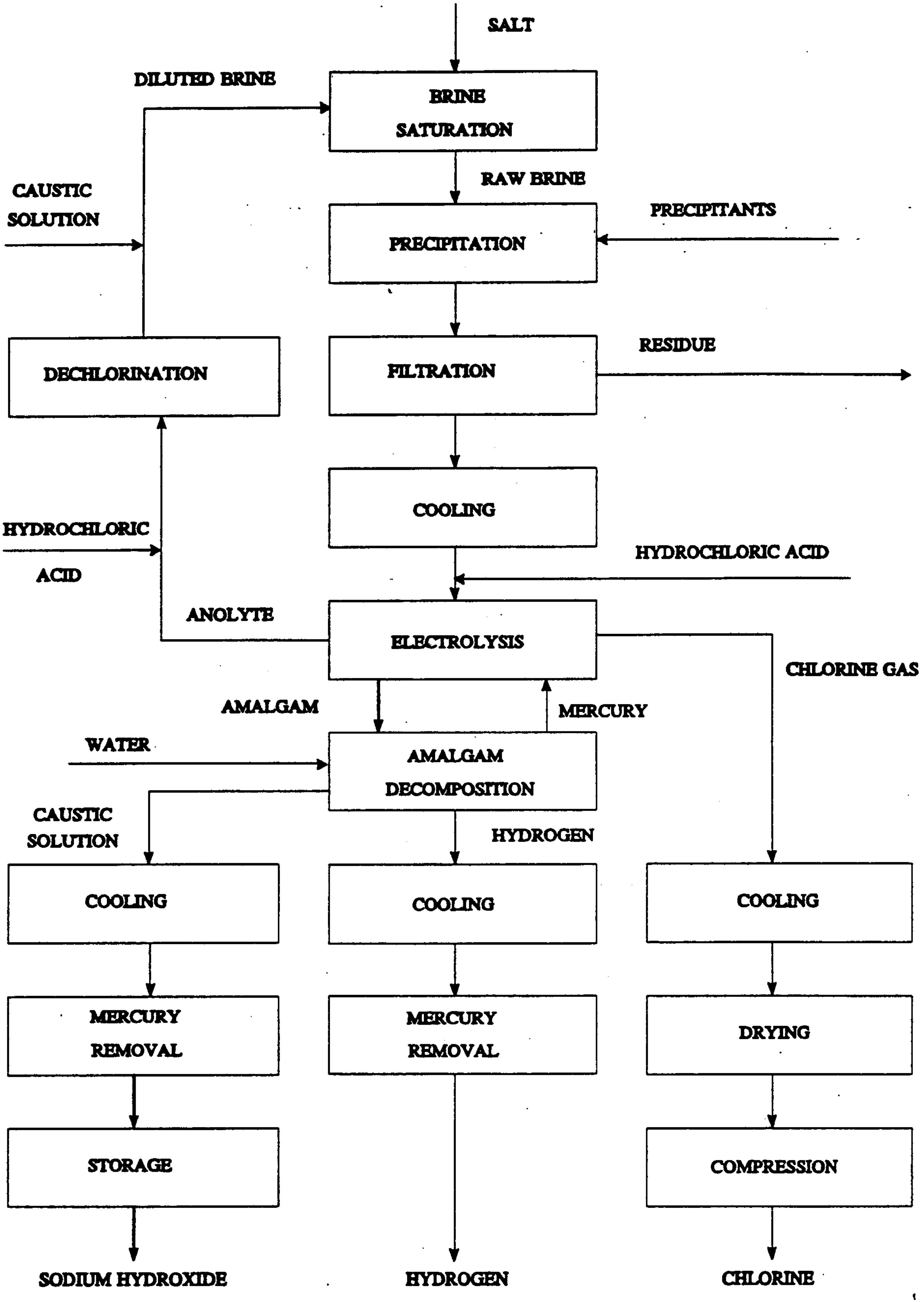

Figure 8.11-2. Simplified diagram of the mercury cell process.

Table 8.11-1 (Metric Units). EMISSION FACTORS FOR CHLORINE FROM CHLOR-ALKALI PLANTS[a]

EMISSION FACTOR RATING: E

Source	Chlorine Gas (kg/Mg Of Chlorine Produced)
Liquefaction blow gases	
Diaphragm cell (SCC 3-01-008-01)	10 - 50
Mercury cell (SCC 3-01-008-02)	20 - 80
Water absorber[b] (SCC 3-01-008-99)	0.830
Caustic scrubber[b] (SCC 3-01-008-99)	0.006
Chlorine loading	
Returned tank car vents (SCC 3-01-008-03)	4.1
Shipping container vents (SCC 3-01-008-04)	8.7
Mercury cell brine air blowing (SCC 3-01-008-05)	2.7

[a] Reference 4. SCC = Source Classification Code.
[b] Control devices.

Table 8.11-2 (English Units). EMISSION FACTORS FOR CHLORINE FROM CHLOR-ALKALI PLANTS[a]

EMISSION FACTOR RATING: E

Source	Chlorine Gas (lb/ton Of Chlorine Produced)
Liquefaction blow gases	
Diaphragm cell (SCC 3-01-008-01)	20 - 100
Mercury cell (SCC 3-01-008-02)	40 - 160
Water absorber[b] (SCC 3-01-008-99)	1.66
Caustic scrubber[b] (SCC 3-01-008-99)	0.012
Chlorine loading	
Returned tank car vents (SCC 3-01-008-03)	8.2
Shipping container vents (SCC 3-01-008-04)	17.3
Mercury cell brine air blowing (SCC 3-01-008-05)	5.4

[a] Reference 4. SCC = Source Classification Code.
[b] Control devices.

Table 8.11-3 (Metric And English Units). EMISSION FACTORS FOR MERCURY FROM MERCURY CELL CHLOR-ALKALI PLANTS[a]

EMISSION FACTOR RATING: E

Type Of Source	Mercury Gas	
	kg/Mg Of Chlorine Produced	lb/ton Of Chlorine Produced
Hydrogen vent (SCC 3-01-008-02)		
Uncontrolled	0.0017	0.0033
Controlled	0.0006	0.0012
End box (SCC 3-01-008-02)	0.005	0.010

[a] SCC = Source Classification Code.

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8.12 Sodium Carbonate

8.12.1 General[1-3]

Sodium carbonate (Na_2CO_3), commonly referred to as soda ash, is one of the largest-volume mineral products in the U. S., with 1991 production of over 9 million megagrams (Mg) (10.2 million tons). Over 85 percent of this soda ash originates in Wyoming, with the remainder coming from Searles Valley, California. Soda ash is used mostly in the production of glass, chemicals, soaps, and detergents, and by consumers. Demand depends to great extent upon the price of, and environmental issues surrounding, caustic soda, which is interchangeable with soda ash in many uses and is widely coproduced with chlorine (see Section 8.11, "Chlor-Alkali").

8.12.2 Process Description[4-7]

Soda ash may be manufactured synthetically or from naturally occurring raw materials such as ore. Only 1 U. S. facility recovers small quantities of Na_2CO_3 synthetically as a byproduct of cresylic acid production. Other synthetic processes include the Solvay process, which involves saturation of brine with ammonia (NH_3) and carbon dioxide (CO_2) gas, and the Japanese ammonium chloride (NH_4Cl) coproduction process. Both of these synthetic processes generate ammonia emissions. Natural processes include the calcination of sodium bicarbonate ($NaHCO_3$), or nahcolite, a naturally occurring ore found in vast quantities in Colorado.

The 2 processes currently used to produce natural soda ash differ only in the recovery stage in primary treatment of the raw material used. The raw material for Wyoming soda ash is mined trona ore, while California soda ash comes from sodium carbonate-rich brine extracted from Searles Lake.

There are 4 distinct methods used to mine the Wyoming trona ore: (1) solution mining, (2) room-and-pillar, (3) longwall, and (4) shortwall. In solution mining, dilute sodium hydroxide (NaOH), commonly called caustic soda, is injected into the trona to dissolve it. This solution is treated with CO_2 gas in carbonation towers to convert the Na_2CO_3 in solution to $NaHCO_3$, which precipitates and is filtered out. The crystals are again dissolved in water, precipitated with carbon dioxide, and filtered. The product is calcined to produce dense soda ash. Brine extracted from below Searles Lake in California is treated similarly.

Blasting is used in the room-and-pillar, longwall, and shortwall methods. The conventional blasting agent is prilled ammonium nitrate (NH_4NO_3) and fuel oil, or ANFO (see Section 13.3, "Explosives Detonation"). Beneficiation is accomplished with either of 2 methods, called the sesquicarbonate and the monohydrate processes. In the sesquicarbonate process, shown schematically in Figure 8.12-1, trona ore is first dissolved in water (H_2O) and then treated as brine. This liquid is filtered to remove insoluble impurities before the sodium sesquicarbonate ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) is precipitated out using vacuum crystallizers. The result is centrifuged to remove remaining water, and can either be sold as a finished product or further calcined to yield soda ash of light to intermediate density. In the monohydrate process, shown schematically in Figure 8.12-2, crushed trona is calcined in a rotary kiln, yielding dense soda ash and carbon dioxide and water as byproducts. The calcined material is combined with water to allow settling out or filtering of impurities such as shale, and is then concentrated by triple-effect evaporators and/or mechanical vapor recompression crystallizers to precipitate sodium carbonate monohydrate ($Na_2CO_3 \cdot H_2O$). Impurities

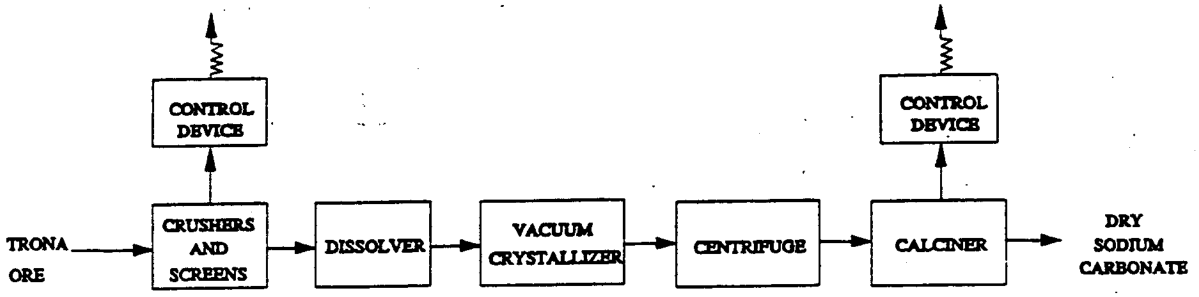

Figure 8.12-1. Flow diagram for sesquicarbonate sodium carbonate processing.

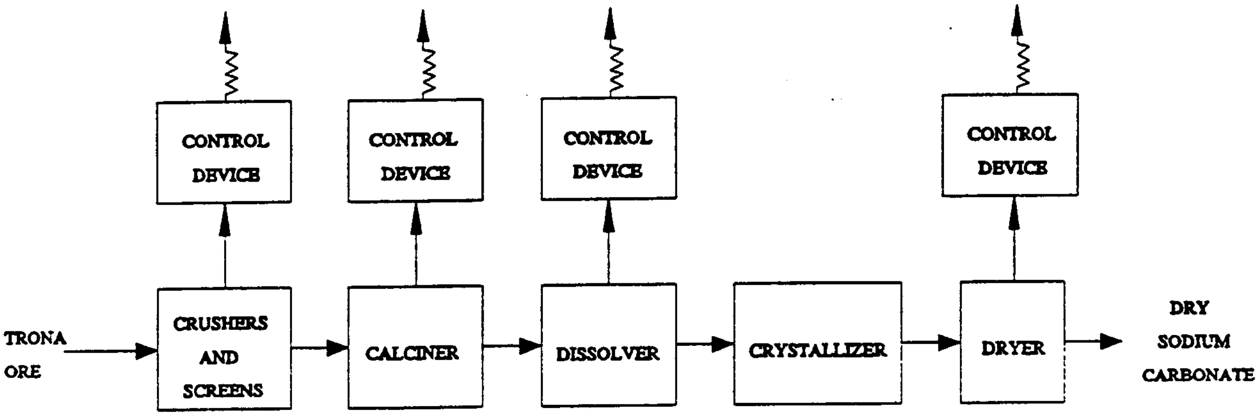

Figure 8.12-2. Flow diagram for monohydrate sodium carbonate processing.

such as sodium chloride (NaCl) and sodium sulfate (Na_2SO_4) remain in solution. The crystals and liquor are centrifuged, and the recovered crystals are calcined again to remove remaining water. The product must then be cooled, screened, and possibly bagged, before shipping.

8.12.3 Emissions And Controls

The principal air emissions from the sodium carbonate production methods now used in the U. S. are particulate emissions from ore calciners; soda ash coolers and dryers; ore crushing, screening, and transporting operations; and product handling and shipping operations. Emissions of products of combustion, such as carbon monoxide, nitrogen oxides, sulfur dioxide, and carbon dioxide, occur from direct-fired process heating units such as ore calcining kilns and soda ash dryers. With the exception of carbon dioxide, which is suspected of contributing to global climate change, insufficient data are available to quantify these emissions with a reasonable level of confidence, but similar processes are addressed in various sections of Chapter 11 of AP-42, "Mineral Products Industry". Controlled emissions of filterable and total particulate matter from individual processes and process components are given in Tables 8.12-1 and 8.12-2. Uncontrolled emissions from these same processes are given in Table 8.12-3. No data quantifying emissions of organic condensable particulate matter from sodium carbonate manufacturing processes are available, but this portion of

Table 8.12-1 (Metric Units). CONTROLLED EMISSION FACTORS FOR PARTICULATE MATTER FROM SODIUM CARBONATE PRODUCTION

Process	Filterable Emissions[a]		Total Emissions[b]	
	kg/Mg Of Product	EMISSION FACTOR RATING	kg/Mg Of Product	EMISSION FACTOR RATING
Ore mining[c] (SCC 3-01-023-99)	0.0016	C	ND	NA
Ore crushing and screening[c] (SCC 3-01-023-99)	0.0010	D	0.0018	C
Ore transfer[c] (SCC 3-01-023-99)	0.00008	E	0.0001	E
Monohydrate process: rotary ore calciner (SCC 3-01-023-04/05)	0.091	A	0.12	B
Sesquicarbonate process: rotary calciner (SCC 3-01-023-99)	0.36	B	0.36	C
Sesquicarbonate process: fluid-bed calciner (SCC 3-01-023-99)	0.021	C	ND	NA
Rotary soda ash dryers (SCC 3-01-023-06)	0.25	C	0.25	D
Fluid-bed soda ash dryers/coolers (SCC 3-01-023-07)	0.015	C	0.019	D
Soda ash screening (SCC 3-01-023-99)	0.0097	E	0.013	E
Soda ash storage/loading and unloading[c] (SCC 3-01-023-99)	0.0021	E	0.0026	E

[a] Filterable particulate matter is that material collected in the probe and filter of a Method 5 or Method 17 sampler. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Total particulate matter includes filterable particulate and inorganic condensable particulate.

[c] For ambient temperature processes, all particulate matter emissions can be assumed to be filterable at ambient conditions. However, particulate sampling according to EPA Reference Method 5 involves the heating of the front half of the sampling train to temperatures that may vaporize some portion of this particulate matter, which will then recondense in the back half of the sampling train. For consistency, particulate matter measured as condensable according to Method 5 is reported as such.

the particulate matter can be assumed to be negligible. Emissions of carbon dioxide from selected processes are given in Table 8.12-4. Emissions from combustion sources such as boilers, and from evaporation of hydrocarbon fuels used to fire these combustion sources, are covered in other chapters of AP-42.

Particulate emissions from calciners and dryers are typically controlled by venturi scrubbers, electrostatic precipitators, and/or cyclones. Baghouse filters are not well suited to applications such as these, because of the high moisture content of the effluent gas. Particulate emissions from ore and product handling operations are typically controlled by either venturi scrubbers or baghouse filters. These control devices are an integral part of the manufacturing process, capturing raw materials and

Table 8.12-2 (English Units). CONTROLLED EMISSION FACTORS FOR PARTICULATE MATTER FROM SODIUM CARBONATE PRODUCTION

Process	Filterable Emissions[a]		Total Emissions[b]	
	lb/ton Of Product	EMISSION FACTOR RATING	lb/ton Of Product	EMISSION FACTOR RATING
Ore mining[c] (SCC 3-01-023-99)	0.0033	C	ND	NA
Ore crushing and screening[c] (SCC 3-01-023-99)	0.0021	D	0.0035	C
Ore transfer[c] (SCC 3-01-023-99)	0.0002	E	0.0002	E
Monohydrate process: rotary ore calciner (SCC 3-01-023-04/05)	0.18	A	0.23	B
Sesquicarbonate process: rotary calciner (SCC 3-01-023-99)	0.72	B	0.73	C
Sesquicarbonate process: fluid-bed calciner (SCC 3-01-023-99)	0.043	C	ND	NA
Rotary soda ash dryers (SCC 3-01-023-06)	0.50	C	0.52	D
Fluid-bed soda ash dryers/coolers (SCC 3-01-023-07)	0.030	C	0.39	D
Soda ash screening (SCC 3-01-023-99)	0.019	E	0.026	E
Soda ash storage/loading and unloading[c] (SCC 3-01-023-99)	0.0041	E	0.0051	E

[a] Filterable particulate matter is that material collected in the probe and filter of a Method 5 or Method 17 sampler. SCC = Source Classficiation Code. ND = no data. NA = not applicable.

[b] Total particulate matter includes filterable particulate and inorganic condensable particulate.

[c] For ambient temperature processes, all particulate matter emissions can be assumed to be filterable at ambient conditions; however, particulate sampling according to EPA Reference Method 5 involves the heating of the front half of the sampling train to temperatures that may vaporize some portion of this particulate matter, which will then recondense in the back half of the sampling train. For consistency, particulate matter measured as condensable according to Method 5 is reported as such.

product for economic reasons. Because of a lack of suitable emissions data for uncontrolled processes, both controlled and uncontrolled emission factors are presented for this industry. The uncontrolled emission factors have been calculated by applying nominal control efficiencies to the controlled emission factors.

Table 8.12-3 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR PARTICULATE MATTER FROM SODIUM CARBONATE

Process	Nominal Control Efficiency (%)	Total[a]		
		kg/Mg Of Product	lb/ton Of Product	EMISSION FACTOR RATING
Ore mining (SCC 3-01-023-99)	99.9	1.6	3.3	D
Ore crushing and screening (SCC 3-01-023-99)	99.9	1.7	3.5	E
Ore transfer (SCC 3-01-023-99)	99.9	0.1	0.2	E
Monohydrate process: rotary ore calciner (SCC 3-01-023-04/05)	99.9	90	180	B
Sesquicarbonate process: rotary calciner (SCC 3-01-023-99)	99	36	72	D
Sesquicarbonate process: fluid-bed calciner (SCC 3-01-023-99)	99	2.1	4.3	D
Rotary soda ash dryers (SCC 3-01-023-06)	99	25	50	E
Fluid-bed soda ash dryers/coolers (SCC 3-01-023-07)	99	1.5	3.0	E
Soda ash screening (SCC 3-01-023-99)	99.9	10	19	E
Soda ash storage/loading and unloading (SCC 3-01-023-99)	99.9	2.6	5.2	E

[a] Values for uncontrolled total particulate matter can be assumed to include filterable particulate and both organic and inorganic condensable particulate. For processes operating at significantly greater than ambient temperatures, these factors have been calculated by applying the nominal control efficiency to the controlled (as-measured) filterable particulate emission factors above.
SCC = Source Classification Code.

Table 8.12-4 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR CARBON DIOXIDE FROM SODIUM CARBONATE PRODUCTION[a]

EMISSION FACTOR RATING: E

Process	Emissions	
	kg/Mg Of Product	lb/ton Of Product
Monohydrate process: rotary ore calciner (SCC 3-01-023-04/05)	200	400
Sesquicarbonate process: rotary calciner (SCC 3-01-023-99)	150	310
Sesquicarbonate process: fluid-bed calciner (SCC 3-01-023-99)	90	180
Rotary soda ash dryers (SCC 3-01-023-06)	63	130

[a] Factors are derived from analyses during emission tests for criteria pollutants, rather than from fuel analyses and material balances. SCC = Source Classification Code. References 8-26.

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8.13 Sulfur Recovery

8.13.1 General[1-2]

Sulfur recovery refers to the conversion of hydrogen sulfide (H_2S) to elemental sulfur. Hydrogen sulfide is a byproduct of processing natural gas and refining high-sulfur crude oils. The most common conversion method used is the Claus process. Approximately 90 to 95 percent of recovered sulfur is produced by the Claus process. The Claus process typically recovers 95 to 97 percent of the hydrogen sulfide feedstream.

Over 5.9 million megagrams (Mg) (6.5 million tons) of sulfur were recovered in 1989, representing about 63 percent of the total elemental sulfur market in the U. S. The remainder was mined or imported. The average production rate of a sulfur recovery plant in the U. S. varies from 51 to 203 Mg (56 to 224 tons) per day.

8.13.2 Process Description[1-2]

Hydrogen sulfide, a byproduct of crude oil and natural gas processing, is recovered and converted to elemental sulfur by the Claus process. Figure 8.13-1 shows a typical Claus sulfur recovery unit. The process consists of multistage catalytic oxidation of hydrogen sulfide according to the following overall reaction:

$$2H_2S + O_2 \rightarrow 2S + 2H_2O \qquad (1)$$

Each catalytic stage consists of a gas reheater, a catalyst chamber, and a condenser.

The Claus process involves burning one-third of the H_2S with air in a reactor furnace to form sulfur dioxide (SO_2) according to the following reaction:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O + \text{heat} \qquad (2)$$

The furnace normally operates at combustion chamber temperatures ranging from 980 to 1540°C (1800 to 2800°F) with pressures rarely higher than 70 kilopascals (kPa) (10 pounds per square inch absolute). Before entering a sulfur condenser, hot gas from the combustion chamber is quenched in a waste heat boiler that generates high to medium pressure steam. About 80 percent of the heat released could be recovered as useful energy. Liquid sulfur from the condenser runs through a seal leg into a covered pit from which it is pumped to trucks or railcars for shipment to end users. Approximately 65 to 70 percent of the sulfur is recovered. The cooled gases exiting the condenser are then sent to the catalyst beds.

The remaining uncombusted two-thirds of the hydrogen sulfide undergoes Claus reaction (reacts with SO_2) to form elemental sulfur as follows:

$$2H_2S + SO_2 \longleftrightarrow 3S + 2H_2O + \text{heat} \qquad (3)$$

The catalytic reactors operate at lower temperatures, ranging from 200 to 315°C (400 to 600°F). Alumina or bauxite is sometimes used as a catalyst. Because this reaction represents an equilibrium chemical reaction, it is not possible for a Claus plant to convert all the incoming sulfur compounds to elemental sulfur. Therefore, 2 or more stages are used in series to recover the sulfur. Each catalytic stage can recover half to two-thirds of the incoming sulfur. The number of catalytic stages depends upon the level of conversion desired. It is estimated that 95 to 97 percent overall recovery can be

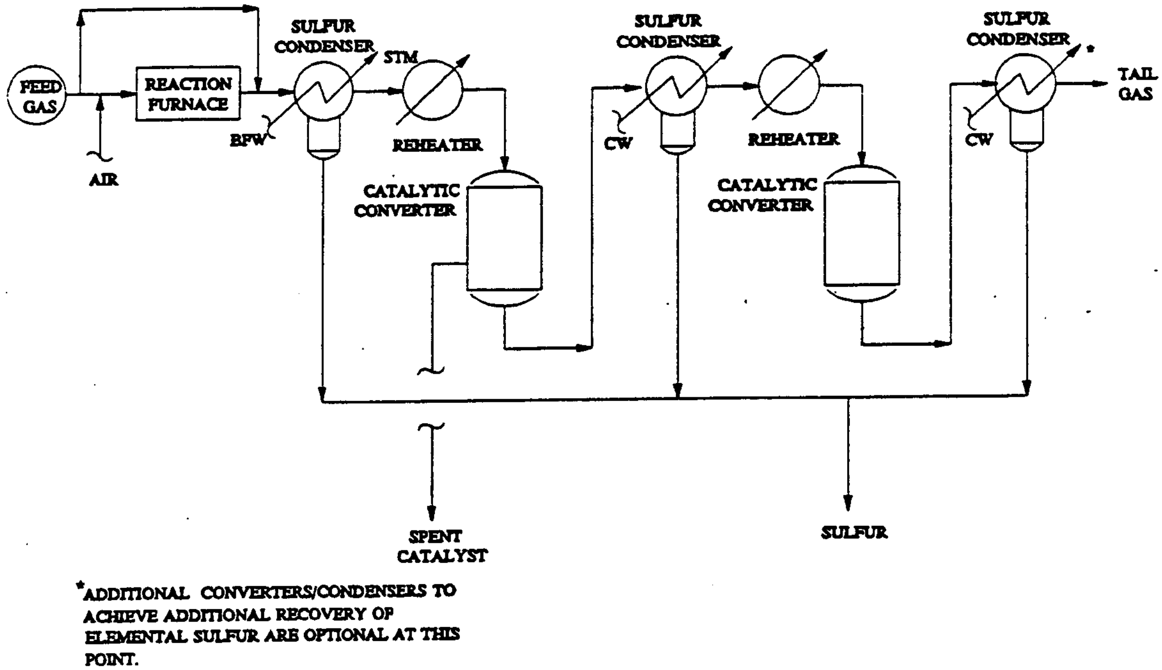

Figure 8.13-1. Typical Claus sulfur recovery unit. CW = Cooling water. STM = Steam. BFW = Boiler feed water.

achieved depending on the number of catalytic reaction stages and the type of reheating method used. If the sulfur recovery unit is located in a natural gas processing plant, the type of reheat employed is typically either auxiliary burners or heat exchangers, with steam reheat being used occasionally. If the sulfur recovery unit is located in a crude oil refinery, the typical reheat scheme uses 3536 to 4223 kPa (500 to 600 pounds per square inch guage [psig]) steam for reheating purposes. Most plants are now built with 2 catalytic stages, although some air quality jurisdictions require 3. From the condenser of the final catalytic stage, the process stream passes to some form of tailgas treatment process. The tailgas, containing H_2S, SO_2, sulfur vapor, and traces of other sulfur compounds formed in the combustion section, escapes with the inert gases from the tail end of the plant. Thus, it is frequently necessary to follow the Claus unit with a tailgas cleanup unit to achieve higher recovery.

In addition to the oxidation of H_2S to SO_2 and the reaction of SO_2 with H_2S in the reaction furnace, many other side reactions can and do occur in the furnace. Several of these possible side reactions are:

$$CO_2 + H_2S \rightarrow COS + H_2O \quad (4)$$

$$COS + H_2S \rightarrow CS_2 + H_2O \quad (5)$$

$$2COS \rightarrow CO_2 + CS_2 \quad (6)$$

8.13.3 Emissions And Controls$^{1-4}$

Table 8.13-1 shows emission factors and recovery efficiencies for modified Claus sulfur recovery plants. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton). Emissions from the Claus process are directly related to the recovery efficiency. Higher

Table 8.13-1 (Metric And English Units). EMISSION FACTORS FOR MODIFIED CLAUS SULFUR RECOVERY PLANTS

EMISSION FACTOR RATING: E

Number of Catalytic Stages	Average % Sulfur Recovery[a]	SO_2 Emissions	
		kg/Mg Of Sulfur Produced	lb/ton Of Sulfur Produced
1, Uncontrolled	93.5[b]	139[b,c]	278[b,c]
3, Uncontrolled	95.5[d]	94[c,d]	188[c,d]
4, Uncontrolled	96.5[e]	73[c,e]	145[c,e]
2, Controlled[f]	98.6	29	57
3, Controlled[g]	96.8	65	129

[a] Efficiencies are for feedgas streams with high H_2S concentrations. Gases with lower H_2S concentrations would have lower efficiencies. For example, a 2- or 3-stage plant could have a recovery efficiency of 95% for a 90% H_2S stream, 93% for 50% H_2S, and 90% for 15% H_2S.

[b] Reference 5. Based on net weight of pure sulfur produced. The emission factors were determined using the average of the percentage recovery of sulfur. Sulfur dioxide emissions are calculated from percentage sulfur recovery by one of the following equations:

$$SO_2 \text{ emissions (kg/Mg)} = \frac{(100\% \text{ recovery})}{\% \text{recovery}} \; 2000$$

$$SO_2 \text{ emissions (lb/ton)} = \frac{(100\% \text{recovery})}{\% \text{ recovery}} \; 4000$$

[c] Typical sulfur recovery ranges from 92 to 95%.

[d] Typical sulfur recovery ranges from 95 to 96%.

[e] Typical sulfur recovery ranges from 96 to 97%.

[f] Reference 6. EMISSION FACTOR RATING: B. Test data indicated sulfur recovery ranges from 98.3 to 98.8%.

[g] References 7-9. EMISSION FACTOR RATING: B. Test data indicated sulfur recovery ranges from 95 to 99.8%.recovery efficiencies. The efficiency depends upon several factors, including the number of catalytic stages, the concentrations of H_2S and contaminants in the feedstream, stoichiometric balance of gaseous components of the inlet, operating temperature, and catalyst maintenance.

recovery efficiencies mean less sulfur emitted in the tailgas. Older plants, or very small Claus plants producing less than 20 Mg (22 tons) per day of sulfur without tailgas cleanup, have varying sulfur recovery efficiencies. The efficiency depends upon several factors, including the number of catalytic stages, the concentrations of H_2S and contaminants in the feedstream, stoichiometric balance of gaseous components of the inlet, operating temperature, and catalyst maintenance.

A 2-bed catalytic Claus plant can achieve 94 to 96 percent efficiency. Recoveries range from 96 to 97.5 percent for a 3-bed catalytic plant and range from 97 to 98.5 percent for a 4-bed catalytic plant. At normal operating temperatures and pressures, the Claus reaction is thermodynamically limited to 97 to 98 percent recovery. Tailgas from the Claus plant still contains 0.8 to 1.5 percent sulfur compounds.

Existing new source performance standards limit sulfur emissions from Claus sulfur recovery plants of greater than 20.32 Mg (22.40 ton) per day capacity to 0.025 percent by volume (250 parts per million volume [ppmv]). This limitation is effective at 0 percent oxygen on a dry basis if emissions are controlled by an oxidation control system or a reduction control system followed by incineration. This is comparable to the 99.8 to 99.9 percent control level for reduced sulfur.

Emissions from the Claus process may be reduced by: (1) extending the Claus reaction into a lower temperature liquid phase, (2) adding a scrubbing process to the Claus exhaust stream, or (3) incinerating the hydrogen sulfide gases to form sulfur dioxide.

Currently, there are 5 processes available that extend the Claus reaction into a lower temperature liquid phase including the BSR/selectox, Sulfreen, Cold Bed Absorption, Maxisulf, and IFP-1 processes. These processes take advantage of the enhanced Claus conversion at cooler temperatures in the catalytic stages. All of these processes give higher overall sulfur recoveries of 98 to 99 percent when following downstream of a typical 2- or 3-stage Claus sulfur recovery unit, and therefore reduce sulfur emissions.

Sulfur emissions can also be reduced by adding a scrubber at the tail end of the plant. There are essentially 2 generic types of tailgas scrubbing processes: oxidation tailgas scrubbers and reduction tailgas scrubbers. The first scrubbing process is used to scrub SO_2 from incinerated tailgas and recycle the concentrated SO_2 stream back to the Claus process for conversion to elemental sulfur. There are at least 3 oxidation scrubbing processes: the Wellman-Lord, Stauffer Aquaclaus, and IFP-2. Only the Wellman-Lord process has been applied successfully to U. S. refineries.

The Wellman-Lord process uses a wet generative process to reduce stack gas sulfur dioxide concentration to less than 250 ppmv and can achieve approximately 99.9 percent sulfur recovery. Claus plant tailgas is incinerated and all sulfur species are oxidized to form SO_2 in the Wellman-Lord process. Gases are then cooled and quenched to remove excess water and to reduce gas temperature to absorber conditions. The rich SO_2 gas is then reacted with a solution of sodium sulfite (Na_2SO_3) and sodium bisulfite ($NaHSO_3$) to form the bisulfite:

$$SO_2 + Na_2SO_3 + H_2O \rightarrow 2NaHSO_3 \quad (7)$$

The offgas is reheated and vented to the atmosphere. The resulting bisulfite solution is boiled in an evaporator-crystallizer, where it decomposes to SO_2 and water (H_2O) vapor and sodium sulfite is precipitated:

$$2NaHSO_3 \rightarrow Na_2SO_3\downarrow + H_2O + SO_2\uparrow \quad (8)$$

Sulfite crystals are separated and redissolved for reuse as lean solution in the absorber. The wet SO_2 gas is directed to a partial condenser where most of the water is condensed and reused to dissolve sulfite crystals. The enriched SO_2 stream is then recycled back to the Claus plant for conversion to elemental sulfur.

In the second type of scrubbing process, sulfur in the tailgas is converted to H_2S by hydrogenation in a reduction step. After hydrogenation, the tailgas is cooled and water is removed.

The cooled tailgas is then sent to the scrubber for H_2S removal prior to venting. There are at least 4 reduction scrubbing processes developed for tailgas sulfur removal: Beavon, Beavon MDEA, SCOT, and ARCO. In the Beavon process, H_2S is converted to sulfur outside the Claus unit using a lean H_2S-to-sulfur process (the Strefford process). The other 3 processes utilize conventional amine scrubbing and regeneration to remove H_2S and recycle back as Claus feed.

Emissions from the Claus process may also be reduced by incinerating sulfur-containing tailgases to form sulfur dioxide. In order to properly remove the sulfur, incinerators must operate at a temperature of 650°C (1,200°F) or higher if all the H_2S is to be combusted. Proper air-to-fuel ratios are needed to eliminate pluming from the incinerator stack. The stack should be equipped with analyzers to monitor the SO_2 level.

References For Section 8.13

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8.14 Hydrogen Cyanide

[Work In Progress]

9. FOOD AND AGRICULTURAL INDUSTRIES

This chapter comprises the activities that are performed before and during the production and preparation of consumer products. With agricultural crops, the land is tilled in preparation for planting, fertilizers and pesticides are applied, and the crops are harvested and stored before processing into consumer products. With animal husbandry, livestock and poultry are raised and sent to slaughterhouses. Food and agricultural industries yield either consumer products directly or related materials that are then used to produce such products (e. g., leather or cotton).

All of the steps in producing such consumer items, from crop planting or animal raising to the processing into end products, present the potential for air pollution problems. For each of these activities, pollutant emission factors are presented where data are available. The primary pollutants emitted by these processes are total organic compounds and particulate.

9.1 Tilling Operations

[Work In Progress]

9.2 Growing Operations

9.2.1 Fertilizer Application

9.2.2 Pesticide Application

9.2.3 Orchard Heaters

9.2.1 Fertilizer Application

[Work In Progress]

9.2.2 Pesticide Application

9.2.2.1 General[1-2]

Pesticides are substances or mixtures used to control plant and animal life for the purposes of increasing and improving agricultural production, protecting public health from pest-borne disease and discomfort, reducing property damage caused by pests, and improving the aesthetic quality of outdoor or indoor surroundings. Pesticides are used widely in agriculture, by homeowners, by industry, and by government agencies. The largest usage of chemicals with pesticidal activity, by weight of "active ingredient" (AI), is in agriculture. Agricultural pesticides are used for cost-effective control of weeds, insects, mites, fungi, nematodes, and other threats to the yield, quality, or safety of food. The annual U. S. usage of pesticide AIs (i. e., insecticides, herbicides, and fungicides) is over 800 million pounds.

Air emissions from pesticide use arise because of the volatile nature of many AIs, solvents, and other additives used in formulations, and of the dusty nature of some formulations. Most modern pesticides are organic compounds. Emissions can result directly during application or as the AI or solvent volatilizes over time from soil and vegetation. This discussion will focus on emission factors for volatilization. There are insufficient data available on particulate emissions to permit emission factor development.

9.2.2.2 Process Description[3-6]

Application Methods -

Pesticide application methods vary according to the target pest and to the crop or other value to be protected. In some cases, the pesticide is applied directly to the pest, and in others to the host plant. In still others, it is used on the soil or in an enclosed air space. Pesticide manufacturers have developed various formulations of AIs to meet both the pest control needs and the preferred application methods (or available equipment) of users. The types of formulations are dry, liquid, and aerosol.

Dry formulations can be dusts, granules, wettable and soluble powders, water dispersible granules, or baits. Dusts contain small particles and are subject to wind drift. Dusts also may present an efficacy problem if they do not remain on the target plant surfaces. Granular formulations are larger, from about 100 to 2,500 micrometers (μm), and are usually intended for soil application. Wettable powders and water-dispersible granules both form suspensions when mixed with water before application. Baits, which are about the same size as granules, contain the AI mixed with a food source for the target pest (e. g., bran or sawdust).

Liquid formulations may be solutions, emulsions (emulsifiable concentrates), aerosols, or fumigants. In a liquid solution, the AI is solubilized in either water or organic solvent. True solutions are formed when miscible liquids or soluble powders are dissolved in either water or organic liquids. Emulsifiable concentrates are made up of the AI, an organic solvent, and an emulsifier, which permits the pesticide to be mixed with water in the field. A flowable formulation contains an AI that is not amenable to the formation of a solution. Therefore, the AI is mixed with a liquid petroleum base and emulsifiers to make a creamy or powdery suspension that can be readily field-mixed with water.

Aerosols, which are liquids with an AI in solution with a solvent and a propellant, are used for fog or mist applications. The ranges of optimum droplet size, by target, are 10 to 50 μm for flying insects, 30 to 50 μm for foliage insects, 40 to 100 μm for foliage, and 250 to 500 μm for soil with drift avoidance.

Herbicides are usually applied as granules to the surface of the soil or are incorporated into the soil for field crops, but are applied directly to plant foliage to control brush and noxious weeds. Dusts or fine aerosols are often used for insecticides but not for herbicides. Fumigant use is limited to confined spaces. Some fumigants are soil-injected, and then sealed below the soil surface with a plastic sheeting cover to minimize vapor loss.

Several types of pesticide application equipment are used, including liquid pumps (manual and power operated), liquid atomizers (hydraulic energy, gaseous energy, and centrifugal energy), dry application, and soil application (liquid injection application).

9.2.2.3 Emissions And Controls[1,7-14]

Organic compounds and particulate matter are the principal air emissions from pesticide application. The active ingredients of most types of synthetic pesticides used in agriculture have some degree of volatility. Most are considered to be essentially nonvolatile or semivolatile organic compounds (SVOC) for analytical purposes, but a few are volatile (e. g., fumigants). Many widely used pesticide formulations are liquids and emulsifiable concentrates, which contain volatile organic solvents (e. g., xylene), emulsifiers, diluents, and other organics. In this discussion, all organics other than the AI that are liquid under ambient conditions, are considered to have the potential to volatilize from the formulation. Particulate matter emissions with adsorbed active ingredients can occur during application of dusts used as pesticide carriers, or from subsequent wind erosion. Emissions also may contain pesticide degradation products, which may or may not be volatile. Most pesticides, however, are sufficiently long lived to allow some volatilization before degradation occurs.

Processes affecting emissions through volatilization of agricultural pesticides applied to soils or plants have been studied in numerous laboratory and field research investigations. The 3 major parameters that influence the rate of volatilization are the nature of the AI, the meteorological conditions, and soil adsorption.

Of these 3 major parameters, the nature of the AI probably has the greatest effect. The nature of the AI encompasses physical properties, such as vapor pressure, Henry's law constant, and water solubility; and chemical properties, including soil particle adsorption and hydrolysis or other degradative mechanisms. At a given temperature, every AI has a characteristic Henry's law constant and vapor pressure. The evaporation rate of an AI is determined in large part by its vapor pressure, and the vapor pressure increases with temperature and decreases with adsorption of the AI to soil. The extent of volatilization depends in part on air and soil temperature. Temperature has a different effect on each component relative to its vapor pressure. An increase in temperature can increase or decrease volatilization because of its influence on other factors such as diffusion of the AI toward or away from the soil surface, and movement of the water in the soil. Usually, an increase in temperature enhances volatilization because the vapor pressure of the AI increases. Wind conditions also can affect the rate of AI volatilization. Increased wind and turbulence decrease the stagnant layers above a soil surface and increase the mixing of air components near the surface, thus increasing volatilization. The effects of the third major parameter, soil adsorption, depend not only on the chemical reactivity of the AI but to a great extent on the characteristics of the soil. Increased amounts of organic matter or clay in soils can increase adsorption and decrease the volatilization rate of many AIs, particularly the more volatile AIs that are nonionic, weakly polar molecules. The soil moisture content can also influence the rate of vaporization of the weakly polar AIs. When soil is very dry, the volatility of the AI is lowered significantly, resulting in a decrease in emissions. The presence of water in the soil can accelerate the evaporation of pesticides because, as water evaporates from the soil surface, the AI present in the soil will be transported to the surface, either in solution or by codistillation or convection effects. This action is called the "wick effect" because the soil acts as a wick for movement of the AI.

Many materials used as inert ingredients in pesticide formulations are organic compounds that are volatile liquids or gases at ambient conditions. All of these compounds are considered to be volatile organic compounds (VOC). During the application of the pesticides and for a subsequent period of time, these organic compounds are volatilized into the atmosphere. Most of the liquid inert ingredients in agriculture pesticide formulations have higher vapor pressures than the AIs. However, not all inert ingredients are VOCs. Some liquid formulations may contain water, and solid formulations typically contain nonvolatile (solid) inert ingredients. Solid formulations contain small quantities of liquid organic compounds in their matrix. These compounds are often incorporated as carriers, stabilizers, surfactants, or emulsifiers, and after field application are susceptible to volatilization from the formulation. The VOC inert ingredients are the major contributors to emissions that occur within 30 days after application. It is assumed that 100 percent of these VOC inert ingredients volatilize within that time.

Two important mechanisms that increase emissions are diffusion and volatilization from plant surfaces. Pesticides in the soil diffuse upward to the surface as the pesticide at the soil surface volatilizes. A pesticide concentration gradient is thus formed between the depleted surface and the more concentrated subsurface. Temperature, pesticide concentration, and soil composition influence the rate of diffusion. The rate of volatilization from plant surfaces depends on the manner in which the pesticide covers the plant structure. Higher volatilization losses can occur from plant surfaces when the pesticide is present as droplets on the surface. Volatilization slows when the remaining pesticide is either left in the regions of the plant structure less exposed to air circulation or is adsorbed onto the plant material.

Alternative techniques for pesticide application or usage are not widely used, and those that are used are often intended to increase cost effectiveness. These techniques include (1) use of application equipment that increases the ratio of amount of pesticide on target plants or soil to that applied; (2) application using soil incorporation; (3) increased usage of water-soluble pesticides in place of solvent-based pesticides; (4) reformulation of pesticides to reduce volatility; and (5) use of integrated pest management (IPM) techniques to reduce the amount of pesticide needed. Microencapsulation is another technique in which the active ingredient is contained in various materials that slowly degrade to allow for timed release of pesticides.

9.2.2.4 Emission Factors[1,15-21]

The variety in pesticide AIs, formulations, application methods, and field conditions, and the limited data base on these aspects combine to preclude the development of single-value emission factors. Modeling approaches have been, therefore, adopted to derive emission factors from readily available data, and algorithms have been developed to calculate emissions for surface application and soil incorporation from product-specific data, supplemented, as necessary, by default values. Emission factors for pesticide AIs, derived through modeling approaches, are given in Table 9.2.2-4. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton). No emission factors are estimated beyond 30 days because after that time degradation processes (e. g., hydrolysis or microbial degradation) and surface runoff can have major effects on the loss of AIs, and volatilization after that time may not be the primary loss mechanism. The emission factors calculated using the model are rated "E" because the estimates are derived from mathematical equations using physical properties of the AIs. Because the factors were developed from a very limited data base, resulting emission estimates should be considered approximations. As additional data become available, the algorithm and emission factors will be revised, when appropriate, to incorporate the new data.

This modeling approach estimates emissions from volatilized organic material. No emission estimates were developed for particulate because the available data were inadequate to establish reliable emission factors. The modeled emission factors also address only surface-applied and soil-incorporated pesticides. In aerial application, drift effects predominate over volatilization, and insufficient data are currently available to develop emission factors for this application method.

The model covers the 2 key types of volatilization emissions, (1) those of active (pesticidal) ingredients, and (2) those VOC constituents of the inert (nonpesticidal) ingredients. For some formulations (e. g., liquids and emulsifiable concentrates), emissions of inert VOCs may be an order of magnitude or more higher than those of the AIs, but for other formulations (e. g., granules) the VOC emissions are either relatively less important or unimportant. Thus, both parts of the model are essential, and both depend on the fact that volatilization rates depend in large measure on the vapor pressure of specific ingredients, whether AIs or inerts. Use of the model, therefore, requires the collection of certain information for each pesticide application.

Both the nature of the pesticide and the method by which it is applied must either be known or estimated. Pesticide formulations contain both an AI and inert ingredients, and the pesticide volatilization algorithm is used to estimate their emissions separately. Ideally, the information available for the algorithm calculation will match closely the actual conditions. The following information is necessary to use the algorithm.

- Total quantity of formulation applied;
- Method by which the formulation was applied (the algorithm cannot be used for aerially applied pesticide formulations);
- Name of the specific AI(s) in the formulation;
- Vapor pressure of the AI(s);
- Type of formulation (e. g., emulsifiable concentrate, granules, microcapsules, powder);
- Percentage of inert ingredients; and
- Quantity or percentage of VOC in the inerts.,

9.2.2.5 Use Of The Algorithm[1,18,20]

The algorithm for estimating volatilization emissions is applied in a 6-step procedure, as follows:

1. Determine both the application method and the quantity of pesticide product applied.
2. Determine the type of formulation used.
3. Determine the specific AI(s) in the formulation and its vapor pressure(s).
4. Determine the percentage of the AI (or each AI) present.

5. Determine the VOC content of the formulation.
6. Perform calculations of emissions.

Information for these steps can be found as follows:

- Item 1 — The quantity can be found either directly from the weight purchased or used for a given application or, alternately, by multiplying the application rate (e. g., kg/acre) times the number of units (acres) treated. The algorithm cannot be used for aerial application.

- Items 2, 3, and 4 — This information is presented on the labels of all pesticide containers. Alternatively, it can be obtained from either the manufacturer, end-use formulator, or local distributor. Table 9.2.2-1 provides vapor pressure data for selected AIs. If the trade name of the pesticide and the type of formulation are known, the specific AI in the formulation can be obtained from Reference 2 or similar sources. Table 9.2.2-2 presents the specific AIs found in several common trade name formulations. Assistance in determining the various formulations for specific AIs applied may be available from the National Agricultural Statistics Service, U. S. Department Of Agriculture, Washington, DC.

- Item 5 — The percent VOC content of the inert ingredient portion of the formulation can be requested from either the manufacturer or end-use formulator. Alternatively, the estimated average VOC content of the inert portions of several common types of formulations is given in Table 9.2.2-3.

- Item 6 — Emissions estimates are calculated separately for the AI using Table 9.2.2-4, and for the VOC inert ingredients as described below and illustrated in the example calculation.

Emissions Of Active Ingredients -

First, the total quantity of AI applied to the crop is calculated by multiplying the percent content of the AI in the formulation by the total quantity of applied formulation. Second, the vapor pressure of the specific AI(s) at 20 to 25°C is determined from Table 9.2.2-1, Reference 20, or other sources. Third, the vapor pressure range that corresponds to the vapor pressure of the specific AI is found in Table 9.2.2-4. Then the emission factor for the AI(s) is calculated. Finally, the total quantity of applied AI(s) is multiplied by the emission factor(s) to determine the total quantity of AI emissions within 30 days after application. Table 9.2.2-4 is not applicable to emissions from fumigant usage, because these gaseous or liquid products are highly volatile and would be rapidly discharged to the atmosphere.

Emissions Of VOC Inert Ingredients -

The total quantity of emissions because of VOCs in the inert ingredient portion of the formulation can be obtained by using the percent of the inert portion contained in the formulated product, the percent of the VOCs contained in the inert portion, and the total quantity of formulation applied to the crop. First, multiply the percentage of inerts in the formulation by the total quantity of applied formulation to obtain the total quantity of inert ingredients applied. Second, multiply the percentage of VOCs in the inert portion by the total quantity of inert ingredient applied to obtain the total quantity of VOC inert ingredients. If the VOC content is not known, use a default value from Table 9.2.2-3 appropriate to the formulation. Emissions of VOC inert ingredients are assumed to be 100 percent by 30 days after application.

Total Emissions -

Add the total quantity of VOC inert ingredients volatilized to the total quantity of emissions from the AI. The sum of these quantities represents the total emissions from the application of the pesticide formulation within 30 days after application.

Example Calculation -

3,629 kg, or 8,000 lb, of Spectracide® have been surface applied to cropland, and an estimate is desired of the total quantity of emissions within 30 days after application.

1. The active ingredient in Spectracide® is diazinon (Reference 2, or Table 9.2.2-2). The pesticide container states that the formulation is an emulsifiable concentrate containing 58 percent active ingredient and 42 percent inert ingredient.

2. Total quantity of AI applied:

   0.58 * 3,629 kg = 2,105 kg (4,640 lb) of diazinon applied

   = 2.105 Mg

   2.105 Mg * 1.1 ton/Mg = 2.32 tons of diazinon applied

From Table 9.2.2-1, the vapor pressure of diazinon is 6 x 10^{-5} millimeters (mm) mercury at about 25°C. From Table 9.2.2-4, the emission factor for AIs with vapor pressures between 1 x 10^{-6} and 1 x 10^{-4} during a 30-day interval after application is 350 kg/Mg (700 lb/ton) applied. This corresponds to a total quantity of diazinon volatilized of 737 kg (1,624 lb) over the 30-day interval.

3. From the pesticide container label, it is determined that the inert ingredient content of the formulation is 42 percent and, from Table 9.2.2.3, it can be determined that the average VOC content of the inert portion of emulsifiable concentrates is 56 percent.

   Total quantity of emissions from inert ingredients:

   0.42 * 3,629 kg * 0.56 = 854 kg (1,882 lb) of VOC inert ingredients

   One hundred percent of the VOC inert ingredients is assumed to volatilize within 30 days.

4. The total quantity of emissions during this 30-day interval is the sum of the emissions from inert ingredients and from the AI. In this example, the emissions are 854 kg (1,882 lb) of VOC plus 737 kg (1,624 lb) of AI, or 1,591 kg (3,506 lb).

Table 9.2.2-1. VAPOR PRESSURES OF SELECTED ACTIVE INGREDIENTS[a]

Active Ingredient	Vapor Pressure (mm Hg at 20 to 25°C)
1,3-Dichloropropene	29
2,4-D acid	8.0×10^{-6}
Acephate	1.7×10^{-6}
Alachlor	1.4×10^{-5}
Aldicarb	3.0×10^{-5}
Aldoxycarb	9×10^{-5}
Amitraz	2.6×10^{-6}
Amitrole (aminotriazole)	4.4×10^{-7}
Atrazine	2.9×10^{-7}
Azinphos-methyl	2.0×10^{-7}
Benefin (benfluralin)	6.6×10^{-5}
Benomyl	$< 1.0 \times 10^{-10}$
Bifenox	2.4×10^{-6}
Bromacil acid	3.1×10^{-7}
Bromoxynil butyrate ester	1.0×10^{-4}
Butylate	1.3×10^{-2}
Captan	8.0×10^{-8}
Carbaryl	1.2×10^{-6}
Carbofuran	6.0×10^{-7}
Chlorobenzilate	6.8×10^{-6}
Chloroneb	3.0×10^{-3}
Chloropicrin	18
Chlorothalonil	1.0×10^{-3} (estimated)
Chlorpyrifos	1.7×10^{-5}
Clomazone (dimethazone)	1.4×10^{-4}
Cyanazine	1.6×10^{-9}
Cyromazine	3.4×10^{-9}
DCNA (dicloran)	1.3×10^{-6}
DCPA (chlorthal-dimethyl; Dacthal®)	2.5×10^{-6}
Diazinon	6.0×10^{-5}
Dichlobenil	1.0×10^{-3}
Dicofol	4.0×10^{-7}
Dicrotofos	1.6×10^{-4}
Dimethoate	2.5×10^{-5}
Dinocap	4.0×10^{-8}

Table 9.2.2-1 (cont.).

Active Ingredient	Vapor Pressure (mm Hg at 20 to 25°C)
Disulfoton	1.5×10^{-4}
Diuron	6.9×10^{-8}
Endosulfan	1.7×10^{-7}
EPTC	3.4×10^{-2}
Ethalfluralin	8.8×10^{-5}
Ethion	2.4×10^{-6}
Ethoprop (ethoprophos)	3.8×10^{-4}
Fenamiphos	1.0×10^{-6}
Fenthion	2.8×10^{-6}
Fluometuron	9.4×10^{-7}
Fonofos	3.4×10^{-4}
Isofenphos	3.0×10^{-6}
Lindane	3.3×10^{-5}
Linuron	1.7×10^{-5}
Malathion	8.0×10^{-6}
Methamidophos	8.0×10^{-4}
Methazole	1.0×10^{-6}
Methiocarb (mercaptodimethur)	1.2×10^{-4}
Methomyl	5.0×10^{-5}
Methyl parathion	1.5×10^{-5}
Metolachlor	3.1×10^{-5}
Metribuzin	$< 1.0 \times 10^{-5}$
Mevinphos	1.3×10^{-4}
Molinate	5.6×10^{-3}
Naled	2.0×10^{-4}
Norflurazon	2.0×10^{-8}
Oxamyl	2.3×10^{-4}
Oxyfluorfen	2.0×10^{-7}
Parathion (ethyl parathion)	5.0×10^{-6}
PCNB	1.1×10^{-4}
Pendimethalin	9.4×10^{-6}
Permethrin	1.3×10^{-8}
Phorate	6.4×10^{-4}
Phosmet	4.9×10^{-7}
Profenofos	9.0×10^{-7}

Table 9.2.2-1 (cont.).

Active Ingredient	Vapor Pressure (mm Hg at 20 to 25°C)
Prometon	7.7×10^{-6}
Prometryn	1.2×10^{-6}
Propachlor	2.3×10^{-4}
Propanil	4.0×10^{-5}
Propargite	3.0×10^{-3}
Propazine	1.3×10^{-7}
Propoxur	9.7×10^{-6}
Siduron	4.0×10^{-9}
Simazine	2.2×10^{-8}
Tebuthiuron	2.0×10^{-6}
Terbacil	3.1×10^{-7}
Terbufos	3.2×10^{-4}
Thiobencarb	2.2×10^{-5}
Thiodicarb	1.0×10^{-7}
Toxaphene	4.0×10^{-6}
Triallate	1.1×10^{-4}
Tribufos	1.6×10^{-6}
Trichlorfon	2.0×10^{-6}
Trifluralin	1.1×10^{-4}
Triforine	2.0×10^{-7}

[a] Reference 20. Vapor pressures of other pesticide active ingredients can also be found there.

Table 9.2.2-2. TRADE NAMES FOR SELECTED ACTIVE INGREDIENTS[a]

Trade Names[b]	Active Ingredient[c]
Insecticides	
AC 8911	Phorate
Acephate-met	Methamidophos
Alkron®	Ethyl Parathion
Alleron®	Ethyl Parathion
Aphamite®	Ethyl Parathion
Bay 17147	Azinphos-methyl
Bay 19639	Disulfoton
Bay 70143	Carbofuran

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Bay 71628	Methamidophos
Benzoepin	Endosulfan
Beosit®	Endosulfan
Brodan®	Chlorpyrifos
BugMaster®	Carbaryl
BW-21-Z	Permethryn
Carbamine®	Carbaryl
Carfene®	Azinphos-methyl
Cekubaryl®	Carbaryl
Cekudifol®	Dicofol
Cekuthoate®	Dimethoate
CGA-15324	Profenofos
Chlorpyrifos 99%	Chlorpyrifos
Chlorthiepin®	Endosulfan
Comite®	Propargite
Corothion®	Ethyl Parathion
Crisulfan®	Endosulfan
Crunch®	Carbaryl
Curacron	Profenofos
Curaterr®	Carbofuran
Cyclodan®	Endosulfan
Cygon 400®	Dimethoate
D1221	Carbofuran
Daphene®	Dimethoate
Dazzel®	Diazinon
Denapon®	Carbaryl
Devicarb®	Carbaryl
Devigon®	Dimethoate
Devisulphan®	Endosulfan
Devithion®	Methyl Parathion
Diagran®	Diazinon
Dianon®	Diazinon
Diaterr-Fos®	Diazinon
Diazajet®	Diazinon
Diazatol®	Diazinon
Diazide®	Diazinon
Dicarbam®	Carbaryl

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Dicomite®	Dicofol
Dimethogen®	Dimethoate
Dimet®	Dimethoate
Dizinon®	Diazinon
DPX 1410	Oxamyl
Dyzol®	Diazinon
E-605	Ethyl Parathion
Ectiban®	Permethryn
Endocide®	Endosulfan
Endosol®	Endosulfan
ENT 27226	Propargite
ENT27164	Carbofuran
Eradex®	Chlorpyrifos
Ethoprop	Ethoprop
Ethoprophos	Ethoprop
Ethylthiodemeton	Disulfoton
Etilon®	Ethyl Parathion
Fezudin	Diazinon
FMC-5462	Endosulfan
FMC-33297	Permethryn
Fonofos	Dyfonate
Force®	Tefluthrin
Fosfamid	Dimethoate
Furacarb®	Carbofuran
G-24480	Diazinon
Gardentox®	Diazinon
Gearphos®	Methyl Parathion
Golden Leaf Tobacco Spray®	Endosulfan
Hexavin®	Carbaryl
Hoe 2671	Endosulfan
Indothrin®	Permethryn
Insectophene®	Endosulfan
Insyst-D®	Disulfoton
Karbaspray®	Carbaryl
Kayazinon®	Diazinon
Kayazol®	Diazinon
Kryocide®	Cryolite

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Lannate® LV	Methomyl
Larvin®	Thiodicarb
Metafos	Methyl Parathion
Metaphos®	Methyl Parathion
Methomex®	Methomyl
Methyl	Methyl Parathion
Metiltriazotion	Azinphos-methyl
Nipsan®	Diazinon
Niran®	Ethyl Parathion
Nivral®	Thiodicarb
NRDC 143	Permethryn
Ortho 124120	Acephate
Orthophos®	Ethyl Parathion
Panthion®	Ethyl Parathion
Paramar®	Ethyl Parathion
Paraphos®	Ethyl Parathion
Parathene®	Ethyl Parathion
Parathion	Methyl Parathion
Parathion	Ethyl Parathion
Parawet®	Ethyl Parathion
Partron M®	Methyl Parathion
Penncap-M®	Methyl Parathion
Phoskil®	Ethyl Parathion
Piridane®	Chlorpyrifos
Polycron®	Profenofos
PP 557	Permethryn
Pramex®	Permethryn
Prokil®	Cryolite
PT265®	Diazinon
Qamlin®	Permethryn
Rampart®	Phorate
Rhodiatox®	Ethyl Parathion
S276	Disulfoton
SD 8530	Trimethacarb
Septene®	Carbaryl
Sevin 5 Pellets®	Carbaryl
Soprathion®	Ethyl Parathion

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Spectracide®	Diazinon
SRA 5172	Methamidophos
Stathion®	Ethyl Parathion
Tekwaisa®	Methyl Parathion
Temik®	Aldicarb
Tercyl®	Carbaryl
Thimul®	Endosulfan
Thiodan	Endosulfan
Thiofor®	Endosulfan
Thiophos	Ethyl Parathion
Tricarnam®	Carbaryl
Trimetion®	Dimethoate
UC 51762	Thiodicarb
UC 27867	Trimethacarb
Uniroyal D014	Propargite
Yaltox®	Carbofuran
None listed	Dicrotophos
None listed	Terbufos
Herbicides	
A-4D	2,4-D
AC 92553	Pendimethalin
Acclaim	Fenoxaprop-ethyl
Acme MCPA Amine 4®	MCPA
Aljaden®	Sethoxydim
Amiben®	Chloramben
Amilon®-WP	Chloramben
Amine®	MCPA
Aqua-Kleen®	2,4-D
Arrhenal®	DSMA
Arsinyl®	DSMA
Assure®	Quizalofop-ethyl
Avadex® BW	Triallate
Banlene Plus®	MCPA
Banvel®	Dicamba
Barrage®	2,4-D
Basagran	Bentazon
Bay 30130	Propanil

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Bay DIC 1468	Metribuzin
Bay 94337	Metribuzin
Benefex®	Benefin
Benfluralin	Benefin
Bentazon	Bentazon
Bethrodine	Benefin
BH® MCPA	MCPA
Bioxone®	Methazole
Blazer®	Aciflurofen
Bolero®	Thiobencarb
Border-Master®	MCPA
Brominex®	Bromoxynil
C-2059	Fluometuron
Cekuiron®	Diuron
Cekuquat®	Paraquat
Cekusima®	Simazine
CGA-24705	Metolachlor
Checkmate®	Sethoxydim
Chloroxone®	2,4-D
Classic®	Chlorimuron-ethyl
Clomazone	Clomazone
Command®	Clomazone
CP50144	Alachlor
Crisuron®	Diuron
Croprider®	2,4-D
Dacthal®	DCPA
Dailon®	Diuron
Depon®	Fenoxaprop-ethyl
Dextrone®	Paraquat
Di-Tac®	DSMA
Diater®	Diuron
DMA	DSMA
DMA-100®	DSMA
DPA	Propanil
DPX-Y6202	Quizalofop-ethyl
EL-110	Benefin
EL-161	Ethalfluralin

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Emulsamine®	2,4-D
Esgram®	Paraquat
Excel®	Fenoxaprop-ethyl
EXP-3864	Quizalofop-ethyl
Expand®	Sethoxydim
Far-Go®	Triallate
Farmco Diuron®	Diuron
Farmco Atrazine Gesaprim®	Atrazine
Fervinal®	Sethoxydim
Ferxone®	2,4-D
Furore®	Fenoxaprop-ethyl
Fusilade 2000	Fluazifop-p-butyl
G-30027	Atrazine
G-34161	Prometryn
G-34162	Ametryn
Gamit®	Clomazone
Genate Plus®	Butylate
Glyphosate Isopropylamine Salt	Glyphosate
Goldquat® 276	Paraquat
Grasidim®	Sethoxydim
HerbAll®	MSMA
Herbaxon®	Paraquat
Herbixol®	Diuron
Higalcoton®	Fluometuron
Hoe 002810	Linuron
Hoe-023408	Diclofop-methyl
Hoe-Grass®	Diclofop-methyl
Hoelon®	Diclofop-methyl
Illoxan®	Diclofop-methyl
Kilsem®	MCPA
Lasso®	Alachlor
Lazo®	Alachlor
Legumex Extra®	MCPA
Lexone® 4L	Metribuzin
Lexone® DF®	Metribuzin
Linorox®	Linuron
LS 801213	Aciflurofen

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
M.T.F.®	Trifluralin
Magister®	Clomazone
Mephanac®	MCPA
Merge 823®	MSMA
Methar® 30	DSMA
Mezopur®	Methazole
Monosodium methane arsenate	MSMA
Nabu®	Sethoxydim
Option®	Fenoxaprop-ethyl
Oxydiazol	Methazole
Paxilon®	Methazole
Pillarquat®	Paraquat
Pillarxone®	Paraquat
Pillarzo®	Alachlor
Pilot®	Quizalofop-ethyl
Plantgard®	2,4-D
Pledge®	Bentazon
PP 005	Fluazifop-p-butyl
Primatol Q®	Prometryn
Probe	Methazole
Prop-Job®	Propanil
Propachlor	Propachlor
Prowl®	Pendimethalin
Rattler®	Glyphosate
RH-6201	Aciflurofen
Rodeo®	Glyphosate
Roundup®	Glyphosate
S 10145	Propanil
Sarclex®	Linuron
Saturno®	Thiobencarb
Saturn®	Thiobencarb
Scepter®	Imazaquin
SD 15418	Cyanazine
Sencor® 4	Metribuzin
Sencor® DF	Metribuzin
Shamrox®	MCPA
Sodar®	DSMA

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Sonalan®	Ethalfluralin
Squadron®	Imazaquin
Squadron®	Pendimethalin
Strel®	Propanil
Surpass®	Vernolate
Targa®	Quizalofop-ethyl
Target MSMA®	MSMA
Telok®	Norflurazon
Tigrex®	Diuron
Total®	Paraquat
Toxer®	Paraquat
Trans-Vert®	MSMA
Tri-4®	Trifluralin
Tri-Scept®	Imazaquin
Tributon®	2,4-D
Trifluralina 600®	Trifluralin
Trinatox D®	Ametryn
Tritex-Extra®	Sethoxydim
Tunic®	Methazole
Unidron®	Diuron
VCS 438	Methazole
Vegiben®	Chloramben
Vernam 10G	Vernolate
Vernam 7E	Vernolate
Vonduron®	Diuron
Weed-Rhap®	MCPA
Weed-B-Gon®	2,4-D
Weedatul®	2,4-D
Weedtrine-II®	2,4-D
Whip®	Fenoxaprop-ethyl
WL 19805	Cyanazine
Zeaphos®	Atrazine
Zelan®	MCPA
None listed	EPTC
None listed	Fomesafen
None listed	Molinate
None listed	Tridiphane

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Other Active Ingredients	
A7 Vapam®	Metam Sodium
Aquacide®	Diquat
Avicol®	PCNB
Carbam (MAF)	Metam Sodium
Clortocaf Ramato®	Chlorothalonil
Clortosip®	Chlorothalonil
Cotton Aide HC®	Cacodylic
De-Green®	Tribufos
DEF®	Tribufos
Deiquat	Diquat
Dextrone®	Diquat
E-Z-Off D®	Tribufos
Earthcide®	PCNB
Exotherm Termil®	Chlorothalonil
Folex®	Tribufos
Folosan®	PCNB
Fos-Fall A®	Tribufos
Karbation®	Metam Sodium
Kobutol®	PCNB
Kobu®	PCNB
Kypman® 80	Maneb
M-Diphar®	Maneb
Mancozin®	Mancozeb
Maneba®	Maneb
Manebe	Maneb
Manzate® 200	Mancozeb
Manzeb	Mancozeb
Manzin®	Mancozeb
Maposol®	Metam Sodium
Metam for the Acid	Metam Sodium
Moncide®	Cacodylic
Montar®	Cacodylic
Nemispor®	Mancozeb
Pentagen®	PCNB
Quintozene	PCNB
Rad-E-Cate® 25	Cacodylic

Table 9.2.2-2 (cont.).

Trade Names[b]	Active Ingredient[c]
Reglon	Diquat
Riozeb®	Mancozeb
RTU® PCNB	PCNB
Sectagon® II	Metam Sodium
SMDC	Metam Sodium
Soil-Prep®	Metam Sodium
Sopranebe®	Maneb
Superman® Maneb F	Maneb
Terrazan®	PCNB
Tersan 1991®	Benomyl
TriPCNB®	PCNB
Tubothane®	Maneb
Weedtrine-D®	Diquat
Ziman-Dithane®	Mancozeb
None listed	Dimethipin
None listed	Ethephon
None listed	Thiadiazuron

[a] Reference 2. See Reference 22 for selected pesticides used on major field crops.
[b] Reference 2.
[c] Common names. See Reference 2 for chemical names.

Table 9.2.2-3. AVERAGE VOC CONTENT OF PESTICIDE INERT INGREDIENT PORTION, BY FORMULATION TYPE[a]

Formulation Type	Average VOC Content Of Inert Position (wt. %)
Oils	66
Solution/liquid (ready to use)	20
Emulsifiable concentrate	56
Aqueous concentrate	21
Gel, paste, cream	40
Pressurized gas	29
Flowable (aqueous) concentrate	21
Microencapsulated	23
Pressurized liquid/sprays/foggers	39
Soluble powder	12
Impregnated material	38

Table 9.2.2-3 (cont.).

Formulation Type	Average VOC Content Of Inert Position (wt. %)
Pellet/tablet/cake/briquette	27
Wettable powder	25
Dust/powder	21
Dry flowable	28
Granule/flake	25
Suspension	15
Paint/coatings	64

[a] Reference 21.

Table 9.2.2-4 (Metric And English Units).
UNCONTROLLED EMISSION FACTORS FOR PESTICIDE ACTIVE INGREDIENTS[a]

EMISSION FACTOR RATING: E

Vapor Pressure Range (mm Hg at 20 to 25°C)[b]	Emission Factor[c]	
	kg/Mg	lb/ton
Surface application (SCC 24-61-800-001)		
1×10^{-4} to 1×10^{-6}	350	700
$>1 \times 10^{-4}$	580	1,160
Soil incorporation (SCC 24-61-800-002)		
$<1 \times 10^{-6}$	2.7	5.4
1×10^{-4} to 1×10^{-6}	21	42
$>1 \times 10^{-4}$	52	104

[a] Factors are functions of application method and vapor pressure. SCC = Source Classification Code.

[b] See Reference 20 for vapor pressures of specific active ingredients.

[c] References 1,15-18. Expressed as equivalent weight of active ingredients volatilized/unit weight of active ingredients applied.

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9.2.3 Orchard Heaters

9.2.3.1 General[1-6]

Orchard heaters are commonly used in various areas of the United States to prevent frost damage to fruit and fruit trees. The 5 common types of orchard heaters—pipeline, lazy flame, return stack, cone, and solid fuel—are shown in Figure 9.2.3-1. The pipeline heater system is operated from a central control and fuel is distributed by a piping system from a centrally located tank. Lazy flame, return stack, and cone heaters contain integral fuel reservoirs, but can be converted to a pipeline system. Solid fuel heaters usually consist only of solid briquettes, which are placed on the ground and ignited.

The ambient temperature at which orchard heaters are required is determined primarily by the type of fruit and stage of maturity, by the daytime temperatures, and by the moisture content of the soil and air.

During a heavy thermal inversion, both convective and radiant heating methods are useful in preventing frost damage; there is little difference in the effectiveness of the various heaters. The temperature response for a given fuel rate is about the same for each type of heater as long as the heater is clean and does not leak. When there is little or no thermal inversion, radiant heat provided by pipeline, return stack, or cone heaters is the most effective method for preventing damage.

Proper location of the heaters is essential to the uniformity of the radiant heat distributed among the trees. Heaters are usually located in the center space between 4 trees and are staggered from 1 row to the next. Extra heaters are used on the borders of the orchard.

9.2.3 Emissions[1,6]

Emissions from orchard heaters are dependent on the fuel usage rate and the type of heater. Pipeline heaters have the lowest particulate emission rates of all orchard heaters. Hydrocarbon emissions are negligible in the pipeline heaters and in lazy flame, return stack, and cone heaters that have been converted to a pipeline system. Nearly all of the hydrocarbon losses are evaporative losses from fuel contained in the heater reservoir. Because of the low burning temperatures used, nitrogen oxide emissions are negligible.

Emission factors for the different types of orchard heaters are presented in Table 9.2.3-1 and Figure 9.2.3-2. Factors are expressed in units of kilograms per heater-hour (kg/htr-hr) and pounds per heater-hour (lb/htr-hr).

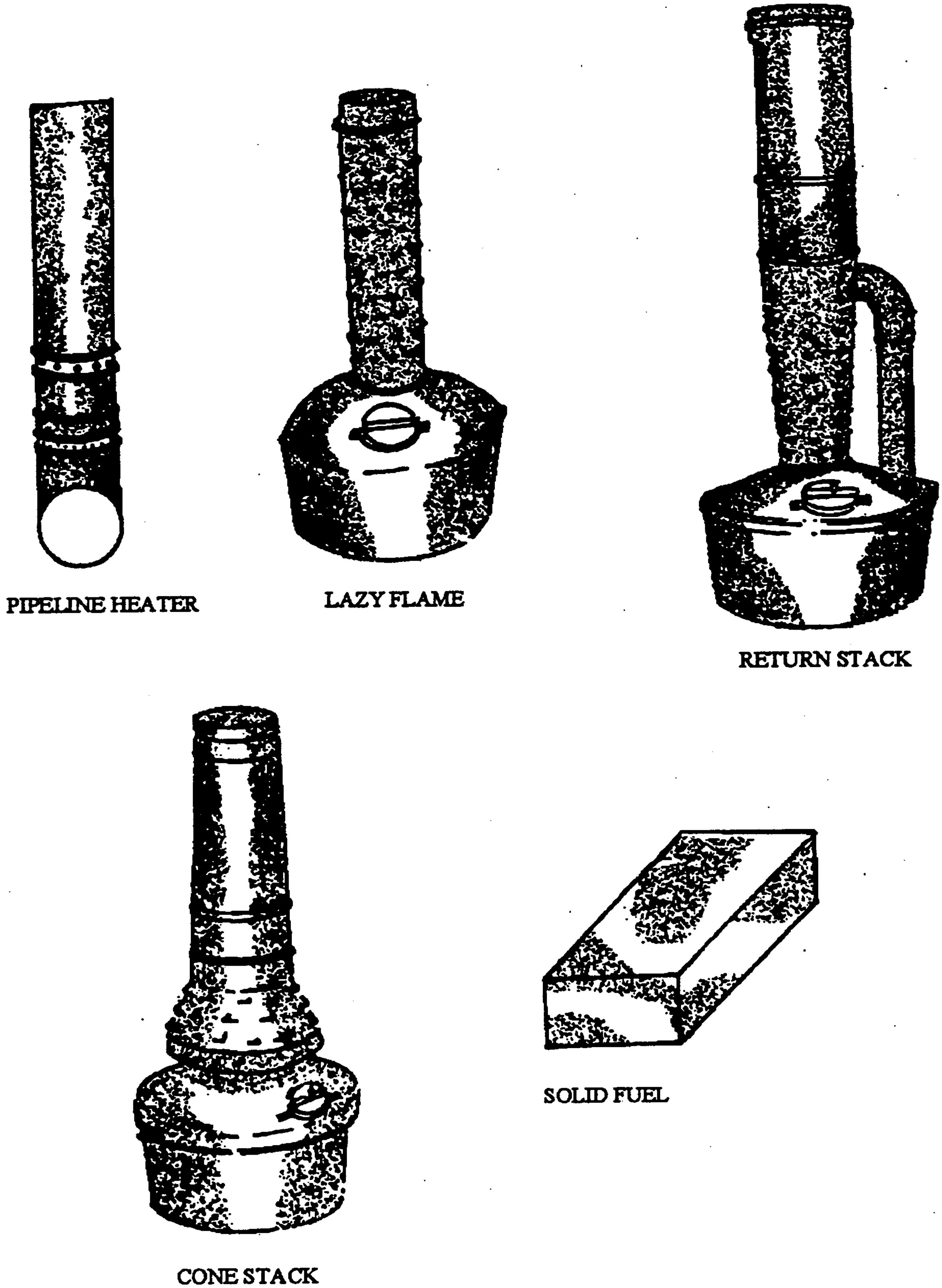

Figure 9.2.3-1. Types of orchard heaters.[6]

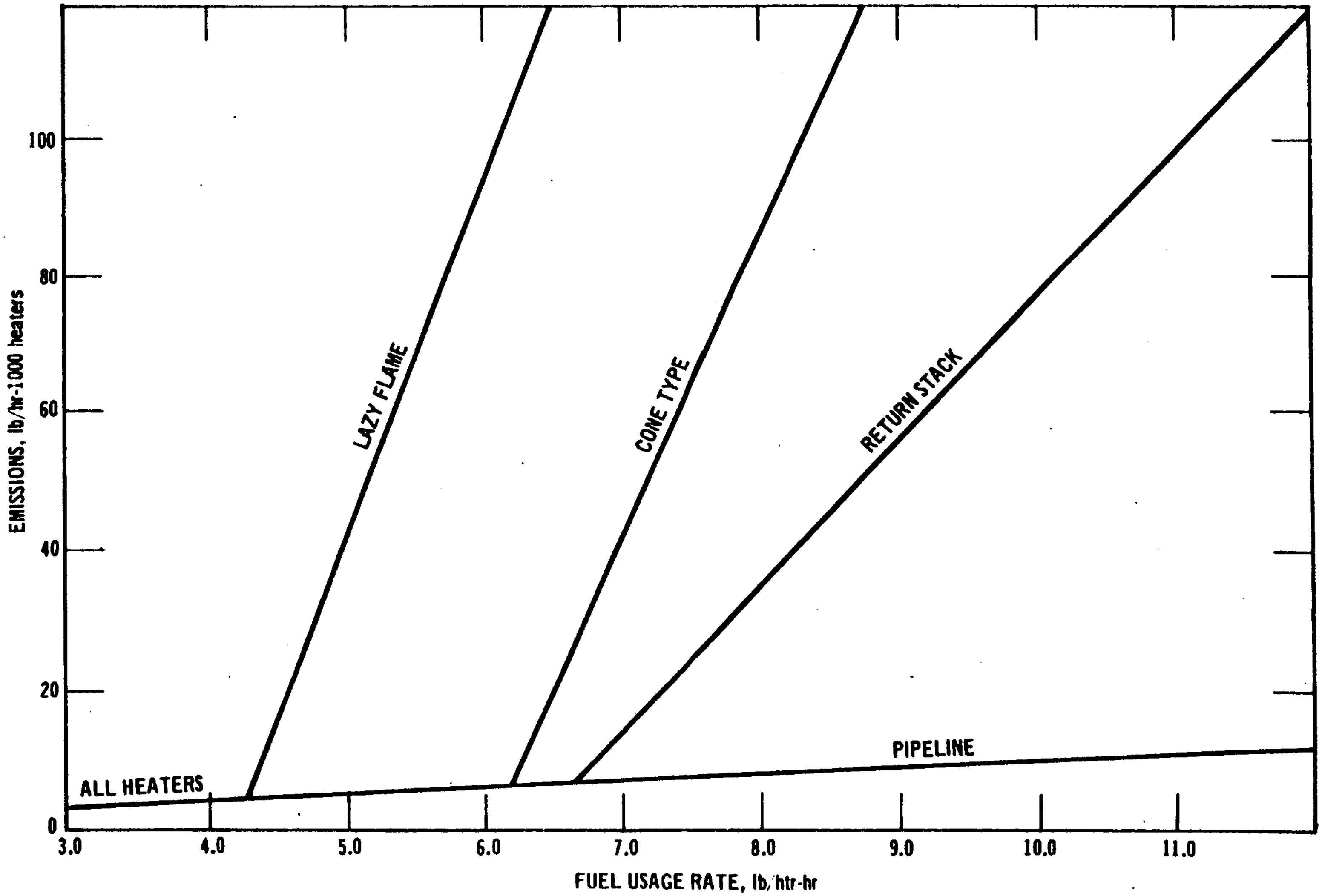

Figure 9.2.3-2. Particulate emissions from orchard heaters.[3,6]

Table 9.2.3-1 (Metric And English Units). EMISSION FACTORS FOR ORCHARD HEATERS[a]

EMISSION FACTOR RATING: C

Pollutant	Type Of Heater				
	Pipeline	Lazy Flame	Return Stack	Cone	Solid Fuel
Particulate					
kg/htr-hr	—[b]	—[b]	—[b]	—[b]	0.023
lb/htr-hr	—[b]	—[b]	—[b]	—[b]	0.05
Sulfur oxides[c]					
kg/htr-hr	0.06S[d]	0.05S	0.06S	0.06S	ND
lb/htr-hr	0.13S	0.11S	0.14S	0.14S	ND
Carbon monoxide					
kg/htr-hr	2.8	ND	ND	ND	ND
lb/htr-hr	6.2	ND	ND	ND	ND
VOCs[e]					
kg/htr-hr	Neg	7.3	7.3	7.3	Neg
lb/htr-hr	Neg	16.0	16.0	16.0	Neg
Nitrogen oxides[f]					
kg/htr-hr	Neg	Neg	Neg	Neg	Neg
lb/htr-hr	Neg	Neg	Neg	Neg	Neg

[a] References 1,3-4, and 6. ND = no data. Neg = negligible.
[b] Particulate emissions for pipeline, lazy flame, return stack, and cone heaters are shown in Figure 9.2.3-2.
[c] Based on emission factors for fuel oil combustion in Section 1.3.
[d] S = sulfur content.
[e] Reference 1. Evaporative losses only. Hydrocarbon emissions from combustion are considered negligible. Evaporative hydrocarbon losses for units that are part of a pipeline system are negligible.
[f] Little nitrogen oxides are formed because of the relatively low combustion temperatures.

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9.3 Harvesting Operations

9.3.1 Cotton Harvesting

9.3.2 Grain Harvesting

9.3.3 Rice Harvesting

9.3.4 Cane Sugar Harvesting

9.3.1 Cotton Harvesting

9.3.1.1 General

Wherever it is grown in the U. S., cotton is defoliated or desiccated prior to harvest. Defoliants are used on the taller varieties of cotton that are machine picked for lint and seed cotton, and desiccants usually are used on short, stormproof cotton varieties of lower yield that are harvested by mechanical stripper equipment. More than 99 percent of the national cotton area is harvested mechanically. The 2 principal harvest methods are machine picking, with 70 percent of the harvest from 61 percent of the area, and machine stripping, with 29 percent of the harvest from 39 percent of the area. Picking is practiced throughout the cotton regions of the U. S., and stripping is limited chiefly to the dry plains of Texas and Oklahoma.

Defoliation may be defined as the process by which leaves are abscised from the plant. The process may be initiated by drought stress, low temperatures, or disease, or it may be chemically induced by topically applied defoliant agents or by overfertilization. The process helps lodged plants to return to an erect position, removes the leaves that can clog the spindles of the picking machine and stain the fiber, accelerates the opening of mature bolls, and reduces boll rots. Desiccation by chemicals is the drying or rapid killing of the leaf blades and petioles, with the leaves remaining in a withered state on the plant. Harvest-aid chemicals are applied to cotton as water-based spray, either by aircraft or by a ground machine.

Mechanical cotton pickers, as the name implies, pick locks of seed cotton from open cotton bolls and leave the empty burs and unopened bolls on the plant. Requiring only 1 operator, typical modern pickers are self-propelled and can simultaneously harvest 2 rows of cotton at a speed of 1.1 to 1.6 meters per second (m/s) (2.5 - 3.6 miles per hour [mph]). When the picker basket gets filled with seed cotton, the machine is driven to a cotton trailer at the edge of the field. As the basket is hydraulically raised and tilted, the top swings open allowing the cotton to fall into the trailer. When the trailer is full, it is pulled from the field, usually by pickup truck, and taken to a cotton gin.

Mechanical cotton strippers remove open and unopened bolls, along with burs, leaves, and stems from cotton plants, leaving only bare branches. Tractor-mounted, tractor-pulled, or self-propelled strippers require only 1 operator. They harvest from 1 to 4 rows of cotton at speeds of 1.8 to 2.7 m/s (4.0 - 6.0 mph). After the cotton is stripped, it enters a conveying system that carries it from the stripping unit to an elevator. Most conveyers utilize either augers or a series of rotating spike-toothed cylinders to move the cotton, accomplishing some cleaning by moving the cotton over perforated, slotted, or wire mesh screen. Dry plant material (burs, stems, and leaves) is crushed and dropped through openings to the ground. Blown air is sometimes used to assist cleaning.

9.3.1.2 Emissions And Controls

Emission factors for the drifting of major chemicals applied to cotton were compiled from literature and reported in Reference 1. In addition, drift losses from arsenic acid spraying were developed by field testing. Two off-target collection stations, with 6 air samplers each, were located downwind from the ground spraying operations. The measured concentration was applied to an infinite line source atmosphere diffusion model (in reverse) to calculate the drift emission rate. This was in turn used for the final emission factor calculation. The emissions occur from July to October, preceding by 2 weeks the period of harvest in each cotton producing region. The drift emission factor for arsenic acid is 8 times lower than previously estimated, since Reference 1 used a ground rig rather than an airplane, and because of the low volatility of arsenic acid. Various methods of controlling drop size, proper timing of application, and modification of equipment are practices that can reduce drift hazards. Fluid additives have been used that increase the viscosity of the spray formulation, and thus decrease the number of fine droplets (< 100 micrometers [μm]). Spray nozzle design and orientation also control the droplet size spectrum. Drift emission factors for the defoliation or desiccation of cotton are listed in Table 9.3.1-1. Factors are expressed in units of grams per kilogram (g/kg) and pounds per ton (lb/ton).

Table 9.3.1-1 (Metric And English Units). EMISSION FACTORS FOR DEFOLIATION OR DESICCATION OF COTTON[a]

EMISSION FACTOR RATING: C

Pollutant	Emission Factor[b]	
	g/kg	lb/ton
Sodium chlorate	10.0	20.0
DEF®[c]	10.0	20.0
Arsenic acid	6.1	12.2
Paraquat	10.0	20.0

[a] Reference 1.
[b] Factor is in terms of quantity of drift per quantity applied.
[c] Pesticide trade name.

Three unit operations are involved in mechanical harvesting of cotton: harvesting, trailer loading (basket dumping), and transport of trailers in the field. Emissions from these operations are in the form of solid particulates. Particulate emissions (<7 μm mean aerodynamic diameter) from these operations were developed in Reference 2. The particulates are composed mainly of raw cotton dust and solid dust, which contains free silica. Minor emissions include small quantities of pesticide, defoliant, and desiccant residues that are present in the emitted particulates. Dust concentrations from harvesting were measured by following each harvesting machine through the field at a constant distance directly downwind from the machine while staying in the visible plume centerline. The procedure for trailer loading was the same, but since the trailer is stationary while being loaded, it was necessary only to stand a fixed distance directly downwind from the trailer while the plume or puff passed over. Readings were taken upwind of all field activity to get background concentrations. Particulate emission factors for the principal types of cotton harvesting operations in the U. S. are shown in Table 9.3.1-2. The factors are based on average machine speed of 1.34 m/s (3.0 mph) for pickers, and 2.25 m/s (5.03 mph) for strippers, on a basket capacity of 109 kg (240 lb), on a trailer capacity of 6 baskets, on a lint cotton yield of 63.0 megagrams per square kilometer (Mg/km^2) (1.17 bales/acre) for pickers and 41.2 Mg/km^2 (0.77 bale/acre) for strippers, and on a transport speed of 4.47 m/s (10.0 mph). Factors are expressed in units of kg/km^2 and pounds per square mile (lb/mi^2). Analysis of particulate samples showed average free silica content of 7.9 percent for mechanical cotton picking and 2.3 percent for mechanical cotton stripping. Estimated maximum percentages for pesticides, defoliants, and desiccants from harvesting are also noted in Table 9.3.1-2. No current cotton harvesting equipment or practices provide for control of emissions. In fact,

Table 9.3.1-2 (Metric And English Units). PARTICULATE EMISSION FACTORS[a] FOR COTTON HARVESTING OPERATIONS

EMISSION FACTOR RATING: C

Type of Harvester	Harvesting		Trailer Loading		Transport		Total	
	kg/km²	lb/mi²	kg/km²	lb/mi²	kg/km²	lb/mi²	kg/km²	lb/mi²
Picker[b]								
Two-row, with basket	0.46	2.6	0.070	0.40	0.43	2.5	0.96	5.4
Stripper[c]								
Two-row, pulled trailer	7.4	42	NA	NA	0.28	1.6	7.7	44
Two-row, with basket	2.3	13	0.092	0.52	0.28	1.6	2.7	15
Four-row, with basket	2.3	13	0.092	0.52	0.28	1.6	2.7	15
Weighted average[d]	4.3	24	0.056	0.32	0.28	1.6	4.6	26

[a] Emission factors are from Reference 2 for particulate of <7 μm mean aerodynamic diameter. NA = not applicable.

[b] Free silica content is 7.9% maximum content of pesticides and defoliants is 0.02%.

[c] Free silica content is 2.3%; maximum content of pesticides and desiccants is 0.2%.

[d] The weighted average stripping factors are based on estimates that 2% of all strippers are 4-row models with baskets and, of the remainder, 40% are 2-row models pulling trailers and 60% are 2-row models with mounted baskets.

equipment design and operating practices tend to maximize emissions. Preharvest treatment (defoliation and desiccation) and harvest practices are timed to minimize moisture and trash content, so they also tend to maximize emissions. Soil dust emissions from field transport can be reduced by lowering vehicle speed.

References For Section 9.3.1

1. J. A. Peters and T. R. Blackwood, *Source Assessment: Defoliation Of Cotton—State Of The Art*, EPA-600/2-77-107g, U. S. Environmental Protection Agency, Cincinnati, OH, July 1977.

2. J. W. Snyder and T. R. Blackwood, *Source Assessment: Mechanical Harvesting Of Cotton—State Of The Art*, EPA-600/2-77-107d, U. S. Environmental Protection Agency, Cincinnati, OH, July 1977.

9.3.2 Grain Harvesting

9.3.2.1 General[1]

Harvesting of grain refers to the activities performed to obtain the cereal kernels of the plant for grain, or the entire plant for forage and/or silage uses. These activities are accomplished by machines that cut, thresh, screen, clean, bind, pick, and shell the crops in the field. Harvesting also includes loading harvested crops into trucks and transporting crops in the grain field.

Crops harvested for their cereal kernels are cut as close as possible to the inflorescence (the flowering portion containing the kernels). This portion is threshed, screened, and cleaned to separate the kernels. The grain is stored in the harvest machine while the remainder of the plant is discharged back onto the field.

Combines perform all of the above activities in 1 operation. Binder machines only cut the grain plants and tie them into bundles, or leave them in a row in the field (called a windrow). The bundles are allowed to dry for threshing later by a combine with a pickup attachment.

Corn harvesting requires the only exception to the above procedures. Corn is harvested by mechanical pickers, picker/shellers, and combines with corn head attachments. These machines cut and husk the ears from the standing stalk. The sheller unit also removes the kernels from the ear. After husking, a binder is sometimes used to bundle entire plants into piles (called shocks) to dry.

For forage and/or silage, mowers, crushers, windrowers, field choppers, binders, and similar cutting machines are used to harvest grasses, stalks, and cereal kernels. These machines cut the plants as close to the ground as possible and leave them in a windrow. The plants are later picked up and tied by a baler.

Harvested crops are loaded onto trucks in the field. Grain kernels are loaded through a spout from the combine, and forage and silage bales are manually or mechanically placed in the trucks. The harvested crop is then transported from the field to a storage facility.

9.3.2.2 Emissions And Controls[1]

Emissions are generated by 3 grain harvesting operations: (1) crop handling by the harvest machine, (2) loading of the harvested crop into trucks, and (3) transport by trucks in the field. Particulate matter, composed of soil dust and plant tissue fragments (chaff), may be entrained by wind. Particulate emissions from these operations (<7 micrometers [μm] mean aerodynamic diameter) were developed in Reference 1. For this study, collection stations with air samplers were located downwind (leeward) from the harvesting operations, and dust concentrations were measured at the visible plume centerline and at a constant distance behind the combines. For product loading, since the trailer is stationary while being loaded, it was necessary only to take measurements a fixed distance downwind from the trailer while the plume or puff passed over. The concentration measured for harvesting and loading was applied to a point source atmospheric diffusion model to calculate the source emission rate. For field transport, the air samplers were again placed a fixed distance downwind from the path of the truck, but this time the concentration measured was applied to a line source diffusion model. Readings taken upwind of all field activity gave background concentrations. Particulate emission factors for wheat and sorghum harvesting operations are shown in Table 9.3.2-1.

Table 9.3.2 (Metric And English Units). EMISSION RATES/FACTORS FROM GRAIN HARVESTING[a]

EMISSION FACTOR RATING: D

	Emission Rate[b]				Emission Factor[c]			
	Wheat		Sorghum		Wheat		Sorghum	
Operation	mg/s	lb/hr	mg/s	lb/hr	g/km^2	lb/mi^2	g/km^2	lb/mi^2
Harvest machine	3.4	0.027	23.0	0.18	170.0	0.96	1110.0	6.5
Truck loading	1.8	0.014	1.8	0.014	12.0	0.07	22.0	0.13
Field transport	47.0	0.37	47.0	0.37	110.0	0.65	200.0	1.2

[a] Reference 1.

[b] Assumptions from References 1 are an average combine speed of 3.36 meters per second, combine swath width of 6.07 meters, and a field transport speed of 4.48 meters per second.

[c] In addition to footnote b, assumptions are a truck loading time of 6 minutes, a truck capacity of 0.052 km^2 for wheat and 0.029 km^2 for sorghum, and a filled truck travel time of 125 seconds per load.

Emission rates are expressed in units of milligrams per second (mg/s) and pounds per hour (lb/hr); factors are expressed in units of grams per square kilometer (g/km^2) and pounds per square mile (lb/mi^2).

There are no control techniques specifically implemented for the reduction of air pollution emissions from grain harvesting. However, several practices and occurrences do affect emission rates and concentration. The use of terraces, contouring, and stripcropping to inhibit soil erosion will suppress the entrainment of harvested crop fragments in the wind. Shelterbelts, positioned perpendicular to the prevailing wind, will lower emissions by reducing the wind velocity across the field. By minimizing tillage and avoiding residue burning, the soil will remain consolidated and less prone to disturbance from transport activities.

Reference For Section 9.3.2

1. R. A. Wachten and T. R. Blackwood, *Source Assessment: Harvesting Of Grain—State Of The Art*, EPA-600/2-79-107f, U. S. Environmental Protection Agency, Cincinnati, OH, July 1977.

9.3.3 Rice Harvesting

[Work In Progress]

9.3.4 Cane Sugar Harvesting

[Work In Progress]

9.4 Livestock And Poultry Feed Operations

9.4.1 Cattle Feedlots

9.4.2 Swine Feedlots

9.4.3 Poultry Houses

9.4.4 Dairy Farms

9.4.1 Cattle Feedlots

[Work In Progress]

9.4.2 Swine Feedlots

[Work In Progress]

9.4.3 Poultry Houses

[Work In Progress]

9.4.4 Dairy Farms

[Work In Progress]

9.5 Animal And Meat Products Preparation

9.5.1 Meat Packing Plants

9.5.2 Meat Smokehouses

9.5.3 Meat Rendering Plants

9.5.4 Manure Processing

9.5.5 Poultry Slaughtering

9.5.1 Meat Packing Plants

[Work In Progress]

9.5.2 Meat Smokehouses

[Work In Progress]

9.5.3 Meat Rendering Plants

[Work In Progress]

9.5.4 Manure Processing

[Work In Progress]

9.5.5 Poultry Slaughtering

[Work In Progress]

9.6 Dairy Products

[Work In Progress]

9.6.1 Natural And Processed Cheese

[Work In Progress]

9.7 Cotton Ginning

[Work In Progress]

9.8 Preserved Fruits And Vegetables

9.8.1 Canned Fruits And Vegetables

9.8.2 Dehydrated Fruits And Vegetables

9.8.3 Pickles, Sauces And Salad Dressings

9.8.1 Canned Fruits And Vegetables

[Work In Progress]

9.8.2 Dehydrated Fruits And Vegetables

[Work In Progress]

9.8.3 Pickles, Sauces And Salad Dressings

[Work In Progress]

9.9 Grain Processing

9.9.1 Grain Elevators And Processes

9.9.2 Cereal Breakfast Food

9.9.3 Pet Food

9.9.4 Alfalfa Dehydration

9.9.5 Pasta Manufacturing

9.9.6 Bread Baking

9.9.7 Corn Wet Milling

9.9.1 Grain Elevators And Processes

[Work In Progress]

9.9.2 Cereal Breakfast Food

[Work In Progress]

9.9.3 Pet Food

[Work In Progress]

9.9.4 Alfalfa Dehydration

[Work In Progress]

9.9.5 Pasta Manufacturing

[Work In Progress]

9.9.6 Bread Baking

[Work In Progress]

9.9.7 Corn Wet Milling

9.9.7.1 General[1]

Establishments in corn wet milling are engaged primarily in producing starch, syrup, oil, sugar, and byproducts such as gluten feed and meal, from wet milling of corn and sorghum. These facilities may also produce starch from other vegetables and grains, such as potatoes and wheat. In 1994, 27 corn wet milling facilities were reported to be operating in the United States.

9.9.7.2 Process Description[1-4]

The corn wet milling industry has grown in its 150 years of existence into the most diversified and integrated of the grain processing industries. The corn refining industry produces hundreds of products and byproducts, such as high fructose corn syrup (HFCS), corn syrup, starches, animal feed, oil, and alcohol.

In the corn wet milling process, the corn kernel (see Figure 9.9.7-1) is separated into 3 principal parts: (1) the outer skin, called the bran or hull; (2) the germ, containing most of the oil; and (3) the endosperm (gluten and starch). From an average bushel of corn weighing 25 kilograms (kg) (56 pounds [lb]), approximately 14 kg (32 lb) of starch is produced, about 6.6 kg (14.5 lb) of feed and feed products, about 0.9 kg (2 lb) of oil, and the remainder is water. The overall corn wet milling process consists of numerous steps or stages, as shown schematically in Figure 9.9.7-2.

Shelled corn is delivered to the wet milling plant primarily by rail and truck and is unloaded into a receiving pit. The corn is then elevated to temporary storage bins and scale hoppers for weighing and sampling. The corn then passes through mechanical cleaners designed to remove unwanted material, such as pieces of cobs, sticks, and husks, as well as meal and stones. The cleaners agitate the kernels over a series of perforated metal sheets through which the smaller foreign materials drop. A blast of air blows away chaff and dust, and electromagnets remove bits of metal. Coming out of storage bins, the corn is given a second cleaning before going into "steep" tanks.

Steeping, the first step in the process, conditions the grain for subsequent milling and recovery of corn constituents. Steeping softens the kernel for milling, helps break down the protein holding the starch particles, and removes certain soluble constituents. Steeping takes place in a series of tanks, usually referred to as steeps, which are operated in continuous-batch process. Steep tanks may hold from 70.5 to 458 cubic meters (m^3) (2,000 to 13,000 bushels [bu]) of corn, which is then submerged in a current of dilute sulfurous acid solution at a temperature of about 52°C (125°F). Total steeping time ranges from 28 to 48 hours. Each tank in the series holds corn that has been steeping for a different length of time.

Corn that has steeped for the desired length of time is discharged from its tank for further processing, and the tank is filled with fresh corn. New steeping liquid is added, along with recycled water from other mill operations, to the tank with the "oldest" corn (in steep time). The liquid is then passed through a series of tanks, moving each time to the tank holding the next "oldest" batch of corn until the liquid reaches the newest batch of corn.

Water drained from the newest corn steep is discharged to evaporators as so-called "light steepwater" containing about 6 percent of the original dry weight of grain. By dry-weight, the solids

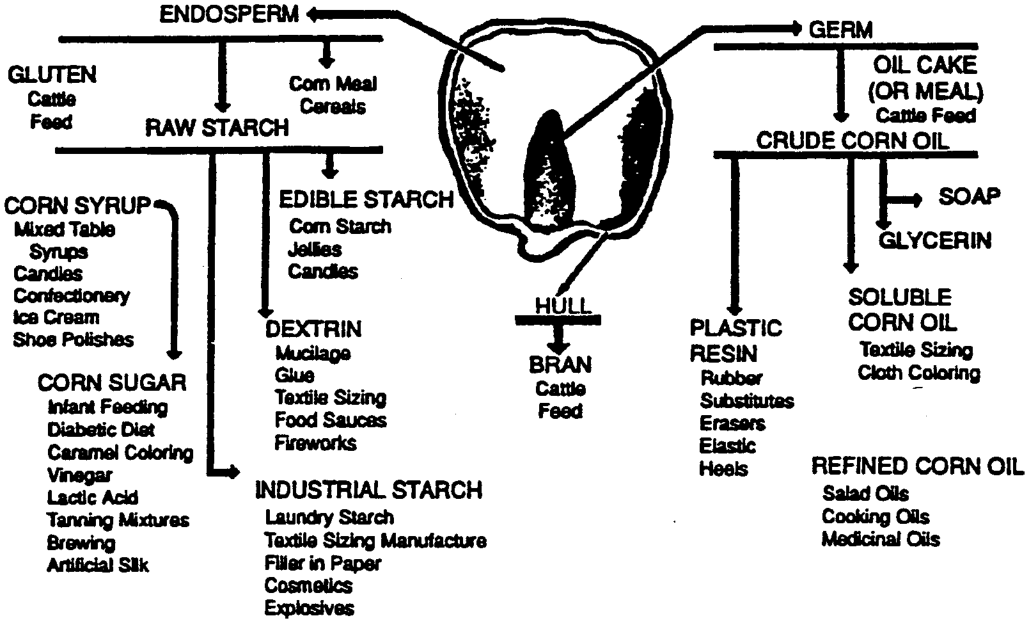

Figure 9.9.7-1. Various uses of corn.

in the steepwater contain 35 to 45 percent protein and are worth recovering as feed supplements. The steepwater is concentrated to 30 to 55 percent solids in multiple-effect evaporators. The resulting steeping liquor, or heavy steepwater, is usually added to the fibrous milling residue, which is sold as animal feed. Some steepwater may also be sold for use as a nutrient in fermentation processes.

The steeped corn passes through degerminating mills, which tear the kernel apart to free both the germ and about half of the starch and gluten. The resultant pulpy material is pumped through liquid cyclones to extract the germ from the mixture of fiber, starch, and gluten. The germ is subsequently washed, dewatered, and dried; the oil extracted; and the spent germ sold as corn oil meal or as part of corn gluten feed. More details on corn oil production are contained in Section 9.11.1, "Vegetable Oil Processing".

The product slurry passes through a series of washing, grinding, and screening operations to separate the starch and gluten from the fibrous material. The hulls are discharged to the feed house, where they are dried for use in animal feeds.

At this point, the main product stream contains starch, gluten, and soluble organic materials. The lower density gluten is separated from the starch by centrifugation, generally in 2 stages. A high-quality gluten, of 60 to 70 percent protein and 1.0 to 1.5 percent solids, is then centrifuged, dewatered, and dried for adding to animal feed. The centrifuge underflow containing the starch is passed to starch washing filters to remove any residual gluten and solubles.

The pure starch slurry is now directed into 1 of 3 basic finishing operations, namely, ordinary dry starch, modified starches, and corn syrup and sugar. In the production of ordinary dry starch, the starch slurry is dewatered with vacuum filters or basket centrifuges. The discharged starch cake has a moisture content of 35 to 42 percent and is further dewatered thermally in 1 of several types of dryers. The dry starch is then packaged or shipped in bulk, or a portion may be kept for use in making dextrin.

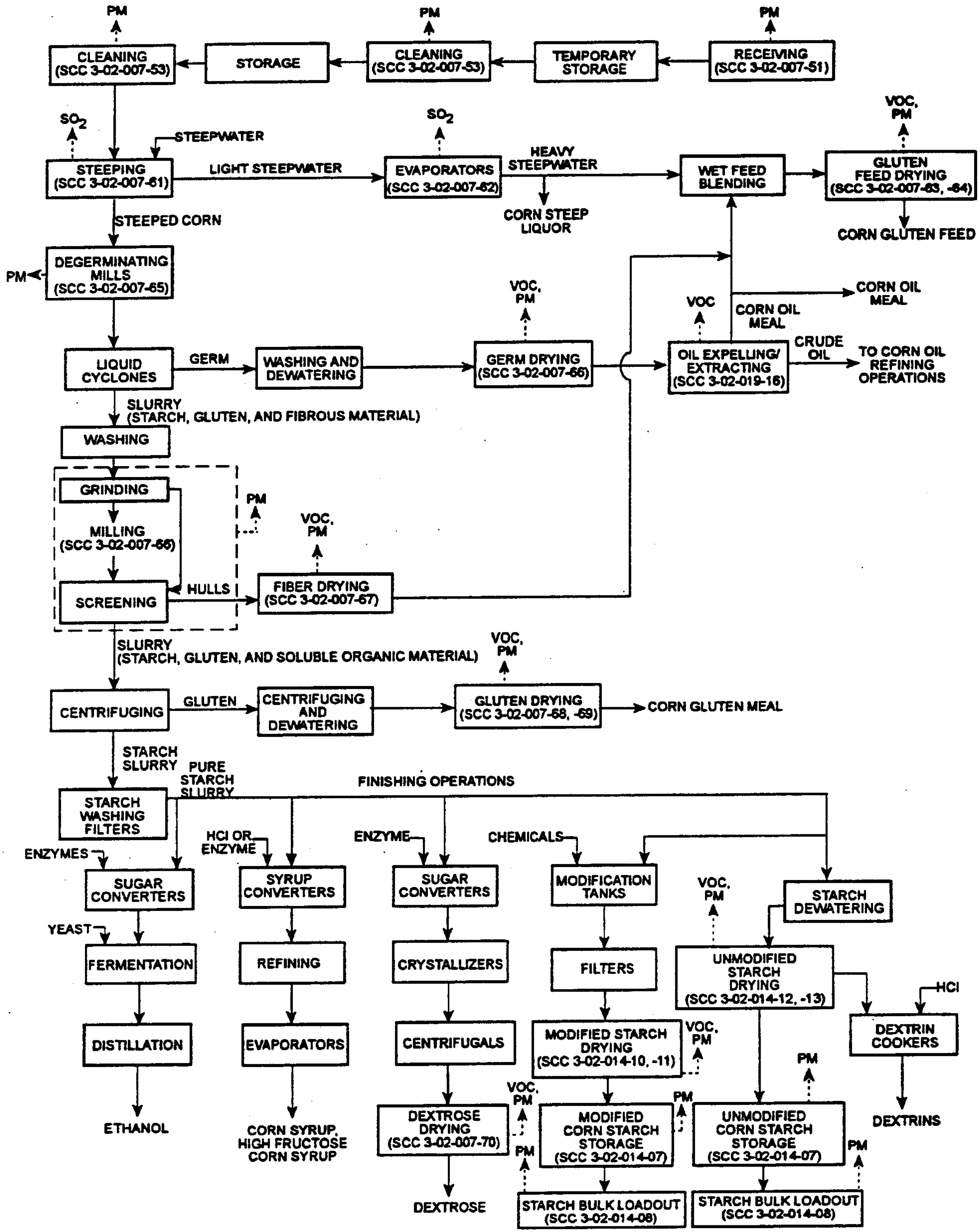

Figure 9.9.7-2. Corn wet milling process flow diagram.[1-4]
(Source Classification Codes in parentheses.)

Modified starches are manufactured for various food and trade industries for which unmodified starches are not suitable. For example, large quantities of modified starches go into the manufacture of paper products as binding for the fiber. Modifying is accomplished in tanks that treat the starch slurry with selected chemicals, such as hydrochloric acid, to produce acid-modified starch; sodium hypochlorite, to produce oxidized starch; and ethylene oxide, to produce hydroxyethyl starches. The treated starch is then washed, dried, and packaged for distribution.

Across the corn wet milling industry, about 80 percent of starch slurry goes to corn syrup, sugar, and alcohol production. The relative amounts of starch slurry used for corn syrup, sugar, and alcohol production vary widely among plants. Syrups and sugars are formed by hydrolyzing the starch — partial hydrolysis resulting in corn syrup, and complete hydrolysis producing corn sugar. The hydrolysis step can be accomplished using mineral acids, enzymes, or a combination of both. The hydrolyzed product is then refined, which is the decolorization with activated carbon and the removal of inorganic salt impurities with ion exchange resins. The refined syrup is concentrated to the desired level in evaporators and is cooled for storage and shipping.

Dextrose production is quite similar to corn syrup production, the major difference being that the hydrolysis process is allowed to go to completion. The hydrolyzed liquor is refined with activated carbon and ion exchange resins, to remove color and inorganic salts, and the product stream is concentrated by evaporation to the 70 to 75 percent solids range. After cooling, the liquor is transferred to crystallizing vessels, where it is seeded with sugar crystals from previous batches. The solution is held for several days while the contents are further cooled and the dextrose crystallizes. After about 60 percent of the dextrose solids crystallize, they are removed from the liquid by centrifuges, are dried, and are packed for shipment.

A smaller portion of the syrup refinery is devoted to the production of corn syrup solids. In this operation, refined corn syrup is further concentrated by evaporation to a high dry substance level. The syrup is then solidified by rapid cooling and subsequently milled to form an amorphous crystalline product.

Ethanol is produced by the addition of enzymes to the pure starch slurry to hydrolyze the starch to fermentable sugars. Following hydrolysis, yeast is added to initiate the fermentation process. After about 2 days, approximately 90 percent of the starch is converted to ethanol. The fermentation broth is transferred to a still where the ethanol (about 50 vol%) is distilled. Subsequent distillation and treatment steps produce 95 percent, absolute, or denatured ethanol. More details on this ethanol production process, emissions, and emission factors is contained in Section 6.21, "Ethanol".

9.9.7.3 Emissions And Controls[1-2,4-8]

The diversity of operations in corn wet milling results in numerous and varied potential sources of air pollution. It has been reported that the number of process emission points at a typical plant is well over 100. The main pollutant of concern in grain storage and handling operations in corn wet milling facilities is particulate matter (PM). Organic emissions (e. g., hexane) from certain operations at corn oil extraction facilities may also be significant. These organic emissions (and related emissions from soybean processing) are discussed in Section 9.11.1, "Vegetable Oil Processing". Other possible pollutants of concern are volatile organic compounds (VOC) and combustion products from grain drying, sulfur dioxide (SO_2) from corn wet milling operations, and organic materials from starch production. The focus here is primarily on PM sources for grain handling operations. Sources of VOC and SO_2 are identified, although no data are available to quantify emissions.

Emission sources associated with grain receiving, cleaning, and storage are similar in character to those involved in all other grain elevator operations, and other PM sources are comparable to those found in other grain processing plants as described in Section 9.9.1, "Grain Elevators And Processes". However, corn wet milling operations differ from other processes in that they are also sources of SO_2 and VOC emissions, as described below.

The corn wet milling process uses about 1.1 to 2.0 kg of SO_2 per megagram (Mg) of corn (0.06 to 0.11 lb/bu). The SO_2 is dissolved in process waters, but its pungent odor is present in the slurries, necessitating the enclosing and venting of the process equipment. Vents can be wet-scrubbed with an alkaline solution to recover the SO_2 before the exhaust gas is discharged to the atmosphere. The most significant source of VOC emissions, and also a source of PM emissions, from corn wet milling is the exhaust from the different drying processes. The starch modification procedures also may be sources of acid mists and VOC emissions, but data are insufficient to characterize or to quantify these emissions.

Dryer exhausts exhibit problems with odor and blue haze (opacity). Germ dryers emit a toasted smell that is not considered objectionable in most areas. Gluten dryer exhausts do not create odor or visible emission problems if the drying temperature does not exceed 427°C (800°F). Higher temperatures promote hot smoldering areas in the drying equipment, creating a burnt odor and a blue-brown haze. Feed drying, where steepwater is present, results in environmentally unacceptable odor if the drying temperature exceeds 427°C (800°F). Blue haze formation is a concern when drying temperatures are elevated. These exhausts contain VOC with acrid odors, such as acetic acid and acetaldehyde. Rancid odors can come from butyric and valeric acids, and fruity smells emanate from many of the aldehydes present.

The objectionable odors indicative of VOC emissions from process dryers have been reduced to commercially acceptable levels with ionizing wet-collectors, in which particles are charged electrostatically with up to 30,000 volts. An alkaline wash is necessary before and after the ionizing sections. Another approach to odor/VOC control is thermal oxidation at approximately 750°C (1382°F) for 0.5 seconds, followed by some form of heat recovery. This hot exhaust can be used as the heat source for other dryers or for generating steam in a boiler specifically designed for this type of operation. Incineration can be accomplished in conventional boilers by routing the dryer exhaust gases to the primary air intake. The limitations of incineration are potential fouling of the boiler air intake system with PM and derated boiler capacity because of low oxygen content. These limitations severely restrict this practice. At least 1 facility has attempted to use a regenerative system, in which dampers divert the gases across ceramic fill where exhaust heats the fumes to be incinerated. Incinerator size can be reduced 20 to 40 percent when some of the dryer exhaust is fed back into the dryer furnace. From 60 to 80 percent of the dryer exhaust may be recycled by chilling it to condense the water before recycling.

The PM emissions generated from grain receiving, handling, and processing operations at corn wet milling facilities can be controlled either by process modifications designed to prevent or inhibit emissions or by application of capture collection systems.

The fugitive emissions from grain handling operations generated by mechanical energy imparted to the dust, both by the operations themselves and by local air currents in the vicinity of the operations, can be controlled by modifying the process or facility to limit the generation of fugitive dust. The primary preventive measures used by facilities are construction and sealing practices that limit the effect of air currents, and minimizing grain free fall distances and grain velocities during handling and transfer. Some recommended construction and sealing practices that minimize emissions are: (1) enclosing the receiving area to the extent practicable; (2) specifying dust-tight cleaning and processing equipment; (3) using lip-type shaft seals at bearings on conveyor and other equipment housings; (4) using flanged inlets and outlets on all spouting, transitions, and miscellaneous hoppers; and (5) fully enclosing and sealing all areas in contact with products handled.

While preventive measures can reduce emissions, most facilities also require ventilation or capture/collection systems to reduce emissions to acceptable levels. Milling operations generally are ventilated, and some facilities use hood systems on all handling and transfer operations. The control devices typically used in conjunction with capture systems for grain handling and processing operations are cyclones (or mechanical collectors) and fabric filters. Both of these systems can achieve acceptable levels of control for many grain handling and processing sources. However, even though cyclone collectors can achieve acceptable performance in some scenarios, and fabric filters are highly efficient, both devices are subject to failure if not properly operated and maintained. Ventilation system malfunction, of course, can lead to increased emissions at the source.

Table 9.9.7-1 shows the filterable PM emission factors developed from the available data on several source/control combinations. Table 9.9.7-2 shows potential sources of VOC and SO_2, although no data are available to characterize these emissions.

Table 9.9.7-1 (Metric And English Units). PARTICULATE MATTER EMISSION FACTORS FOR CORN WET MILLING OPERATIONS[a]

EMISSION FACTOR RATING: E

Emission Source	Type Of Control	Filterable PM[b]	
		kg/Mg	lb/ton
Grain receiving[c] (trucks) (SCC 3-02-007-51)	Fabric filter	0.016	0.033
Grain handling[c] (legs, belts, etc.) (SCC 3-02-007-52)	None	0.43	0.87
Grain cleaning[d] (SCC 3-02-007-53)	None	0.82	1.6
Grain cleaning[d] (SCC 3-02-007-53)	Cyclone	0.086	0.17
Starch storage bin[e] (SCC 3-02-014-07)	Fabric filter	0.0007	0.0014
Starch bulk loadout[f] (SCC 3-02-014-08)	Fabric filter	0.00025	0.00049
Gluten feed drying			
Direct-fired rotary dryers[g] (SCC 3-02-007-63)	Product recovery cyclone	0.13	0.27
Indirect-fired rotary dryers[g] (SCC 3-02-007-64)	Product recovery cyclone[h]	0.25	0.49
Starch drying			
Flash dryers[j] (SCC 3-02-014-10, -12)	Wet scrubber	0.29	0.59
Spray dryers[k] (SCC 3-02-014-11, -13)	Fabric filter	0.080	0.16
Gluten drying			
Direct-fired rotary dryers[g] (SCC 3-02-007-68)	Product recovery cyclone	0.13	0.27
Indirect-fired rotary dryers[g] (SCC 3-02-007-69)	Product recovery cyclone	0.25	0.49
Fiber drying (SCC 3-02-007-67)	ND	ND	ND
Germ drying (SCC 3-02-007-66)	ND	ND	ND
Dextrose drying (SCC 3-02-007-70)	ND	ND	ND
Degerminating mills (SCC 3-02-007-65)	ND	ND	ND
Milling (SCC 3-02-007-56)	ND	ND	ND

Table 9.9.7-1 (cont.).

[a] For grain transfer and handling operations, factors are for an aspirated collection system of 1 or more capture hoods ducted to a particulate collection device. Because of natural removal processes, uncontrolled emissions may be overestimated. ND = no data. SCC = Source Classification Code.

[b] Emission factors based on weight of PM, regardless of size, per unit weight of corn throughput unless noted.

[c] Assumed to be similar to country grain elevators (see Section 9.9.1).

[d] Assumed to be similar to country grain elevators (see Section 9.9.1). If 2 cleaning stages are used, emission factor should be doubled.

[e] Reference 9.

[f] Reference 9. Emission factor based on weight of PM per unit weight of starch loaded.

[g] Reference 10. Type of material dried not specified, but expected to be gluten meal or gluten feed. Emission factor based on weight of PM, regardless of size, per unit weight of gluten meal or gluten feed produced.

[h] Includes data for 4 (out of 9) dryers known to be vented through product recovery cyclones, and other systems are expected to have such cyclones. Emission factor based on weight of PM, regardless of size, per unit weight of gluten meal or gluten feed produced.

[j] References 11-13. EMISSION FACTOR RATING: D. Type of material dried is starch, but whether the starch is modified or unmodified is not known. Emission factor based on weight of PM, regardless of size, per unit weight of starch produced.

[k] Reference 14. Type of material dried is starch, but whether the starch is modified or unmodified is not known. Emission factor based on weight of PM, regardless of size, per unit weight of starch produced.

Table 9.9.7-2 (Metric And English Units). EMISSION FACTORS FOR CORN WET MILLING OPERATIONS

Emission Source	Type Of Control	VOC		SO_2	
		kg/Mg	lb/ton	kg/Mg	lb/ton
Steeping (SCC 3-02-007-61)	ND	ND	ND	ND	ND
Evaporators (SCC 3-02-007-62)	ND	ND	ND	ND	ND
Gluten feed drying (SCC 3-02-007-63, -64)	ND	ND	ND	ND	ND
Germ drying (SCC 3-02-007-66)	ND	ND	ND	ND	ND
Fiber drying (SCC 3-02-007-67)	ND	ND	ND	ND	ND
Gluten drying (SCC 3-02-007-68, -69)	ND	ND	ND	ND	ND
Starch drying (SCC 3-02-014-10, -11, -12, -13)	ND	ND	ND	ND	ND
Dextrose drying (SCC 3-02-007-70)	ND	ND	ND	ND	ND
Oil expelling/extraction (SCC 3-02-019-16)	ND	ND	ND	ND	ND

ND = no data. SCC = Source Classification Code.

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12. *No. 4 Starch Flash Dryer*, Report No. I-7231-1, prepared by The Almega Corporation, Bensenville, IL, May 1993.

13. *No. 1 Starch Flash Dryer*, Report No. 86-177-3, prepared by Burns & McDonnell, Kansas City, MO, August 1986.

14. *Starch Spray Dryer*, Report No. 21511, prepared by Mostardi-Platt Associates, Inc., Bensenville, IL, August 1992.

9.10 Confectionery Products

9.10.1 Sugar Processing

9.10.2 Salted And Roasted Nuts and Seeds

9.10.1 Sugar Processing

9.10.1.1 Cane Sugar Processing

9.10.1.2 Beet Sugar Processing

9.10.1.1 Cane Sugar Processing

9.10.1.1.1 General[1-3]

Sugar cane is burned in the field prior to harvesting to remove unwanted foliage as well as to control rodents and insects. Harvesting is done by hand or, where possible, by mechanical means.

After harvesting, the cane goes through a series of processing steps for conversion to the final sugar product. It is first washed to remove dirt and trash, then crushed and shredded to reduce the size of the stalks. The juice is next extracted by 1 of 2 methods, milling or diffusion. In milling, the cane is pressed between heavy rollers to squeeze out the juice; in diffusion, the sugar is leached out by water and thin juices. The raw sugar then goes through a series of operations including clarification, evaporation, and crystallization in order to produce the final product. The fibrous residue remaining after sugar extraction is called bagasse.

All mills fire some or all of their bagasse in boilers to provide power necessary in their milling operation. Some, having more bagasse than can be utilized internally, sell the remainder for use in the manufacture of various chemicals such as furfural.

9.10.1.1.2 Emissions[2,3]

The largest sources of emissions from sugar cane processing are the openfield burning in the harvesting of the crop, and the burning of bagasse as fuel. In the various processes of crushing, evaporation, and crystallization, relatively small quantities of particulates are emitted. Emission factors for sugar cane field burning are shown in Table 2.5-2. Emission factors for bagasse firing in boilers are included in Section 1.8.

References For Section 9.10.1.1

1. "Sugar Cane," In: *Kirk-Othmer Encyclopedia Of Chemical Technology*, Vol. IX, New York, John Wiley and Sons, Inc., 1964.

2. E. F. Darley, "Air Pollution Emissions From Burning Sugar Cane And Pineapple From Hawaii", In: *Air Pollution From Forest And Agricultural Burning*, Statewide Air Pollution Research Center, University of California, Riverside, California, Prepared for the U. S. Environmental Protection Agency, Research Triangle Park, NC, under Grant No. R800711, August 1974.

3. *Background Information For Establishment Of National Standards Of Performance For New Sources*, Raw Cane Sugar Industry, Environmental Engineering, Inc., Gainesville, FL, Prepared for the U. S. Environmental Protection Agency, Research Triangle Park, NC, under Contract No. CPA 70-142, Task Order 9c, July 15, 1971.

9.10.1.2 Beet Sugar Processing

[Work In Progress]

9.10.2 Salted And Roasted Nuts And Seeds

This industry encompasses a range of edible nuts and seeds processed primarily for human consumption. The salted and roasted nuts and seeds industry primarily includes establishments that produce salted, roasted, dried, cooked, or canned nuts, or that process grains and seeds for snack use. This industry does not encompass facilities that manufacture candy-coated nuts or those that manufacture peanut butter. The overall production of finished salted and roasted nuts and seeds has two primary components. Typically, nuts undergo post harvest processing such as hulling and shelling, either by the farmer on the farm, or by contractor companies either on the farm or at facilities near the farm, called crop preparation service facilities. The shelled nuts or seeds are shipped to food processing plants to produce the final product.

Many of the post-harvest operations and processes are common to most of the nuts and seeds, including field harvesting and loading, unloading, precleaning, drying, screening, and hulling. Other operations specific to individual nuts and seeds include sizing, grading, skinning, and oil or dry roasting. The processing of harvested nuts and seeds can produce particulate emissions primarily from the unloading, precleaning, hulling or shelling, and screening operations. In almond processing, all of the operations, except for unloading, are usually controlled to reduce the level of ambient particulate. The emissions from the unloading operation are usually uncontrolled.

In this document, the industry is divided into Section 9.10.2.1, "Almond Processing", and Section 9.10.2.2, "Peanut Processing". Sections on other nuts and seeds may be published in later editions if sufficient data on the processes are available.

9.10.2.1 Almond Processing

9.10.2.1.1 General[1-2]

Almonds are edible tree nuts, grown principally in California. The nuts are harvested from orchards and transported to almond processing facilities, where the almonds are hulled and shelled. The function of an almond huller/sheller is to remove the hull and shell of the almond from the nut, or meat. Orchard debris, soil, and pebbles represent 10 to 25 percent of the field weight of material brought to the almond processing facility. Clean almond meats are obtained as about 20 percent of the field weight. Processes for removing the debris and almond hulls and shells are potential sources of air emissions.

9.10.2.1.2 Process Description[1-7]

After almonds are collected from the field, they undergo two processing phases, post-harvest processing and finish processing. These phases are typically conducted at two different facilities. There are two basic types of almond post-harvest processing facilities: those that produce hulled, in-shell almonds as a final product (known as hullers), and those that produce hulled, shelled, almond meats as a final product (known as huller/shellers). Almond precleaning, hulling, and separating operations are common to both types of facilities. The huller/sheller includes additional steps to remove the almond meats from their shells. A typical almond hulling operation is shown in Figure 9.10.2.1-1. A typical almond huller/sheller is depicted in Figure 9.10.2.1-2. The hulled, shelled almond meats are shipped to large production facilities where the almonds may undergo further processing into various end products. Almond harvesting, along with precleaning, hulling, shelling, separating, and final processing operations, is discussed in more detail below.

Almond harvesting and processing are a seasonal industry, typically beginning in August and running from two to four months. However, the beginning and duration of the season vary with the weather and with the size of the crop. The almonds are harvested either manually, by knocking the nuts from the tree limbs with a long pole, or mechanically, by shaking them from the tree. Typically the almonds remain on the ground for 7 to 10 days to dry. The fallen almonds are then swept into rows. Mechanical pickers gather the rows for transport to the almond huller or huller/sheller. Some portion of the material in the gathered rows includes orchard debris, such as leaves, grass, twigs, pebbles, and soil. The fraction of debris is a function of farming practices (tilled versus untilled), field soil characteristics, and age of the orchard, and it can range from less than 5 to 60 percent of the material collected. On average, field weight yields 13 percent debris, 50 percent hulls, 14 percent shells, and 23 percent clean almond meats and pieces, but these ratios can vary substantially from farm to farm.

The almonds are delivered to the processing facility and are dumped into a receiving pit. The almonds are transported by screw conveyors and bucket elevators to a series of vibrating screens. The screens selectively remove orchard debris, including leaves, soil, and pebbles. A destoner removes stones, dirt clods, and other larger debris. A detwigger removes twigs and small sticks. The air streams from the various screens, destoners, and detwiggers are ducted to cyclones or fabric filters for particulate matter removal. The recovered soil and fine debris, such as leaves and grass, are disposed of by spreading on surrounding farmland. The recovered twigs may be chipped and used as fuel for co-generation plants. The precleaned almonds are transferred from the precleaner area by another series of conveyors and elevators to storage bins to await further processing. (In

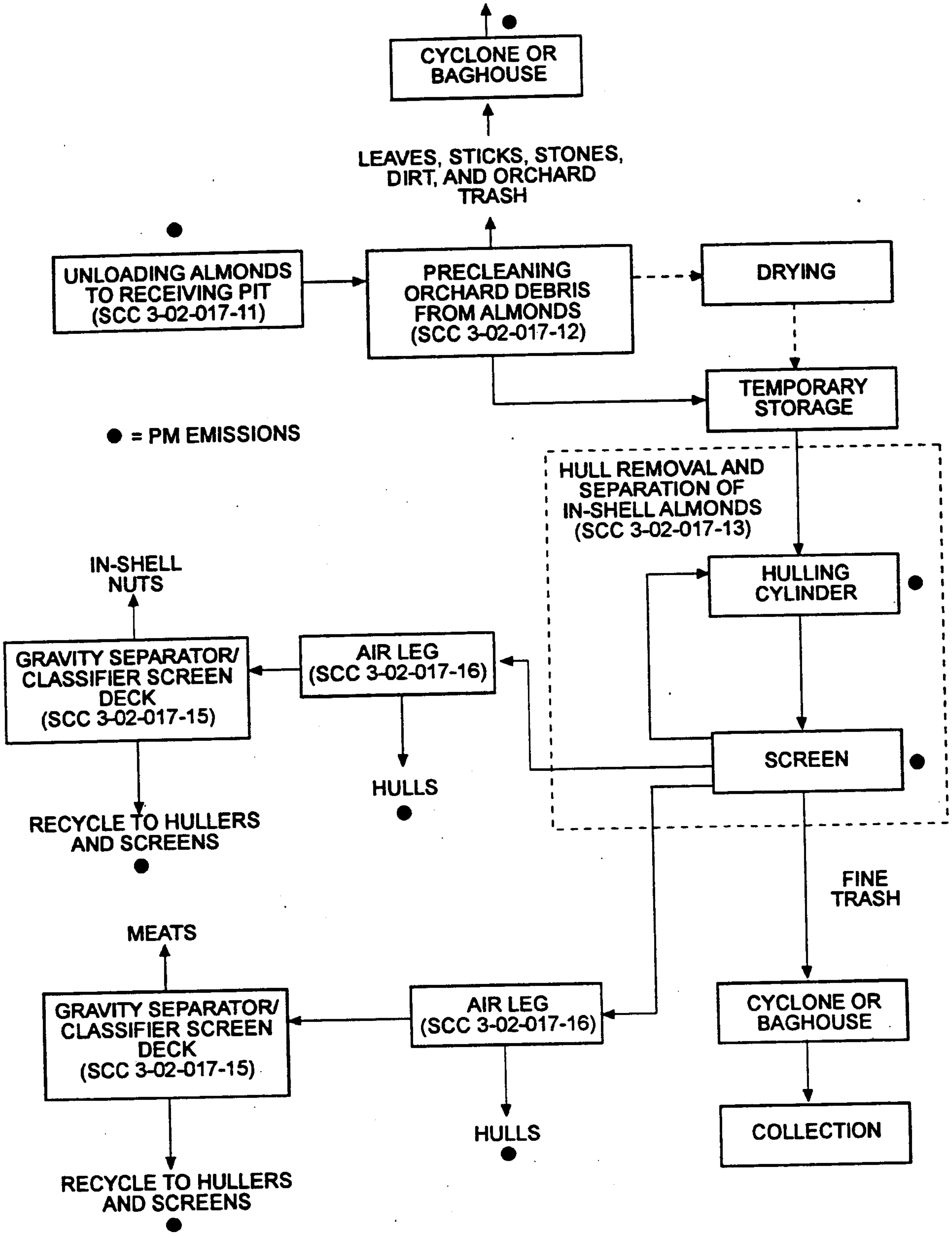


Figure 9.10.2.1-1. Representative almond hulling process flow diagram. (Source Classification Codes in parentheses.)

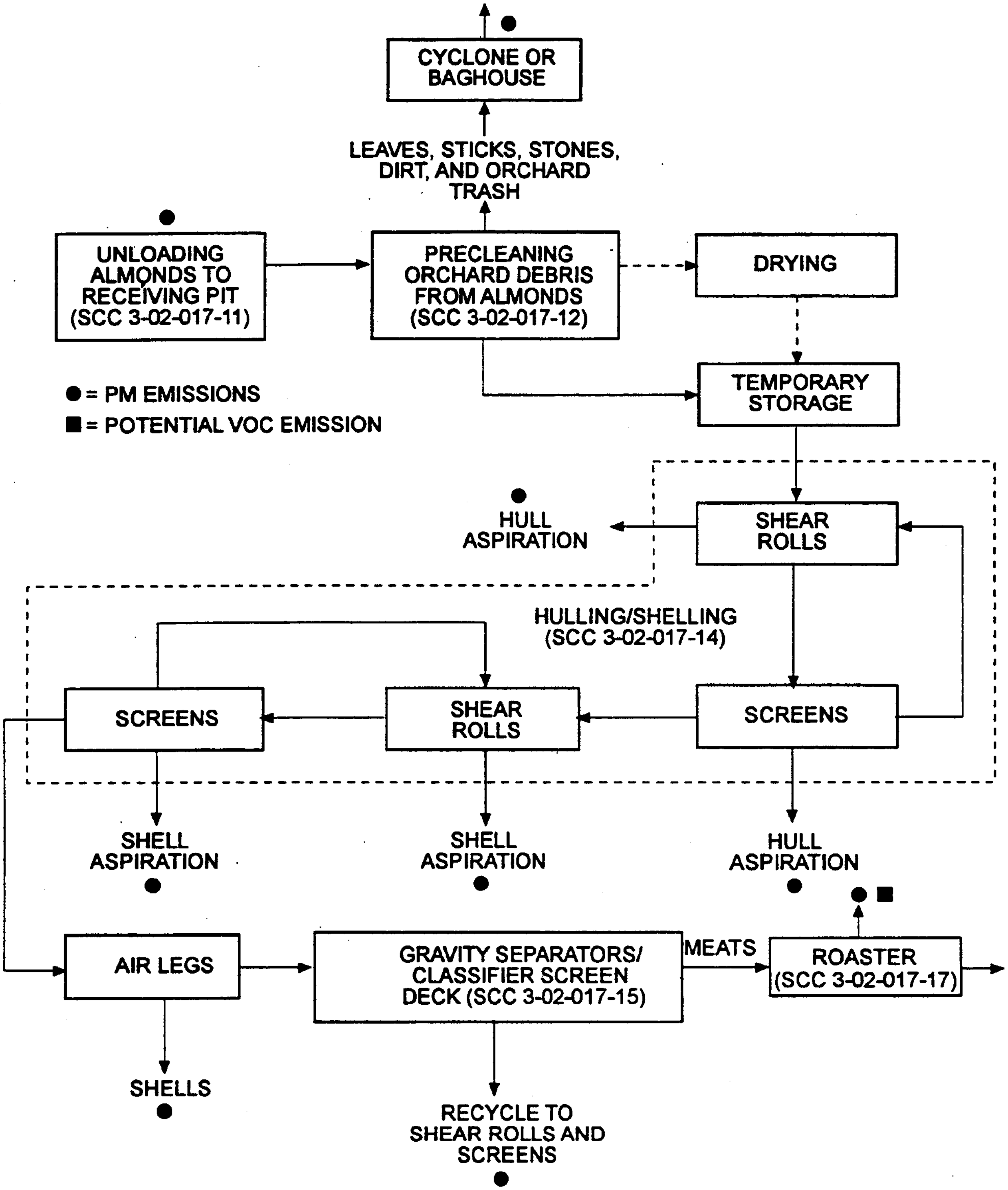


Figure 9.10.2.1-2. Representative almond huller/sheller process flow diagram.
(Source Classification Codes in parentheses.)

some instances, the precleaned almonds may be conveyed to a dryer before storage. However, field drying is used in most operations.)

Almonds are conveyed on belt and bucket conveyors to a series of hulling cylinders or shear rolls, which crack the almond hulls. Hulling cylinders are typically used in almond huller facilities. Series of shear rolls are generally used in huller/shellers. The hulling cylinders have no integral provision for aspiration of shell pieces. Shear rolls, on the other hand, do have integral aspiration to remove shell fragments from loose hulls and almond meats. The cracked almonds are then discharged to a series of vibrating screens or a gravity table, which separates hulls and unhulled almonds from the in-shell almonds, almond meats, and fine trash. The remaining unhulled almonds pass through additional hulling cylinders or shear rolls and screen separators. The number of passes and the combinations of equipment vary among facilities. The hulls are conveyed to storage and sold as an ingredient in the manufacture of cattle feed. The fine trash is ducted to a cyclone or fabric filter for collection and disposal.

In a hulling facility, the hulled, in-shell almonds are separated from any remaining hull pieces in a series of air legs (counter-flow forced air gravity separators) and are then graded, collected, and sold as finished product, along with an inevitable small percentage of almond meats. In huller/shellers, the in-shell almonds continue through more shear rolls and screen separators.

As the in-shell almonds make additional passes through sets of shear rolls, the almond shells are cracked or sheared away from the meat. More sets of vibrating screens separate the shells from the meats and small shell pieces. The separated shells are aspirated and collected in a fabric filter or cyclone, and then conveyed to storage for sale as fuel for co-generation plants. The almond meats and small shell pieces are conveyed on vibrating conveyor belts and bucket elevators to air classifiers or air legs that separate the small shell pieces from the meats. The number of these air separators varies among facilities. The shell pieces removed by these air classifiers are also collected and stored for sale as fuel for co-generation plants. The revenues generated from the sale of hulls and shells are generally sufficient to offset the costs of operating the almond processing facility.

The almond meats are then conveyed to a series of gravity tables or separators (classifier screen decks), which sort the meats by lights, middlings, goods, and heavies. Lights, middlings, and heavies, which still contain hulls and shells, are returned to various points in the process. Goods are conveyed to the finished meats box for storage. Any remaining shell pieces are aspirated and sent to shell storage.

The almond meats are now ready either for sales as raw product or for further processing, typically at a separate facility. The meats may be blanched, sliced, diced, roasted, salted, or smoked. Small meat pieces may be ground into meal or pastes for bakery products. Almonds are roasted by gradual heating in a rotating drum. They are heated slowly to prevent the skins and outer layers from burning. Roasting time develops the flavor and affects the color of the meats. To obtain almonds with a light brown color and a medium roast requires a 500-pound roaster fueled with natural gas about 1.25 hours at 118°C (245°F).

9.10.2.1.3 Emissions And Controls[1-3,5-9]

Particulate matter (PM) is the primary air pollutant emitted from almond post-harvest processing operations. All operations in an almond processing facility involve dust generation from the movement of trash, hulls, shells, and meats. The quantity of PM emissions varies depending on the type of facility, harvest method, trash content, climate, production rate, and the type and number of controls used by the facility. Fugitive PM emissions are attributable primarily to unloading operations, but some fugitive emissions are generated from precleaning operations and subsequent screening operations.

Because farm products collected during harvest typically contain some residual dirt, which includes trace amounts of metals, it stands to reason that some amount of these metals will be emitted from the various operations along with the dust. California Air Resources Board (CARB) data indicate that metals emitted from almond processing include arsenic, beryllium, cadmium, copper, lead, manganese, mercury, and nickel in quantities on the order of 5×10^{-11} to 5×10^{-4} kilograms (kg) of metal per kg of PM emissions (5×10^{-11} to 5×10^{-4} pounds [lb] of metal per lb of PM emissions). It has been suggested that sources of these metals other than the inherent trace metal content of soil may include fertilizers, other agricultural sprays, and groundwater.

In the final processing operations, almond roasting is a potential source of volatile organic compound (VOC) emissions. However, no chemical characterization data are available to hypothesize what compounds might be emitted, and no emission source test data are available to quantify these potential emissions.

Emission control systems at almond post-harvest processing facilities include both ventilation systems to capture the dust generated during handling and processing of almonds, shells, and hulls, and an air pollution control device to collect the captured PM. Cyclones formerly served as the principal air pollution control devices for PM emissions from almond post harvest processing operations. However, fabric filters, or a combination of fabric filters and cyclones, are becoming common. Practices of combining and controlling specific exhaust streams from various operations vary considerably among facilities. The exhaust stream from a single operation may be split and ducted to two or more control devices. Conversely, exhaust streams from several operations may be combined and ducted to a single control device. According to one source within the almond processing industry, out of approximately 350 almond hullers and huller/shellers, no two are alike.

Emission factors for almond processing sources are presented in Table 9.10.2.1-1.

Table 9.10.2.1-1 (Metric And English Units). EMISSION FACTORS FOR ALMOND PROCESSING[a]

EMISSION FACTOR RATING: E

Source	Filterable PM		Condensable Inorganic PM		PM-10[b]	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Unloading[c] (SCC 3-02-017-11)	0.030	0.060	ND	ND	ND	ND
Precleaning cyclone[d] (SCC 3-02-017-12)	0.48	0.95	ND	ND	0.41	0.82
Precleaning baghouse[e] (SCC 3-02-017-12)	0.0084	0.017	ND	ND	0.0075	0.015
Hulling/separating cyclone[d] (SCC 3-02-017-13)	0.57	1.1	ND	ND	0.41	0.81
Hulling/separating baghouse[e] (SCC 3-02-017-13)	0.0078	0.016	ND	ND	0.0065	0.013
Hulling/shelling baghouse[f] (SCC 3-02-017-14)	0.026	0.051	0.0068	0.014	ND	ND
Classifier screen deck cyclone[d] (SCC 3-02-017-15)	0.20	0.40	ND	ND	0.16	0.31
Air leg[d] (SCC 3-02-017-16)	0.26	0.51	ND	ND	ND	ND
Roaster[g] (SCC 3-02-017-17)	ND	ND	ND	ND	ND	ND

[a] Process weights used to calculate emission factors include nuts and orchard debris as taken from the field, unless noted. ND = no data. SCC = Source Classification Code.

[b] PM-10 factors are based on particle size fractions found in Reference 1 applied to the filterable PM emission factor for that source. See Reference 3 for a detailed discussion of how these emission factors were developed.

[c] References 1-3,10-11.

[d] Reference 1. Emission factor is for a single air leg/classifier screen deck cyclone. Facilities may contain multiple cyclones.

[e] References 1,9.

[f] Reference 10.

[g] Factors are based on finished product throughputs.

References For Section 9.10.2.1

1. *Report On Tests Of Emissions From Almond Hullers In The San Joaquin Valley*, File No. C-4-0249, California Air Resources Board, Division Of Implementation And Enforcement, Sacramento, CA, 1974.

2. *Proposal To Almond Hullers And Processors Association For Pooled Source Test*, Eckley Engineering, Fresno, CA, December 1990.

3. *Emission Factor Documentation For AP-42 Section 9.10.2, Salted And Roasted Nuts And Seeds*, EPA Contract No. 68-D2-0159, Midwest Research Institute, Cary, NC, May 1994.

4. Jasper Guy Woodroof, *Tree Nuts: Production, Processing Product*, Avi Publishing, Inc., Westport, CT, 1967.

5. Written communication from Darin Lundquist, Central California Almond Growers Association, Sanger, CA, to Dallas Safriet, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 9, 1993.

6. Written communication from Jim Ryals, Almond Hullers and Processors Association, Bakersfield, CA, to Dallas Safriet, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 7, 1993.

7. Written communication from Wendy Eckley, Eckley Engineering, Fresno, CA, to Dallas Safriet, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 7, 1993.

8. Private communications between Wendy Eckley, Eckley Engineering, Fresno, CA, and Lance Henning, Midwest Research Institute, Kansas City, MO, August-September 1992, March 1993.

9. *Almond Huller Baghouse Emissions Tests*, Superior Farms, Truesdail Laboratories, Los Angeles, CA, November 5, 1980.

10. *Emission Testing On Two Baghouses At Harris Woolf California Almonds*, Steiner Environmental, Inc., Bakersfield, CA, October 1991.

11. *Emission Testing On One Baghouse At Harris Woolf California Almonds*, Steiner Environmental, Inc., Bakersfield, CA, October 1992.

9.10.2.2 Peanut Processing

9.10.2.2.1 General

Peanuts (*Arachis hypogaea*), also known as groundnuts or goobers, are an annual leguminous herb native to South America. The peanut peduncle, or peg (the stalk that holds the flower), elongates after flower fertilization and bends down into the ground, where the peanut seed matures. Peanuts have a growing period of approximately 5 months. Seeding typically occurs mid-April to mid-May, and harvesting during August in the United States.

Light, sandy loam soils are preferred for peanut production. Moderate rainfall of between 51 and 102 centimeters (cm) (20 and 40 inches [in.]) annually is also necessary. The leading peanut producing states are Georgia, Alabama, North Carolina, Texas, Virginia, Florida, and Oklahoma.

9.10.2.2.2 Process Description

The initial step in processing is harvesting, which typically begins with the mowing of mature peanut plants. Then the peanut plants are inverted by specialized machines, peanut inverters, that dig, shake, and place the peanut plants, with the peanut pods on top, into windrows for field curing. After open-air drying, mature peanuts are picked up from the windrow with combines that separate the peanut pods from the plant using various thrashing operations. The peanut plants are deposited back onto the fields and the pods are accumulated in hoppers. Some combines dig and separate the vines and stems from the peanut pods in 1 step, and peanuts harvested by this method are cured in storage. Some small producers still use traditional harvesting methods, plowing the plants from the ground and manually stacking them for field curing.

Harvesting is normally followed by mechanical drying. Moisture in peanuts is usually kept below 12 percent, to prevent aflatoxin molds from growing. This low moisture content is difficult to achieve under field conditions without overdrying vines and stems, which reduces combine efficiency (less foreign material is separated from the pods). On-farm dryers usually consist of either storage trailers with air channels along the floor or storage bins with air vents. Fans blow heated air (approximately 35°C [95°F]) through the air channels and up through the peanuts. Peanuts are dried to moistures of roughly 7 to 10 percent.

Local peanut mills take peanuts from the farm to be further cured (if necessary), cleaned, stored, and processed for various uses (oil production, roasting, peanut butter production, etc.). Major process steps include processing peanuts for in-shell consumption and shelling peanuts for other uses.

9.10.2.2.2.1 In-shell Processing -

Some peanuts are processed for in-shell roasting. Figure 9.10.2.2-1 presents a typical flow diagram for in-shell peanut processing. Processing begins with separating foreign material (primarily soil, vines, stems, and leaves) from the peanut pods using a series of screens and blowers. The pods are then washed in wet, coarse sand that removes stains and discoloration. The sand is then screened from the peanuts for reuse. The nuts are then dried and powdered with talc or kaolin to whiten the shells. Excess talc/kaolin is shaken from the peanut shells.

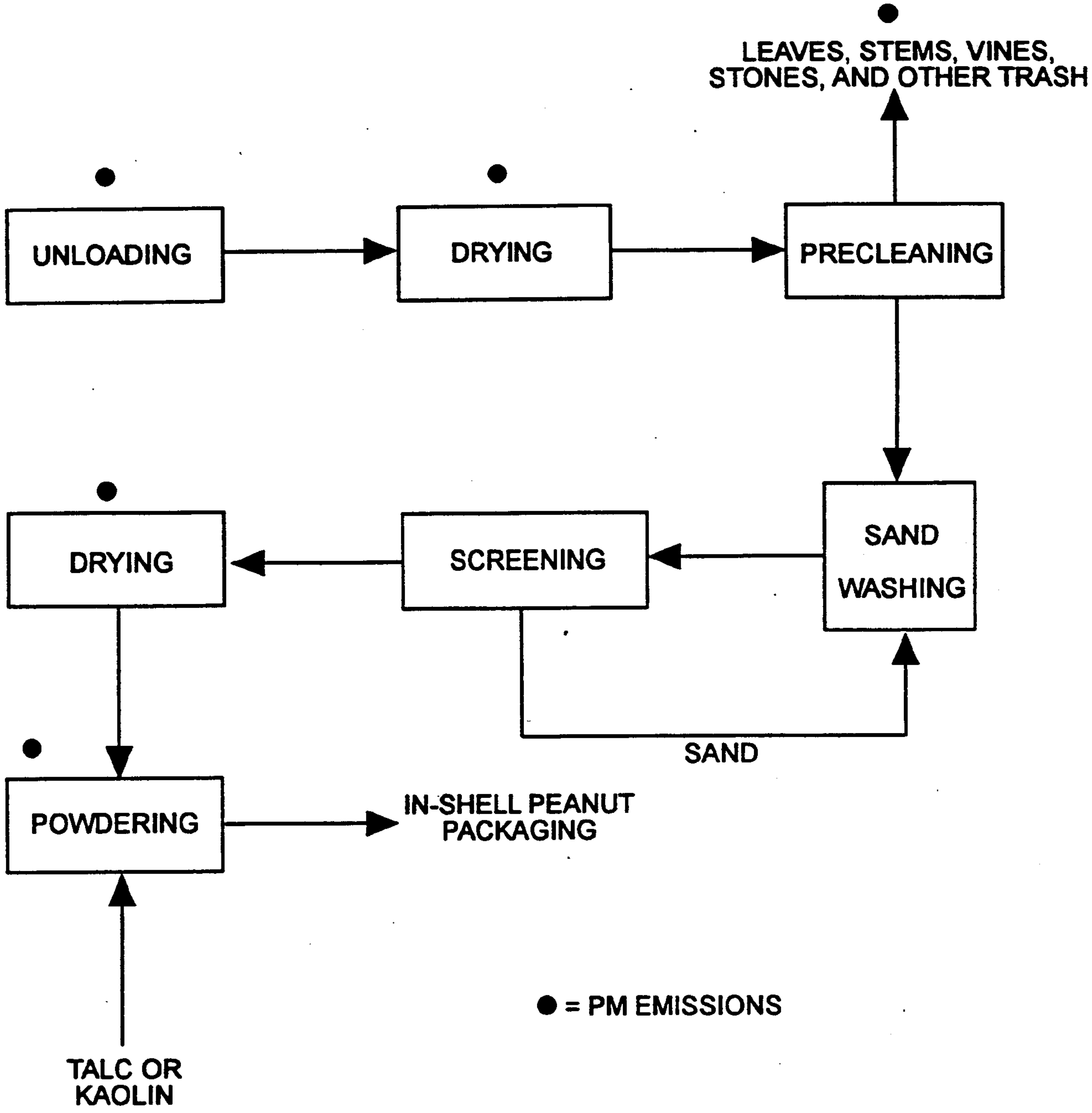


Figure 9.10.2.2-1. Typical in-shell peanut processing flow diagram.

9.10.2.2.2 Shelling -

A typical shelled peanut processing flow diagram is shown in Figure 9.10.2.2-2. Shelling begins with separating the foreign material with a series of screens, blowers, and magnets. The cleaned peanuts are then sized with screens (size graders). Sizing is required so that peanut pods can be crushed without also crushing the peanut kernels.

Next, shells of the sized peanuts are crushed, typically by passing the peanuts between rollers that have been adjusted for peanut size. The gap between rollers must be narrow enough to crack the peanut hulls, but wide enough to prevent damage to the kernels. A horizontal drum, with a perforated and ridged bottom and a rotating beater, is also used to hull peanuts. The rotating beater crushes the peanuts against the bottom ridges, pushing both the shells and peanuts through the perforations. The beater can be adjusted for different sizes of peanuts, to avoid damaging the peanut kernels. Shells are aspirated from the peanut kernels as they fall from the drum. The crushed shells and peanut kernels are then separated with oscillating shaker screens and air separators. The separation process also removes undersized kernels and split kernels.

Following crushing and hull/kernel separation, peanut kernels are sized and graded. Sizing and grading can be done by hand, but most mills use screens to size kernels and electric eye sorters for grading. Electric eye sorters can detect discoloration and can separate peanuts by color grades. The sized and graded peanuts are bagged in 45.4-kg (100-lb) bags for shipment to end users, such as peanut butter plants and nut roasters. Some peanuts are shipped in bulk in rail hopper cars.

9.10.2.2.3 Roasting -

Roasting imparts the typical flavor many people associate with peanuts. During roasting, amino acids and carbohydrates react to produce tetrahydrofuran derivatives. Roasting also dries the peanuts further and causes them to turn brown as peanut oil stains the peanut cell walls. Following roasting, peanuts are prepared for packaging or for further processing into candies or peanut butter. Typical peanut roasting processes are shown in Figure 9.10-2.2-3. There are 2 primary methods for roasting peanuts, dry roasting and oil roasting.

Dry Roasting -

Dry roasting is either a batch or continuous process. Batch roasters offer the advantage of adjusting for different moisture contents of peanut lots from storage. Batch roasters are typically natural gas-fired revolving ovens (drum-shaped). The rotation of the oven continuously stirs the peanuts to produce an even roast. Oven temperatures are approximately 430°C (800°F), and peanut temperature is raised to approximately 160°C (320°F) for 40 to 60 min. Actual roasting temperatures and times vary with the condition of the peanut batch and the desired end characteristics.

Continuous dry roasters vary considerably in type. Continuous roasting reduces labor, ensures a steady flow of peanuts for other processes (packaging, candy production, peanut butter production, etc.), and decreases spillage. Continuous roasters may move peanuts through an oven on a conveyor or by gravity feed. In one type of roaster, peanuts are fed by a conveyor into a stream of countercurrent hot air that roasts the peanuts. In this system, the peanuts are agitated to ensure that air passes around the individual kernels to promote an even roast.

Dry roasted peanuts are cooled and blanched. Cooling occurs in cooling boxes or on conveyors where large quantities of air are blown over the peanuts immediately following roasting. Cooling is necessary to stop the roasting process and maintain a uniform quality. Blanching removes the skin of the peanut as well as dust, molds, and other foreign material. There are several blanching methods including dry, water, spin, and air impact.

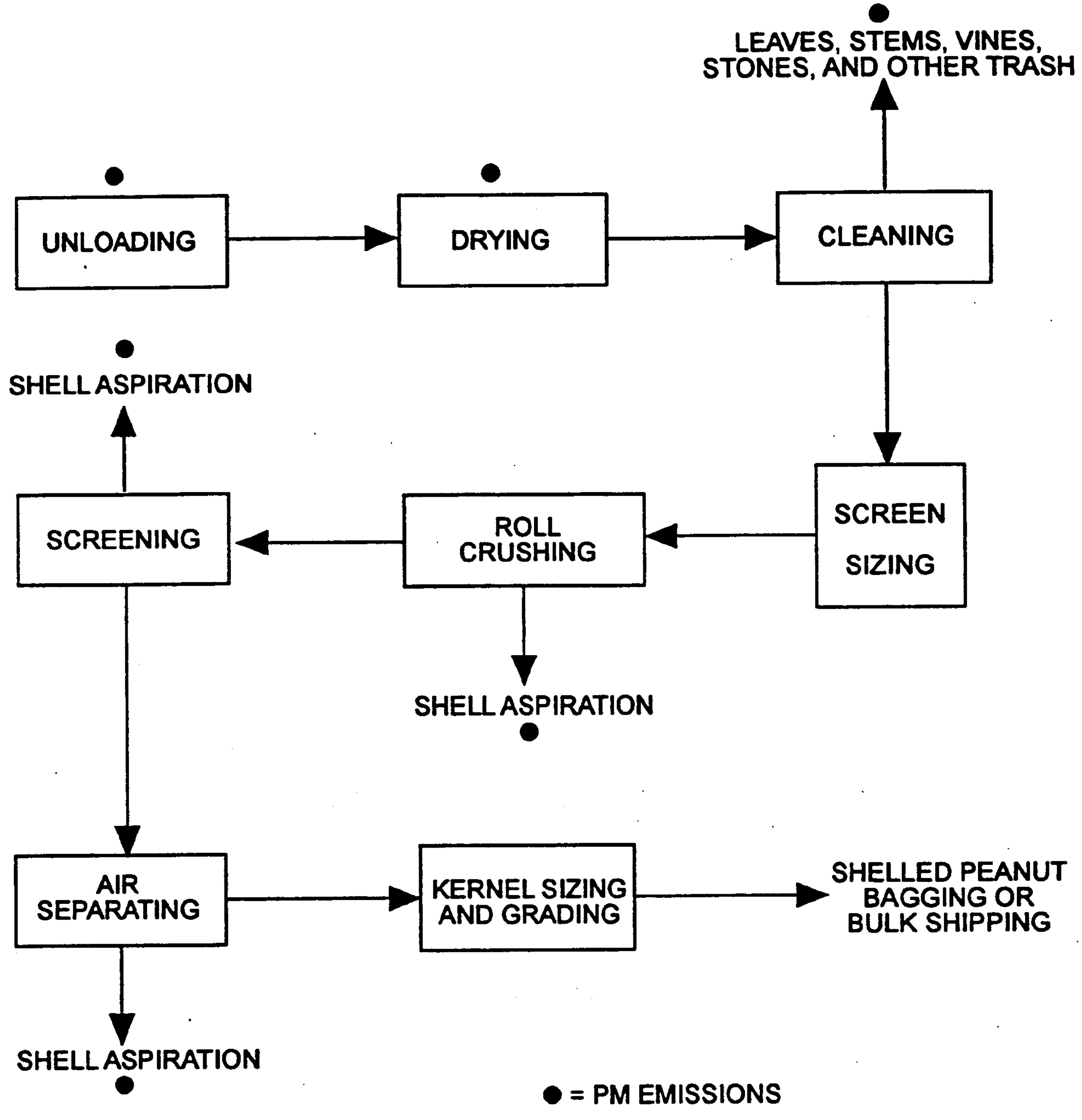


Figure 9.10.2.2-2. Typical shelled peanut processing flow diagram.

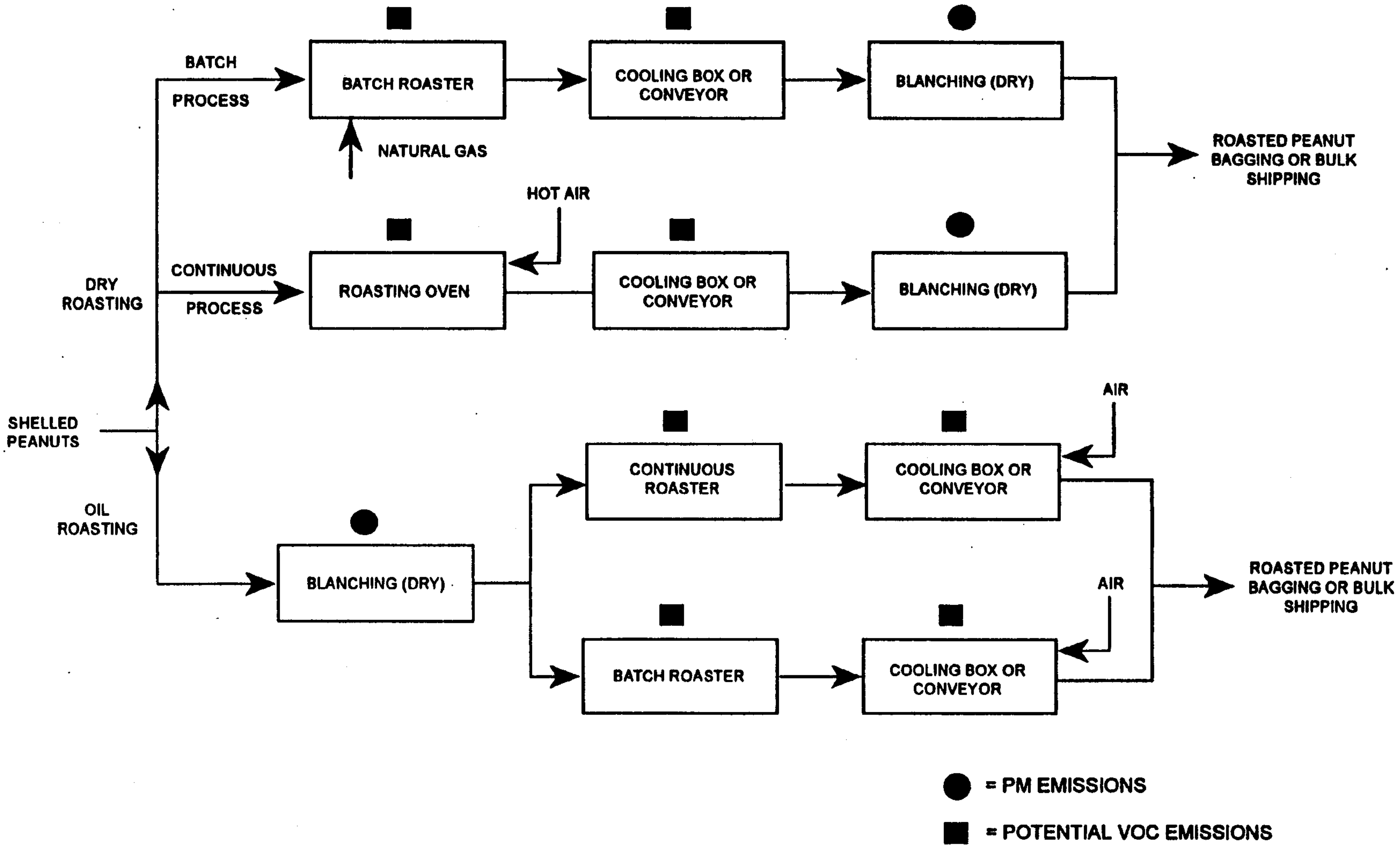


Figure 9.10.2.2-3. Typical shelled peanut roasting processing flow diagram.

Dry blanching is used primarily in peanut butter production, because it removes the kernel hearts which affect peanut butter flavor. Dry blanching heats the peanuts to approximately 138°C (280°F) for 25 minutes to crack and loosen the skins. The heated peanuts are then cooled and passed through either brushes or ribbed rubber belting to rub off the skins. Screening is used to separate the hearts from the cotyledons (peanut halves).

Water blanching passes the peanuts on conveyors through stationary blades that slit the peanut skins. The skins are then loosened with hot water sprayers and removed by passing the peanuts under oscillating canvas-covered pads on knobbed conveyor belts. Water blanching requires drying the peanuts back to a moisture content of 6 to 12 percent.

Spin blanching uses steam to loosen the skins of the peanuts. Steaming is followed by spinning the peanuts on revolving spindles as the peanuts move, single file, down a grooved conveyor. The spinning unwraps the peanut skins.

Air impact blanching uses a horizontal drum (cylinder) in which the peanuts are placed and rotated. The inner surface of the drum has an abrasive surface that aids in the removal of the skins as the drum rotates. Inside the drum are air jets that blow the peanuts counter to the rotation of the drum creating air impact which loosens the skin. The combination of air impacts and the abrasive surface of the drum results in skin removal. Either batch or continuous air impact blanching can be conducted.

Oil Roasting -

Oil roasting is also done on a batch or continuous basis. Before roasting, the peanuts are blanched to remove the skins. Continuous roasters move the peanuts on a conveyor through a long tank of heated oil. In both batch and continuous roasters, oil is heated to temperatures of 138 to 143°C (280 to 290°F), and roasting times vary from 3 to 10 minutes depending on desired characteristics and peanut quality. Oil roaster tanks have heating elements on the sides to prevent charring the peanuts on the bottom. Oil is constantly monitored for quality, and frequent filtration, neutralization, and replacement are necessary to maintain quality. Coconut oil is preferred, but oils such as peanut and cottonseed are frequently used.

Cooling also follows oil roasting, so that a uniform roast can be achieved. Cooling is achieved by blowing large quantities of air over the peanuts either on conveyors or in cooling boxes.

9.10.2.2.3 Emissions And Controls

No information is currently available on emissions or emission control devices for the peanut processing industry. However, the similarities of some of the processes to those in the almond processing industry make it is reasonable to assume that emissions would be comparable. No data are available, however, to make any comparisons about relative quantities of these emissions.

Reference For Section 9.10.2.2

1. Jasper Guy Woodroof, *Peanuts: Production, Processing, Products*, 3rd Edition, Avi Publishing Company, Westport, CT, 1983.

9.11 Fats And Oils

[Work In Progress]

9.11.1 Vegetable Oil Processing

[Work In Progress]

9.12 Beverages

9.12.1 Malt Beverages

9.12.2 Wines And Brandy

9.12.3 Distilled And Blended Liquors

9.12.1 Malt Beverages

[Work In Progress]

9.12.2 Wines And Brandy

[Work In Progress]

9.12.3 Distilled And Blended Liquors

[Work In Progress]

9.13 Miscellaneous Food And Kindred Products

9.13.1 Fish Processing

9.13.2 Coffee Roasting

9.13.3 Snack Chip Deep Fat Frying

9.13.4 Yeast Production

9.13.1 Fish Processing

9.13.1.1 General

Fish canning and byproduct manufacturing are conducted in 136 plants in 12 states. The majority of these plants are in Washington, Alaska, Maine, Louisiana, and California. Some processing occurs in Delaware, Florida, Illinois, Maryland, New York, and Virginia. The industry experienced an 18 percent increase in the quantity of fish processed in 1990, and additional increases were expected in 1992 as well. Exports of canned fish and fish meal also are increasing because of diminishing supply in other countries.

9.13.1.2 Process Description

Fish processing includes both the canning of fish for human consumption and the production of fish byproducts such as meal and oil. Either a precooking method or a raw pack method can be used in canning. In the precooking method, the raw fish are cleaned and cooked before the canning step. In the raw pack method, the raw fish are cleaned and placed in cans before cooking. The precooking method is used typically for larger fish such as tuna, while the raw pack method is used for smaller fish such as sardines.

The byproduct manufacture segment of the fish industry uses canning or filleting wastes and fish that are not suitable for human consumption to produce fish meal and fish oil.

Canning -

The precooking method of canning (Figure 9.13.1-1) begins with thawing the fish, if necessary. The fish are eviscerated and washed, then cooked. Cooking is accomplished using steam, oil, hot air, or smoke for 1.5 to 10 hours, depending on fish size. Precooking removes the fish oils and coagulates the protein in the fish to loosen the meat. The fish are then cooled, which may take several hours. Refrigeration may be used to reduce the cooling time. After cooling, the head, fins, bones, and undesirable meat are removed, and the remainder is cut or chopped to be put in cans. Oil, brine, and/or water are added to the cans, which are sealed and pressure cooked before shipment.

The raw pack method of canning (Figure 9.13.1-2) also begins with thawing and weighing the fish. They are then washed and possibly brined, or "nobbed", which is removing the heads, viscera, and tails. The fish are placed in cans and then cooked, drained, and dried. After drying, liquid, which may be oil, brine, water, sauce, or other liquids, is added to the cans. Finally, the cans are sealed, washed, and sterilized with steam or hot water.

Byproduct Manufacture -

The only process used in the U. S. to extract oil from the fish is the wet steam process. Fish byproduct manufacturing (Figure 9.13.1-3) begins with cooking the fish at 100°C (lower for some species) in a continuous cooker. This process coagulates the protein and ruptures the cell walls to release the water and oil. The mixture may be strained with an auger in a perforated casing before pressing with a screw press. As the fish are moved along the screw press, the pressure is increased and the volume is decreased. The liquid from the mixture, known as pressing liquor, is squeezed out through a perforated casing.

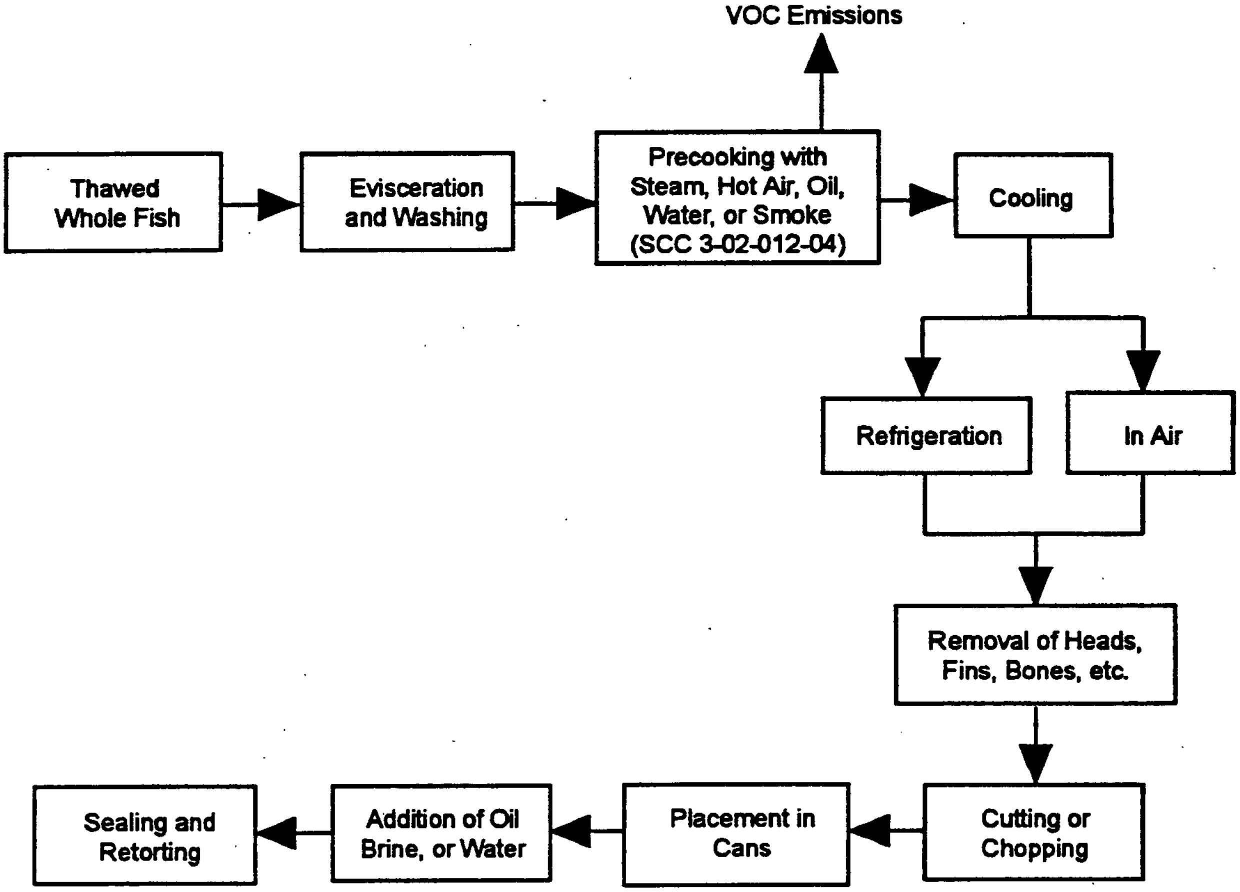


Figure 9.13.1-1. Flow diagram of precooking method.
(Source Classification Codes in parentheses.)

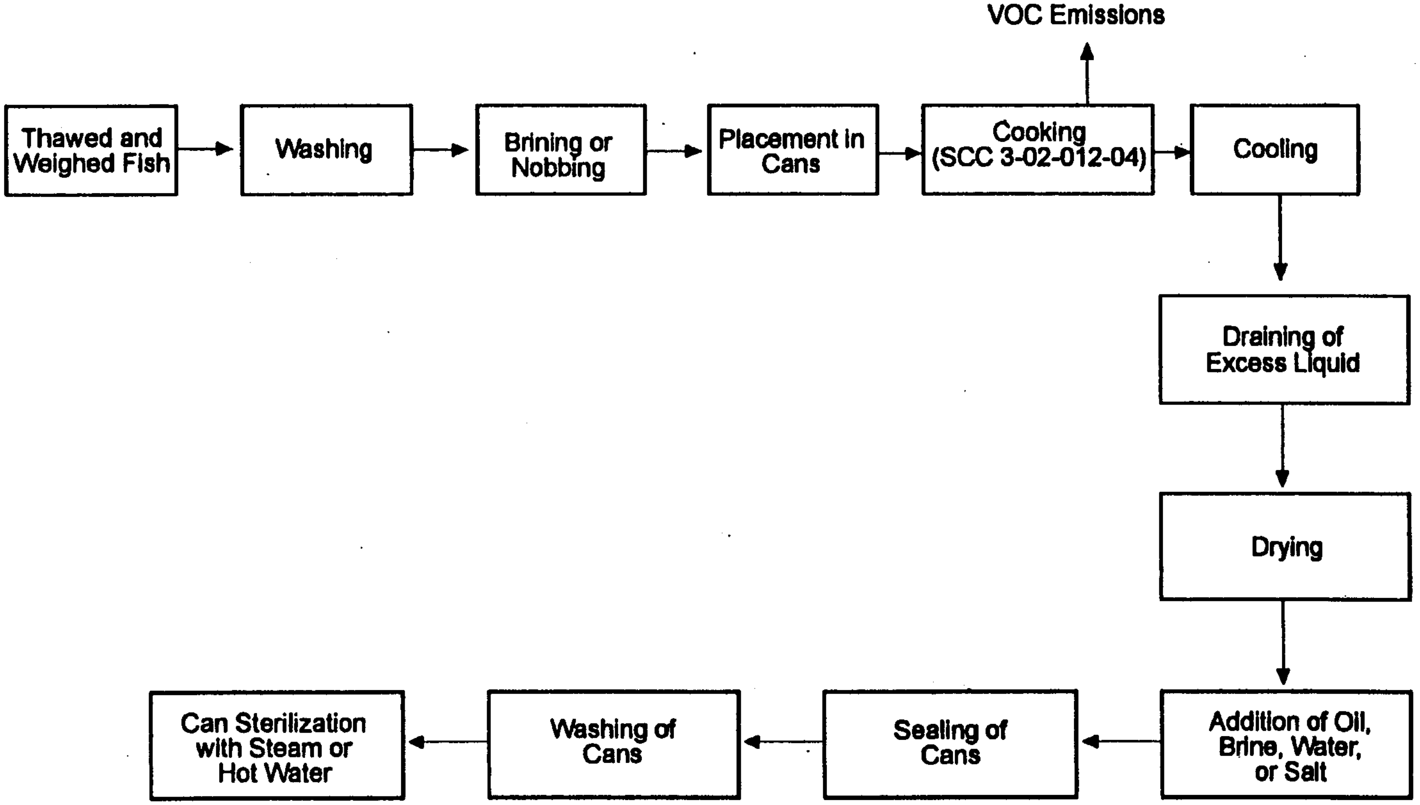
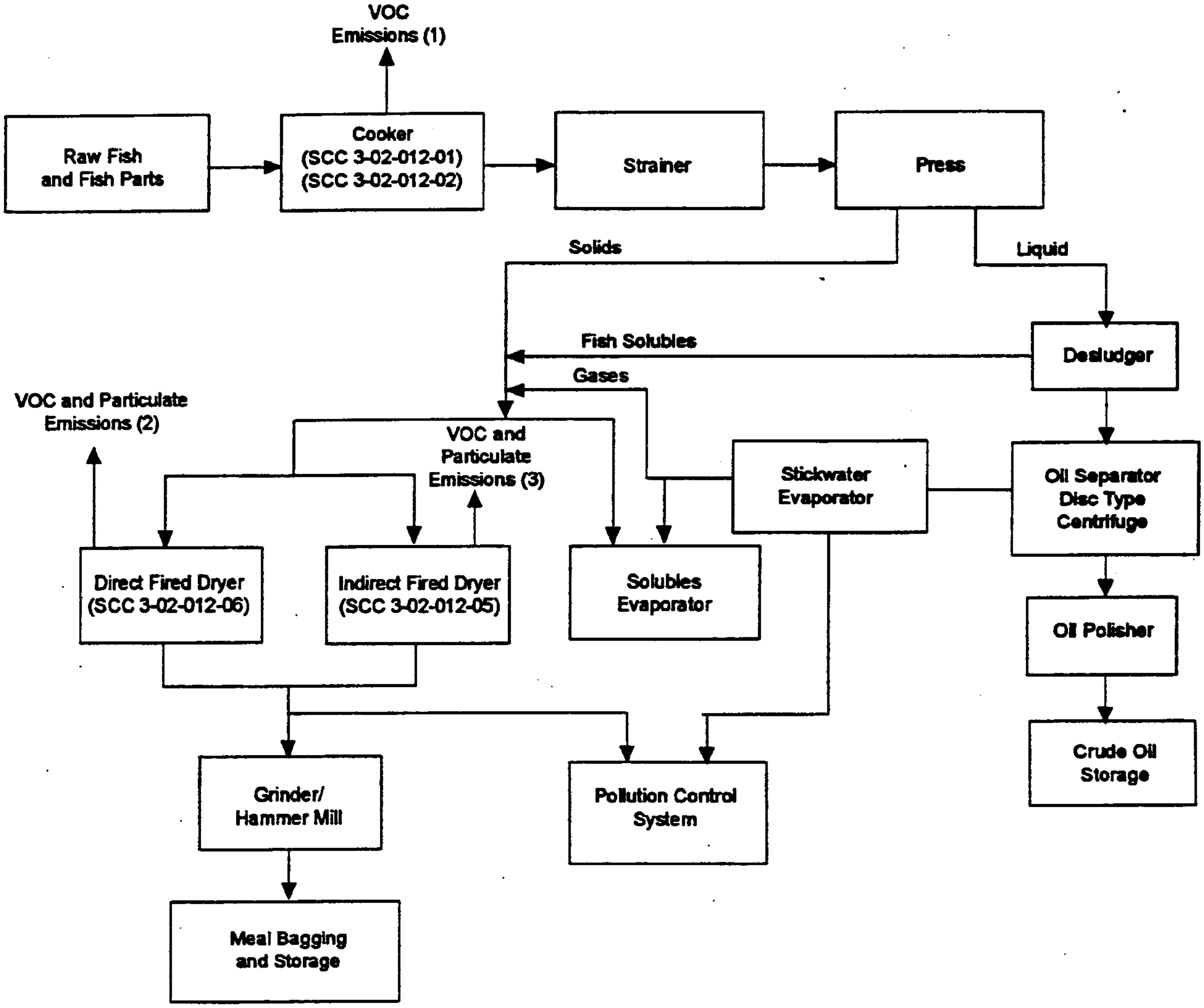


Figure 9.13.1-2. Flow diagram of raw packing method.
(Source Classification Codes in parentheses.)



(1) VOC emissions consist of H_2S and $(CH_3)_3N$, but no particulates

(2) Large odor source, as well as smoke

(3) Slightly less odor than direct fired dryers, and no smoke

Figure 9.13.1-3. Flow diagram of fish meal and crude fish oil processing. (Source Classification Codes in parentheses.)

The pressing liquor, which consists of water, oil, and some solids, is transported to a centrifuge or desludger where the solids are removed. These solids are later returned to the press cake in the drying step. The oil and water are separated using a disc-type centrifuge in the oil separator. The oil is "polished" by using hot water washes and centrifugation and is then sent to an oil-refining operation. The water removed from the oil (stickwater) goes to an evaporator to concentrate the solids.

The press cake, stickwater, and solids are mixed and sent to either a direct-fired or an indirect-fired dryer (steam tube dryer). A direct-fired dryer consists of a slowly rotating cylinder through which air, heated to about 600°C by an open flame, passes through the meal to evaporate the liquid. An indirect-fired dryer consists of a fixed cylinder with rotating scrapers that heat the meal with steam or hot fluids flowing through discs, tubes, coils, or the dryer casing itself. Air also passes through this apparatus, but it is not heated and flows in the opposite direction to the meal to entrain the evaporated water. Indirect-fired dryers require twice as much time to dry the meal as direct-fired dryers.

The dried meal is cooled, ground to a size that passes through a U. S. No. 7 standard screen, and transferred by pneumatic conveyor to storage. The ground meal is stored in bulk or in paper, burlap, or woven plastic bags. This meal is used in animal and pet feed because of its high protein content.

The "polished oil" is further purified by a process called "hardening" (Figure 9.13.1-4). First, the polished oil is refined by mixing the oil with an alkaline solution in a large stirred vat. The alkaline solution reacts with the free fatty acids in the oil to form insoluble soaps. The mixture is allowed to settle overnight, and the cleared oil is extracted off the top. The oil is then washed with hot water to remove any remaining soaps.

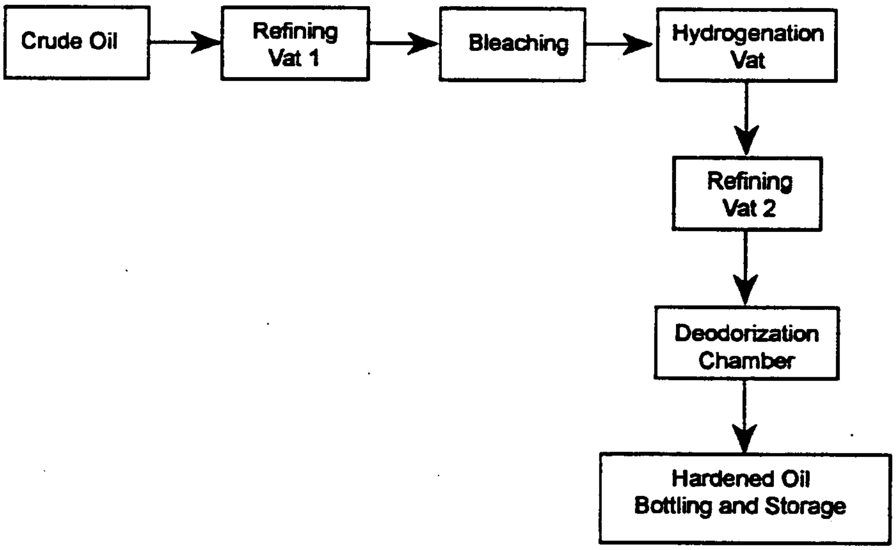


Figure 9.13.1-4. Oil hardening process.

Bleaching occurs in the next step by mixing the oil with natural clays to remove oil pigments and colored matter. This process proceeds at temperatures between 80 and 116°C, in either a batch or continuous mode. After bleaching, hydrogenation of the unsaturated fatty acid chains is the next step. A nickel catalyst, at a concentration of 0.05 to 0.1 percent by weight, is added to a vat of oil, the mixture is heated and stirred, and hydrogen is injected into the mixture to react with the unsaturated fatty acid chains. After the hydrogenation is completed, the oil is cooled and filtered to remove the nickel.

The hydrogenated oil is refined again before the deodorization step, which removes odor and flavor-producing chemicals. Deodorization occurs in a vacuum chamber where dry, oxygen-free steam is bubbled through the oil to remove the undesirable chemicals. Volatilization of the undesirable chemicals occurs at temperatures between 170 to 230°C. The oil is then cooled to about 38°C before exposure to air to prevent formation of undesirable chemicals.

9.13.1.2 Emissions And Controls

Although smoke and particulate may be a problem, odors are the most objectionable emissions from fish processing plants. The fish byproducts segment results in more of these odorous contaminants than canning, because the fish are often in a further state of decomposition, which usually results in greater concentrations of odors.

The largest odor source in the fish byproducts segment is the fish meal driers. Usually, direct-fired driers emit more odors than steam-tube driers. Direct-fired driers also emit smoke and particulate.

Odorous gases from reduction cookers consist primarily of hydrogen sulfide (H_2S) and trimethylamine [$(CH_3)_3N$] but are emitted from this stage in appreciably smaller volumes than from fish meal driers. There are virtually no particulate emissions from reduction cookers.

Some odors are produced by the canning processes. Generally, the precooked method emits fewer odorous gases than the raw pack method. In the precooked process, the odorous exhaust gases are trapped in the cookers, whereas in the raw pack process, the steam and odorous gases typically are vented directly to the atmosphere.

Fish cannery and fish byproduct processing odors can be controlled with afterburners, chlorinator-scrubbers, or condensers. Afterburners are most effective, providing virtually 100 percent odor control, but they are costly from a fuel-use standpoint. Chlorinator scrubbers have been found to be 95 to 99 percent effective in controlling odors from cookers and driers. Condensers are the least effective control device.

Particulate emissions from the fish meal process are usually limited to the dryers, primarily the direct-fired dryers, and to the grinding and conveying of the dried fish meal. Because there is a relatively small quantity of fines in the ground fish meal, particulate emissions from the grinding, pneumatic conveyors and bagging operations are expected to be very low. Generally, cyclones have been found to be an effective means to collect particulate from the dryers, grinders and conveyors, and from the bagging of the ground fish meal.

Emission factors for fish processing are presented in Table 9.13.1-1. Factors are expressed in units of kilograms per megagram (kg/Mg) and pounds per ton (lb/ton).

Table 9.13.1-1 (Metric And English Units). UNCONTROLLED EMISSION FACTORS FOR FISH CANNING AND BYPRODUCT MANUFACTURE[a]

EMISSION FACTOR RATING: C

Process	Particulate		Trimethylamine [$(CH_3)_3N$]		Hydrogen Sulfide (H_2S)	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Cookers, canning (SCC 3-02-012-04)	Neg	Neg	—[c]	—[c]	—[c]	—[c]
Cookers, scrap						
Fresh fish (SCC 3-02-012-01)	Neg	Neg	0.15[c]	0.3[c]	0.005[c]	0.01[c]
Stale fish (SCC 3-02-012-02)	Neg	Neg	1.75[c]	3.5[c]	0.10[c]	0.2[c]
Steam tube dryer (SCC 3-02-012-05)	2.5	5	—[b]	—[b]	—[b]	—[b]
Direct-fired dryer (SCC 3-02-012-06)	4	8	—[b]	—[b]	—[b]	—[b]

[a] Reference 1. Factors are in terms of raw fish processed. SCC = Source Classification Code. Neg = negligible.
[b] Emissions suspected, but data are not available for quantification.
[c] Reference 2.

References For Section 9.13.1

1. W. H. Prokop, "Fish Processing", *Air Pollution Engineering Manual*, Van Nostrand Reinhold, New York, 1992.
2. W. Summer, *Methods Of Air Deodorization*, Elsevier Publishing, New York City, 1963.
3. M. T. Gillies, *Seafood Processing*, Noyes Data Corporation, Park Ridge, NJ, 1971.
4. F. W. Wheaton and T. B. Lawson, *Processing Aquatic Food Products*, John Wiley and Sons, New York, 1985.
5. M. Windsor and S. Barlow, *Introduction To Fishery Byproducts*, Fishing News Books, Ltd., Surrey, England, 1981.
6. D. Warne, *Manual On Fish Canning*, Food And Agricultural Organization Of The United Nations, Rome, Italy, 1988.

9.13.2 Coffee Roasting

[Work In Progress]

9.13.3 Snack Chip Deep Fat Frying

9.13.3.1 General[1-3]

The production of potato chips, tortilla chips, and other related snack foods is a growing, competitive industry. Sales of such snack chips in the United States are projected to grow 5.7 percent between 1991 and 1995. Between 1987 and 1991, potato chip sales increased from 649×10^6 kilograms (kg) to 712×10^6 kg ($1,430 \times 10^6$ pounds [lb] to $1,570 \times 10^6$ lb), an increase of 63×10^6 kg (140×10^6 lb) (10 percent). Snack chip plants are widely dispersed across the country, with the highest concentrations in California and Texas.

New products and processes are being developed to create a more health-conscious image for snack chips. Examples include the recent introduction of multigrain chips and the use of vegetable oils (noncholesterol) in frying. Health concerns are also encouraging the promotion and introduction of nonfried snack products like pretzels, popcorn, and crackers.

9.13.3.2 Process Description[1]

Vegetables and other raw foods are cooked by industrial deep fat frying and are packaged for later use by consumers. The batch frying process consists of immersing the food in the cooking oil until it is cooked and then removing it from the oil. When the raw food is immersed in hot cooking oil, the oil replaces the naturally occurring moisture in the food as it cooks. Batch and continuous processes may be used for deep fat frying. In the continuous frying method, the food is moved through the cooking oil on a conveyor. Potato chips are one example of a food prepared by deep fat frying. Other examples include corn chips, tortilla corn chips, and multigrain chips.

Figure 9.13.3-1 provides general diagrams for the deep fat frying process for potato chips and other snack chips. The differences between the potato chip process and other snack chip processing operations are also shown. Some snack food processes (e. g., tortilla chips) include a toasting step. Because the potato chip processes represent the largest industry segment, they are discussed here as a representative example.

In the initial potato preparation, dirt, decayed potatoes, and other debris are first removed in cleaning hoppers. The potatoes go next to washers, then to abrasion, steam, or lye peelers. Abrasion is the most popular method. Preparation is either batch or continuous, depending on the number of potatoes to be peeled.

The next step is slicing, which is performed by a rotary slicer. Potato slice widths will vary with the condition of the potatoes and with the type of chips being made. The potato slices move through rotating reels where high-pressure water separates the slices and removes starch from the cut surfaces. The slices are then transferred to the rinse tank for final rinsing.

Next, the surface moisture is removed by 1 or more of the following methods: perforated revolving drum, sponge rubber-covered squeeze roller, compressed air systems, vibrating mesh belt, heated air, or centrifugal extraction.

The partially dried chips are then fried. Most producers use a continuous process, in which the slices are automatically moved through the fryer on a mesh belt. Batch frying, which is used for

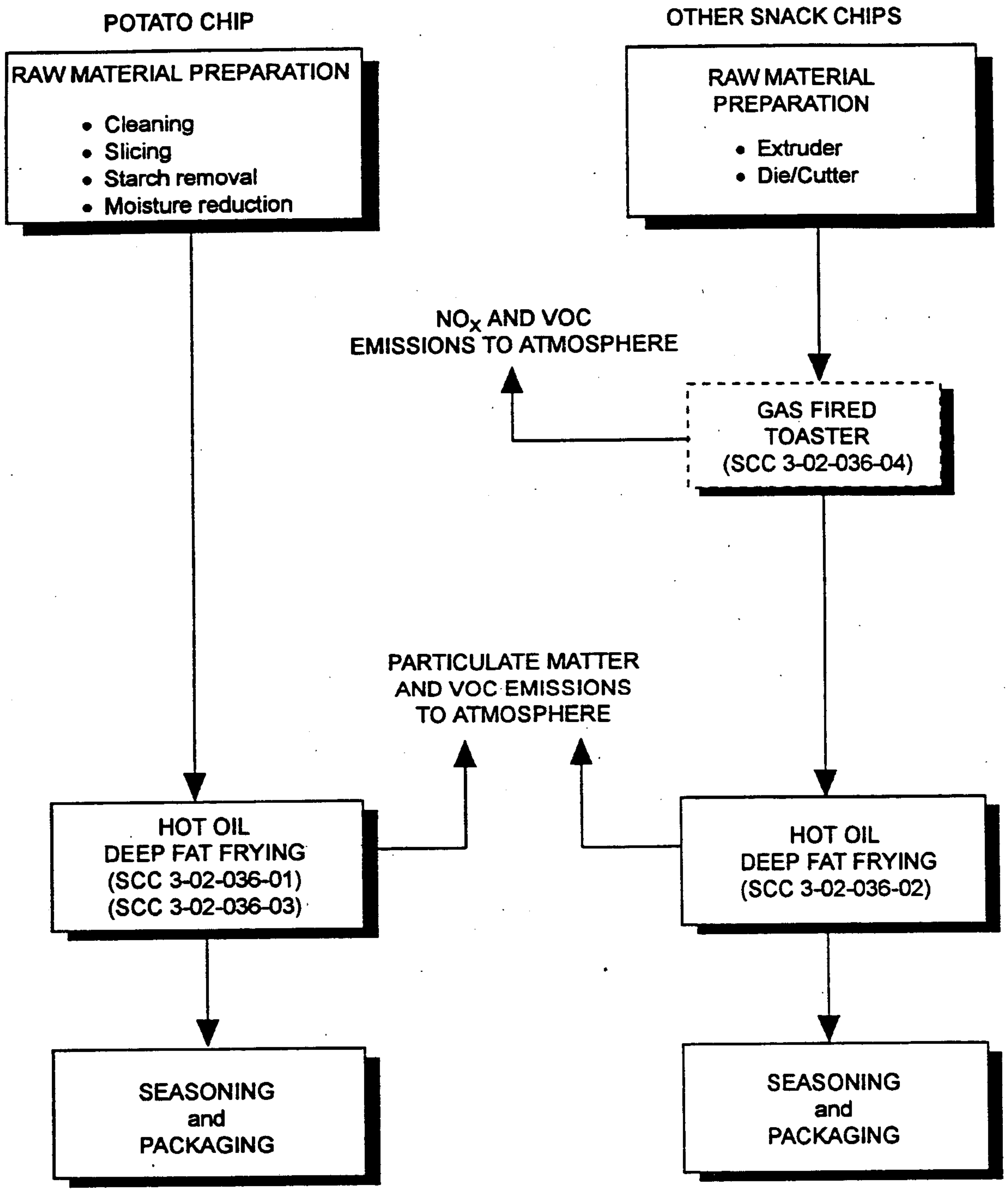


Figure 9.13.3-1. Generalized deep fat frying process for snack foods. (Source Classification Codes in parentheses.)

a smaller quantity of chips, involves placing the chips in a frying kettle for a period of time and then removing them. A variety of oils may be used for frying chips, with cottonseed, corn, and peanut oils being the most popular. Canola and soybean oils also are used. Animal fats are rarely used in this industry.

As indicated in Figure 9.13.3-1, the process for other snack chips is similar to that for potato chip frying. Typically, the raw material is extruded and cut before entering the fryer. In some cases, the chips may be toasted before frying.

9.13.3.2 Emissions And Controls[2-3]

Emissions -

Particulate matter is the major air pollutant emitted from the deep fat frying process. Emissions are released when moist foodstuff, such as potatoes, is introduced into hot oil. The rapid vaporization of the moisture in the foodstuff results in violent bubbling, and cooking oil droplets, and possibly vapors, become entrained in the water vapor stream. The emissions are exhausted from the cooking vat and into the ventilation system. Where emission controls are employed, condensed water and oil droplets in the exhaust stream are collected by control devices before the exhaust is routed to the atmosphere. The amount of particulate matter emitted depends on process throughput, oil temperature, moisture content of the feed material, equipment design, and stack emission controls.

Volatile organic compounds (VOC) are also produced in deep fat frying, but they are not a significant percentage of total frying emissions because of the low vapor pressure of the vegetable oils used. However, when the oil is entrained into the water vapor produced during frying, the oil may break down into volatile products. Small amounts of VOC and combustion products may also be emitted from toasters, but quantities are expected to be negligible.

Tables 9.13.3-1 and 9.13.3-2 provide uncontrolled and controlled particulate matter emission factors, in metric and English units, for snack chip frying. Table 9.13.3-3 provides VOC emission factors, in metric and English units, for snack chip frying without controls. Emission factors are calculated as the weight of particulate matter or VOC per ton of finished product, including salt and seasonings.

Controls -

Particulate matter emission control equipment is typically installed on potato chip fryer exhaust streams because of the elevated particulate loadings caused by the high volume of water contained in potatoes. Examples of control devices are mist eliminators, impingement devices, and wet scrubbers. One manufacturer has indicated that catalytic and thermal incinerators are not practical because of the high moisture content of the exhaust stream.

Table 9.13.3-1 (Metric Units). PARTICULATE MATTER EMISSION FACTORS FOR SNACK CHIP DEEP FAT FRYING[a]

EMISSION FACTOR RATING: E (except as noted)

Process	Filterable PM		Condensable PM			Total PM-10
	PM	PM-10	Inorganic	Organic	Total	
Continuous deep fat fryer–potato chips[b] (SCC 3-02-036-01)	0.83	ND	ND	ND	0.19	ND
Continuous deep fat fryer–other snack chips[b] (SCC 3-02-036-02)	0.28	ND	ND	ND	0.12	ND
Continuous deep fat fryer with standard mesh pad mist eliminator–potato chips[c] (SCC 3-02-036-01)	0.35[d]	0.30	0.0040[d]	0.19[d]	0.19	0.49
Continuous deep fat fryer with high-efficiency mesh pad mist eliminator–potato chips[e] (SCC 3-02-036-01)	0.12	ND	0.12	0.064	0.18	ND
Continuous deep fat fryer with standard mesh pad mist eliminator–other snack chips[f] (SCC 3-02-036-02)	0.11[d]	0.088	0.017	0.022	0.039	0.13
Batch deep fat fryer with hood scrubber–potato chips[g] (SCC 3-02-036-03)	0.89[d]	ND	0.66[d]	0.17	0.83	ND

[a] Factors are for uncontrolled emissions, except as noted. All emission factors in kg/Mg of chips produced. SCC = Source Classification Code. ND = no data.

[b] Reference 3.

[c] References 6, 10-11. The standard mesh pad mist eliminator, upon which these emission factors are based, includes a single, 6-inch, 2-layer mist pad that operates with a pressure drop of about 0.5-inch water column (when clean).

[d] EMISSION FACTOR RATING: D

[e] References 4-5. The high-efficiency mesh pad eliminator, upon which these emission factors are based, includes a coarse-weave 4-inch mist pad and a 6-inch fine weave pad, and operates with a 2.5- to 3-inch water column pressure drop (when clean).

[f] References 6-7.

[g] References 8-9.

Table 9.13.3-2 (English Units). PARTICULATE MATTER EMISSION FACTORS FOR SNACK CHIP DEEP FAT FRYING[a]

EMISSION FACTOR RATING: E (except as noted)

Process	Filterable PM		Condensable PM			Total PM-10
	PM	PM-10	Inorganic	Organic	Total	
Continuous deep fat fryer–potato chips[b] (SCC 3-02-036-01)	1.6	ND	ND	ND	0.39	ND
Continuous deep fat fryer–other snack chips[b] (SCC 3-02-036-02)	0.56	ND	ND	ND	0.24	ND
Continuous deep fat fryer with standard mesh pad mist eliminator–potato chips[c] (SCC 3-02-036-01)	0.70[d]	0.60	0.0080[d]	0.37[d]	0.38	0.98
Continuous deep fat fryer with high-efficiency mesh pad mist eliminator–potato chips[e] (SCC 3-02-036-01)	0.24	ND	0.23	0.13	0.36	ND
Continuous deep fat fryer with standard mesh pad mist eliminator–other snack chips[f] (SCC 3-02-036-02)	0.22[d]	0.18	0.034	0.044	0.078	0.26
Batch deep fat fryer with hood scrubber–potato chips[g] (SCC 3-02-036-03)	1.8[d]	ND	1.3[d]	0.33	1.6	ND

[a] Factors are for uncontrolled emissions, except as noted. All emission factors in lb/ton of chips produced. SCC = Source Classification Code. ND = no data.

[b] Reference 3.

[c] References 6, 10-11. The standard mesh pad mist eliminator, upon which these emission factors are based, includes a single, 6-inch, 2-layer mist pad that operates with a pressure drop of about 0.5 inch water column (when clean).

[d] EMISSION FACTOR RATING: D

[e] References 4-5. The high-efficiency mesh pad eliminator, upon which these emission factors are based, includes a coarse-weave 4-inch mist pad and a 6-inch fine weave pad and operates with a 2.5- to 3-inch water column pressure drop (when clean).

[f] References 6-7.

[g] References 8-9.

Table 9.13.3-3 (Metric Units). UNCONTROLLED VOC EMISSION FACTORS FOR SNACK CHIP DEEP FAT FRYING[a,b]

EMISSION FACTOR RATING: E

Process	VOC	
	kg/Mg	lb/ton
Deep fat fryer—potato chips (SCC 3-02-036-01)	0.0099	0.020
Deep fat fryer—other snack chips (SCC 3-02-036-02)	0.043	0.085

[a] Reference 3. SCC = Source Classification Code.

[b] Expressed as equivalent weight of methane (CH_4)/unit weight of product.

References For Section 9.13.3

1. O. Smith, *Potatoes: Production, Storing, Processing*, Avi Publishing, Westport, CT, 1977.

2. *Background Document For AP-42 Section 9.13.3, Snack Chip Deep Fat Frying*, Midwest Research Institute, Kansas City, MO, August 1994.

3. *Characterization Of Industrial Deep Fat Fryer Air Emissions*, Frito-Lay Inc., Plano, TX, 1991.

4. *Emission Performance Testing For Two Fryer Lines*, Western Environmental Services, Redondo Beach, CA, November 19, 20, and 21, 1991.

5. *Emission Performance Testing On One Continuous Fryer*, Western Environmental Services, Redondo Beach, CA, January 26, 1993.

6. *Emission Performance Testing Of Two Fryer Lines*, Western Environmental Services, Redondo Beach, CA, November 1990.

7. *Emission Performance Testing Of One Tortilla Continuous Frying Line*, Western Environmental Services, Redondo Beach, CA, October 20-21, 1992.

8. *Emission Performance Testing Of Fryer No. 5*, Western Environmental Services, Redondo Beach, CA, February 4-5, 1992.

9. *Emission Performance Testing Of Fryer No. 8*, Western Environmental Services, Redondo Beach, CA, February 3-4, 1992.

10. *Emission Performance Testing Of Two Fryer Lines*, Western Environmental Services, Redondo Beach, CA, November 1989.

11. *Emission Performance Testing Of Two Fryer Lines*, Western Environmental Services, Redondo Beach, CA, June 1989.

9.13.4 Yeast Production

9.13.4.1 General[1]

Baker's yeast is currently manufactured in the United States at 13 plants owned by 6 major companies. Two main types of baker's yeast are produced, compressed (cream) yeast and dry yeast. The total U. S. production of baker's yeast in 1989 was 223,500 megagrams (Mg) (245,000 tons). Of the total production, approximately 85 percent of the yeast is compressed (cream) yeast, and the remaining 15 percent is dry yeast. Compressed yeast is sold mainly to wholesale bakeries, and dry yeast is sold mainly to consumers for home baking needs. Compressed and dry yeasts are produced in a similar manner, but dry yeasts are developed from a different yeast strain and are dried after processing. Two types of dry yeast are produced, active dry yeast (ADY) and instant dry yeast (IDY). Instant dry yeast is produced from a faster-reacting yeast strain than that used for ADY. The main difference between ADY and IDY is that ADY has to be dissolved in warm water before usage, but IDY does not.

9.13.4.2 Process Description[1]

Figure 9.13.4-1 is a process flow diagram for the production of baker's yeast. The first stage of yeast production consists of growing the yeast from the pure yeast culture in a series of fermentation vessels. The yeast is recovered from the final fermentor by using centrifugal action to concentrate the yeast solids. The yeast solids are subsequently filtered by a filter press or a rotary vacuum filter to concentrate the yeast further. Next, the yeast filter cake is blended in mixers with small amounts of water, emulsifiers, and cutting oils. After this, the mixed press cake is extruded and cut. The yeast cakes are then either wrapped for shipment or dried to form dry yeast.

Raw Materials[1-3] -

The principal raw materials used in producing baker's yeast are the pure yeast culture and molasses. The yeast strain used in producing compressed yeast is *Saccharomyces cerevisiae*. Other yeast strains are required to produce each of the 2 dry yeast products, ADY and IDY. Cane molasses and beet molasses are the principal carbon sources to promote yeast growth. Molasses contains 45 to 55 weight percent fermentable sugars, in the forms of sucrose, glucose, and fructose.

The amount and type of cane and beet molasses used depend on the availability of the molasses types, costs, and the presence of inhibitors and toxins. Usually, a blend consisting of both cane and beet molasses is used in the fermentations. Once the molasses mixture is blended, the pH is adjusted to between 4.5 and 5.0 because an alkaline mixture promotes bacteria growth. Bacteria growth occurs under the same conditions as yeast growth, making pH monitoring very important. The molasses mixture is clarified to remove any sludge and is then sterilized with high-pressure steam. After sterilization, it is diluted with water and held in holding tanks until it is needed for the fermentation process.

A variety of essential nutrients and vitamins is also required in yeast production. The nutrient and mineral requirements include nitrogen, potassium, phosphate, magnesium, and calcium, with traces of iron, zinc, copper, manganese, and molybdenum. Normally, nitrogen is supplied by adding ammonium salts, aqueous ammonia, or anhydrous ammonia to the feedstock. Phosphates and magnesium are added, in the form of phosphoric acid or phosphate salts and magnesium salts. Vitamins are also required for yeast growth (biotin, inositol, pantothenic acid, and thiamine).

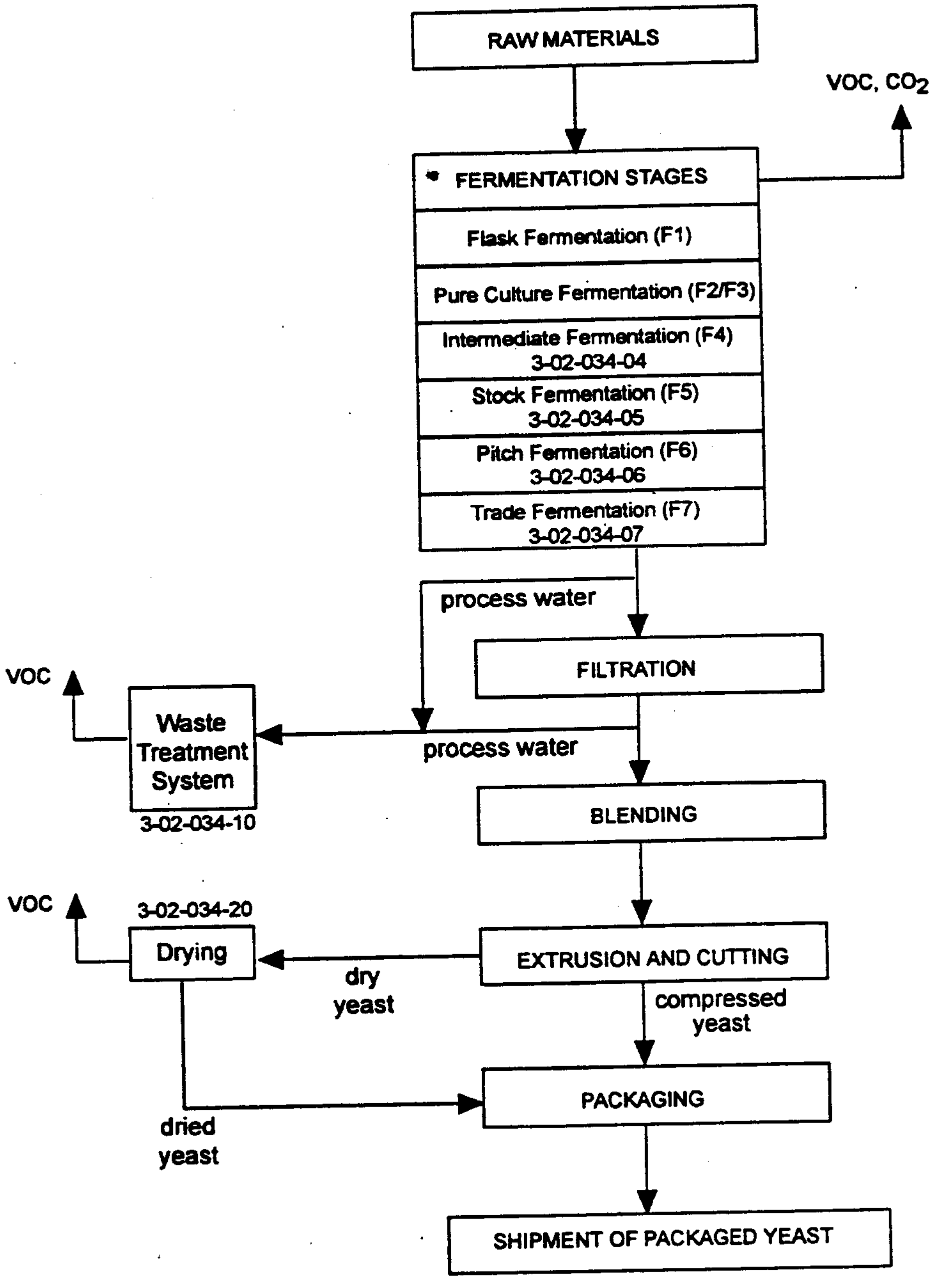


Figure 9.13.4-1. Typical process flow diagram for the seven-stage production of baker's yeast, with Source Classification Codes shown for compressed yeast. Use 3-02-035-XX for compressed yeast.

Thiamine is added to the feedstock. Most other vitamins and nutrients are already present in sufficient amounts in the molasses malt.

Fermentation[1-3] -

Yeast cells are grown in a series of fermentation vessels. Yeast fermentation vessels are operated under aerobic conditions (free oxygen or excess air present) because under anaerobic conditions (limited or no oxygen) the fermentable sugars are consumed in the formation of ethanol and carbon dioxide, which results in low yeast yields.

The initial stage of yeast growth takes place in the laboratory. A portion of the pure yeast culture is mixed with molasses malt in a sterilized flask, and the yeast is allowed to grow for 2 to 4 days. The entire contents of this flask are used to inoculate the first fermentor in the pure culture stage. Pure culture fermentations are batch fermentations, where the yeast is allowed to grow for 13 to 24 hours. Typically, 1 to 2 fermentors are used in this stage of the process. The pure culture fermentations are basically a continuation of the flask fermentation, except that they have provisions for sterile aeration and aseptic transfer to the next stage.

Following the pure culture fermentations, the yeast mixture is transferred to an intermediate fermentor that is either batch or fed-batch. The next fermentation stage is a stock fermentation. The contents from the intermediate fermentor are pumped into the stock fermentor, which is equipped for incremental feeding with good aeration. This stage is called stock fermentation, because after fermentation is complete, the yeast is separated from the bulk of the fermentor liquid by centrifuging, which produces a stock, or pitch, of yeast for the next stage. The next stage, pitch fermentation, also produces a stock, or pitch, of yeast. Aeration is vigorous, and molasses and other nutrients are fed incrementally. The liquor from this fermentor is usually divided into several parts for pitching the final trade fermentations (adding the yeast to start fermentation). Alternately, the yeast may be separated by centrifuging and stored for several days before its use in the final trade fermentations.

The final trade fermentation has the highest degree of aeration, and molasses and other nutrients are fed incrementally. Large air supplies are required during the final trade fermentations, so these vessels are often started in a staggered fashion to reduce the size of the air compressors. The duration of the final fermentation stages ranges from 11 to 15 hours. After all of the required molasses has been fed into the fermentor, the liquid is aerated for an additional 0.5 to 1.5 hours to permit further maturing of the yeast, making it more stable for refrigerated storage.

The amount of yeast growth in the main fermentation stages described above increases with each stage. Yeast growth is typically 120 kilograms (270 pounds) in the intermediate fermentor, 420 kilograms (930 pounds) in the stock fermentor, 2,500 kilograms (5,500 pounds) in the pitch fermentor, and 15,000 to 100,000 kilograms (33,000 to 220,000 pounds) in the trade fermentor.

The sequence of the main fermentation stages varies among manufacturers. About half of existing yeast operations are 2-stage processes, and the remaining are 4-stage processes. When the 2-stage final fermentation series is used, the only fermentations following the pure culture stage are the stock and trade fermentations. When the 4-stage fermentation series is used, the pure culture stage is followed by intermediate, stock, pitch, and trade fermentations.

Harvesting And Packaging[1-2] -

Once an optimum quantity of yeast has been grown, the yeast cells are recovered from the final trade fermentor by centrifugal yeast separators. The centrifuged yeast solids are further concentrated by a filter press or rotary vacuum filter. A filter press forms a filter cake containing 27 to 32 percent solids. A rotary vacuum filter forms cakes containing approximately 33 percent solids. This filter cake is then blended in mixers with small amounts of water, emulsifiers, and cutting oils to form the end product. The final packaging steps, as described below, vary depending on the type of yeast product.

In compressed yeast production (SCC 3-02-035-XX), emulsifiers are added to give the yeast a white, creamy appearance and to inhibit water spotting of the yeast cakes. A small amount of oil, usually soybean or cottonseed oil, is added to help extrude the yeast through nozzles to form continuous ribbons of yeast cake. The ribbons are cut, and the yeast cakes are wrapped and cooled to below 8°C (46°F), at which time they are ready for shipment in refrigerated trucks.

In dry yeast production (SCC 3-02-034-XX), the product is sent to an extruder after filtration, where emulsifiers and oils (different from those used for compressed yeast) are added to texturize the yeast and to aid in extruding it. After the yeast is extruded in thin ribbons, it is cut and dried in either a batch or a continuous drying system. Following drying, the yeast is vacuum packed or packed under nitrogen gas before heat sealing. The shelf life of ADY and IDY at ambient temperature is 1 to 2 years.

9.13.4.3 Emissions[1,4-5]

Volatile organic compound (VOC) emissions are generated as byproducts of the fermentation process. The 2 major VOCs emitted are ethanol and acetaldehyde. Other byproducts consist of other alcohols, such as butanol, isopropyl alcohol, 2,3-butanediol, organic acids, and acetates. Based on emission test data, approximately 80 to 90 percent of total VOC emissions is ethanol, and the remaining 10 to 20 percent consists of other alcohols and acetaldehyde. Acetaldehyde is a hazardous air pollutant as defined under Section 112 of the *Clean Air Act*.

Volatile byproducts form as a result of either excess sugar (molasses) present in the fermentor or an insufficient oxygen supply to it. Under these conditions, anaerobic fermentation occurs, breaking down the excess sugar into alcohols and carbon dioxide. When anaerobic fermentation occurs, 2 moles of ethanol and 2 moles of carbon dioxide are formed from 1 mole of glucose. Under anaerobic conditions, the ethanol yield is increased, and yeast yields are decreased. Therefore, in producing baker's yeast, it is essential to suppress ethanol formation in the final fermentation stages by incremental feeding of the molasses mixture with sufficient oxygen to the fermentor.

The rate of ethanol formation is higher in the earlier stages (pure culture stages) than in the final stages of the fermentation process. The earlier fermentation stages are batch fermentors, where excess sugars are present and less aeration is used during the fermentation process. These fermentations are not controlled to the degree that the final fermentations are controlled because the majority of yeast growth occurs in the final fermentation stages. Therefore, there is no economical reason for manufacturers to equip the earlier fermentation stages with process control equipment.

Another potential emission source at yeast manufacturing facilities is the system used to treat process waste waters. If the facility does not use an anaerobic biological treatment system, significant quantities of VOCs could be emitted from this stage of the process. For more information on waste water treatment systems as an emission source of VOCs, please refer to EPA's Control Technology Center document on industrial waste water treatment systems, *Industrial Wastewater Volatile Organic Compound Emissions - Background Information For BACT/LAER*, or see Section 4.3 of AP-42. At facilities manufacturing dry yeast, VOCs may also be emitted from the yeast dryers, but no information is available on the relative quantity of VOC emissions from this source.

9.13.4.4 Controls[6]

Only 1 yeast manufacturing facility uses an add-on pollution control system to reduce VOC emissions from the fermentation process. However, all yeast manufacturers suppress ethanol formation through varying degrees of process control, such as incrementally feeding the molasses mixture to the fermentors so that excess sugars are not present, or supplying sufficient oxygen to the fermentors to optimize the dissolved oxygen content of the liquid in the fermentor. The adequacy of oxygen distribution depends upon the proper design and operation of the aeration and mechanical agitation systems of the fermentor. The distribution of oxygen by the air sparger system to the malt mixture is critical. If oxygen is not being transferred uniformly throughout the malt, then ethanol will be produced in the oxygen-deficient areas of the fermentor. The type and position of baffles and/or a highly effective mechanical agitation system can ensure proper distribution of oxygen.

A more sophisticated form of process control involves using a continuous monitoring system and feedback control. In such a system, process parameters are monitored, and the information is sent to a computer. The computer is then used to calculate sugar consumption rates through material balance techniques. Based on the calculated data, the computer continuously controls the addition of molasses. This type of system is feasible, but it is difficult to design and implement. Such enhanced process control measures can suppress ethanol formation from 75 to 95 percent.

The 1 facility with add-on control uses a wet scrubber followed by a biological filter. Performance data from this unit suggest an emission control efficiency of better than 90 percent.

9.13.4.5 Emission Factors[1,6-9]

Table 9.13.4-1 provides emission factors for a typical yeast fermentation process with a moderate degree of process control. The process emission factors in Table 9.13.4-1 were developed from 4 test reports from 3 yeast manufacturing facilities. Separate emission factors are given for intermediate, stock/pitch, and trade fermentations. The emission factors in Table 9.13.4-1 are expressed in units of VOC emitted per fermentor per unit of yeast produced in that fermentor.

In order to use the emission factors for each fermentor, the amount of yeast produced in each fermentor must be known. The following is an example calculation for a typical facility:

Fermentation Stage	Yeast Yield Per Batch, lb (A)	No. Of Batches Processed Per Year, #/yr (B)	Total Yeast Production Per Stage, tons/yr (C = A x B/2,000)	Emission Factor, lb/ton (D)	Emissions, lb (E = C x D)	Percent of Total Emissions
Intermediate	265	156	21	36	756	0.84
Stock	930	208	97	5	485	0.54
Pitch	5,510	208	573	5	2,865	3.18
Trade	33,070	1,040	17,196	5	85,980	95.44
TOTAL	—	—	—	—	90,086	100

In most cases, the annual yeast production per stage will not be available. However, a reasonable estimate can be determined based on the emission factor for the trade fermentor and the total yeast production for the facility. Trade fermentors produce the majority of all VOCs emitted from the facility because of the number of batches processed per year and of the amount of yeast grown in these fermentors. Based on emission test data and process data regarding the number of batches processed per year, 80 to 90 percent of VOCs emitted from fermentation operations are a result of the trade fermentors.

Using either a 2-stage or 4-stage fermentation process has no significant effect on the overall emissions for the facility. Facilities that use the 2-stage process may have larger fermentors or may produce more batches per year than facilities that use a 4-stage process. The main factors affecting emissions are the total yeast production for a facility and the degree of process control used.

Table 9.13.4-1 (Metric And English Units). VOLATILE ORGANIC COMPOUND (VOC) EMISSION FACTORS FOR YEAST MANUFACTURING[a]

EMISSION FACTOR RATING: E

Emission Point[b]	VOC[c]	
	VOC Emitted Per Stage Per Amount Of Yeast Produced In A Stage, kg VOC/Mg Yeast	VOC Emitted Per Stage Per Amount Of Yeast Produced In A Stage, lb VOC/ton Yeast
Fermentation stages[d]		
Flask (F1)	ND	ND
Pure culture (F2/F3)	ND	ND
Intermediate (F4) (SCC 3-02-034-04)	18	36
Stock (F5) (SCC 3-02-034-05)	2.5	5.0
Pitch (F6) (SCC 3-02-034-06)	2.5	5.0
Trade (F7) (SCC 3-02-034-07)	2.5	5.0
Waste treatment (SCC 3-02-034-10)	See Section 4.3 of AP-42	
Drying (SCC 3-02-034-20)	ND	ND

[a] References 1,6-10. Total VOC as ethanol. SCC = Source Classification Code. ND = no data. F numbers refer to fermentation stages (see Figure 9.13.4-1).

[b] Factors are for both dry yeast (SCC 3-02-034-XX) and compressed yeast (SCC 3-02-035-XX).

[c] Factors should be used only when plant-specific emission data are not available because of the high degree of emissions variability among facilities and among batches within a facility.

[d] Some yeast manufacturing facilities use a 2-stage final fermentation process, and others use a 4-stage final fermentation process. Factors for each stage cannot be summed to determine an overall emission factor for a facility, since they are based on yeast yields in each fermentor rather than total yeast production. Total yeast production for a facility equals only the yeast yield from the trade fermentations. Note that CO_2 is also a byproduct of fermentation, but no data are available on the amount emitted.

References For Section 9.13.4

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6. Written communication from R. Jones, Midwest Research Institute, Cary, NC, to the project file, April 28, 1993.

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10. *Fermentor Emissions Test Report, Universal Foods, Inc., Baltimore, MD*, Universal Foods, Inc., Milwaukee, WI, 1990.

9.14 Tobacco Products

[Work In Progress]

9.15 Leather Tanning

[Work In Progress]

9.16 Agricultural Wind Erosion

[Work In Progress]

10. WOOD PRODUCTS INDUSTRY

Wood processing in this industry involves the conversion of trees into useful consumer products and/or building materials such as paper, charcoal, treated and untreated lumber, plywood, particle board, wafer board, and medium density fiber board. During the conversion processes, the major pollutants of concern are particulate, PM-10, and volatile organic compounds. There also may be speciated organic compounds that may be toxic or hazardous.

10.1 Lumber

[Work In Progress]

10.2 Chemical Wood Pulping

10.2.1 General

Chemical wood pulping involves the extraction of cellulose from wood by dissolving the lignin that binds the cellulose fibers together. The 4 processes principally used in chemical pulping are kraft, sulfite, neutral sulfite semichemical (NSSC), and soda. The first 3 display the greatest potential for causing air pollution. The kraft process alone accounts for over 80 percent of the chemical pulp produced in the United States. The choice of pulping process is determined by the desired product, by the wood species available, and by economic considerations.

10.2.2 Kraft Pulping

10.2.2.1 Process Description[1] -

The kraft pulping process (see Figure 10.2-1) involves the digesting of wood chips at elevated temperature and pressure in "white liquor", which is a water solution of sodium sulfide and sodium hydroxide. The white liquor chemically dissolves the lignin that binds the cellulose fibers together.

There are 2 types of digester systems, batch and continuous. Most kraft pulping is done in batch digesters, although the more recent installations are of continuous digesters. In a batch digester, when cooking is complete, the contents of the digester are transferred to an atmospheric tank usually referred to as a blow tank. The entire contents of the blow tank are sent to pulp washers, where the spent cooking liquor is separated from the pulp. The pulp then proceeds through various stages of washing, and possibly bleaching, after which it is pressed and dried into the finished product. The "blow" of the digester does not apply to continuous digester systems.

The balance of the kraft process is designed to recover the cooking chemicals and heat. Spent cooking liquor and the pulp wash water are combined to form a weak black liquor which is concentrated in a multiple-effect evaporator system to about 55 percent solids. The black liquor is then further concentrated to 65 percent solids in a direct-contact evaporator, by bringing the liquor into contact with the flue gases from the recovery furnace, or in an indirect-contact concentrator. The strong black liquor is then fired in a recovery furnace. Combustion of the organics dissolved in the black liquor provides heat for generating process steam and for converting sodium sulfate to sodium sulfide. Inorganic chemicals present in the black liquor collect as a molten smelt at the bottom of the furnace.

The smelt is dissolved in water to form green liquor, which is transferred to a causticizing tank where quicklime (calcium oxide) is added to convert the solution back to white liquor for return to the digester system. A lime mud precipitates from the causticizing tank, after which it is calcined in a lime kiln to regenerate quicklime.

For process heating, for driving equipment, for providing electric power, etc., many mills need more steam than can be provided by the recovery furnace alone. Thus, conventional industrial boilers that burn coal, oil, natural gas, or bark and wood are commonly used.

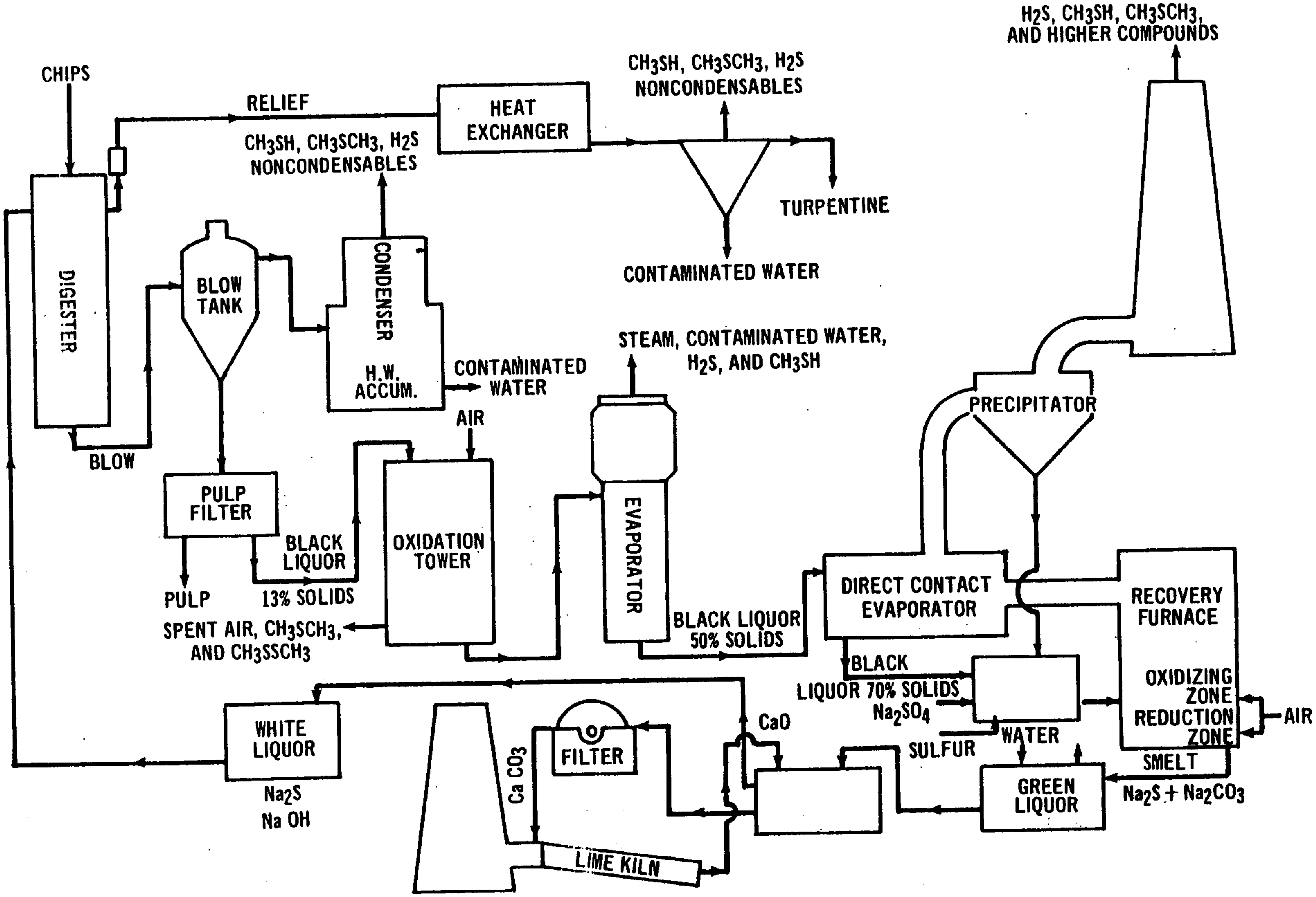

Figure 10.2-1. Typical kraft sulfate pulping and recovery process.

10.2.2.2 Emissions And Controls[1-7] -

Particulate emissions from the kraft process occur largely from the recovery furnace, the lime kiln and the smelt dissolving tank. These emissions are mainly sodium salts, with some calcium salts from the lime kiln. They are caused mostly by carryover of solids and sublimation and condensation of the inorganic chemicals.

Particulate control is provided on recovery furnaces in a variety of ways. In mills with either cyclonic scrubber or cascade evaporator as the direct-contact evaporator, further control is necessary, as these devices are generally only 20 to 50 percent efficient for particulates. Most often in these cases, an electrostatic precipitator (ESP) is employed after the direct-contact evaporator, for an overall particulate control efficiency of from 85 to more than 99 percent. Auxiliary scrubbers may be added at existing mills after a precipitator or a venturi scrubber to supplement older and less efficient primary particulate control devices.

Particulate control on lime kilns is generally accomplished by scrubbers. Electrostatic precipitators have been used in a few mills. Smelt dissolving tanks usually are controlled by mesh pads, but scrubbers can provide further control.

The characteristic odor of the kraft mill is caused by the emission of reduced sulfur compounds, the most common of which are hydrogen sulfide, methyl mercaptan, dimethyl sulfide, and dimethyl disulfide, all with extremely low odor thresholds. The major source of hydrogen sulfide is the direct contact evaporator, in which the sodium sulfide in the black liquor reacts with the carbon dioxide in the furnace exhaust. Indirect contact evaporators can significantly reduce the emission of hydrogen sulfide. The lime kiln can also be a potential source of odor, as a similar reaction occurs with residual sodium sulfide in the lime mud. Lesser amounts of hydrogen sulfide are emitted with the noncondensables of offgases from the digesters and multiple-effect evaporators.

Methyl mercaptan and dimethyl sulfide are formed in reactions with the wood component, lignin. Dimethyl disulfide is formed through the oxidation of mercaptan groups derived from the lignin. These compounds are emitted from many points within a mill, but the main sources are the digester/blow tank systems and the direct contact evaporator.

Although odor control devices, per se, are not generally found in kraft mills, emitted sulfur compounds can be reduced by process modifications and improved operating conditions. For example, black liquor oxidation systems, which oxidize sulfides into less reactive thiosulfates, can considerably reduce odorous sulfur emissions from the direct contact evaporator, although the vent gases from such systems become minor odor sources themselves. Also, noncondensable odorous gases vented from the digester/blow tank system and multiple effect evaporators can be destroyed by thermal oxidation, usually by passing them through the lime kiln. Efficient operation of the recovery furnace, by avoiding overloading and by maintaining sufficient oxygen, residence time, and turbulence, significantly reduces emissions of reduced sulfur compounds from this source as well. The use of fresh water instead of contaminated condensates in the scrubbers and pulp washers further reduces odorous emissions.

Several new mills have incorporated recovery systems that eliminate the conventional direct-contact evaporators. In one system, heated combustion air, rather than fuel gas, provides direct-contact evaporation. In another, the multiple-effect evaporator system is extended to replace the direct-contact evaporator altogether. In both systems, sulfur emissions from the recovery furnace/direct-contact evaporator can be reduced by more than 99 percent.

Sulfur dioxide is emitted mainly from oxidation of reduced sulfur compounds in the recovery furnace. It is reported that the direct contact evaporator absorbs about 75 percent of these emissions, and further scrubbing can provide additional control.

Potential sources of carbon monoxide emissions from the kraft process include the recovery furnace and lime kilns. The major cause of carbon monoxide emissions is furnace operation well above rated capacity, making it impossible to maintain oxidizing conditions.

Some nitrogen oxides also are emitted from the recovery furnace and lime kilns, although amounts are relatively small. Indications are that nitrogen oxide emissions are on the order of 0.5 to 1.0 kilograms per air-dried megagram (kg/Mg) (1 to 2 pounds per air-dried ton [lb/ton]) of pulp produced from the lime kiln and recovery furnace, respectively.[5-6]

A major source of emissions in a kraft mill is the boiler for generating auxiliary steam and power. The fuels are coal, oil, natural gas, or bark/wood waste. See Chapter 1, "External Combustion Sources", for emission factors for boilers.

Table 10.2-1 presents emission factors for a conventional kraft mill. The most widely used particulate control devices are shown, along with the odor reductions through black liquor oxidation and incineration of noncondensable offgases. Tables 10.2-2, 10.2-3, 10.2-4, 10.2-5, 10.2-6, and 10.2-7 present cumulative size distribution data and size-specific emission factors for particulate emissions from sources within a conventional kraft mill. Uncontrolled and controlled size-specific emission factors[7] are presented in Figure 10.2-2, Figure 10.2-3, Figure 10.2-4, Figure 10.2-5, Figure 10.2-6, and Figure 10.2-7. The particle sizes are expressed in terms of the aerodynamic diameter in micrometers (μm).

10.2.3 Acid Sulfite Pulping

10.2.3.1 Process Description -

The production of acid sulfite pulp proceeds similarly to kraft pulping, except that different chemicals are used in the cooking liquor. In place of the caustic solution used to dissolve the lignin in the wood, sulfurous acid is employed. To buffer the cooking solution, a bisulfite of sodium, magnesium, calcium, or ammonium is used. A diagram of a typical magnesium-base process is shown in Figure 10.2-8.

Digestion is carried out under high pressure and high temperature, in either batch mode or continuous digesters, and in the presence of a sulfurous acid/bisulfite cooking liquid. When cooking is completed, either the digester is discharged at high pressure into a blow pit, or its contents are pumped into a dump tank at lower pressure. The spent sulfite liquor (also called red liquor) then drains through the bottom of the tank and is treated and discarded, incinerated, or sent to a plant for recovery of heat and chemicals. The pulp is then washed and processed through screens and centrifuges to remove knots, bundles of fibers, and other material. It subsequently may be bleached, pressed, and dried in papermaking operations.

Because of the variety of cooking liquor bases used, numerous schemes have evolved for heat and/or chemical recovery. In calcium base systems, found mostly in older mills, chemical recovery is not practical, and the spent liquor is usually discharged or incinerated. In ammonium base operations, heat can be recovered by combusting the spent liquor, but the ammonium base is thereby consumed. In sodium or magnesium base operations, the heat, sulfur, and base all may be feasibly recovered.

Table 10.2-1 (Metric And English Units). EMISSION FACTORS FOR KRAFT PULPING[a]

EMISSION FACTOR RATING: A

Source	Type Of Control	Particulate		Sulfur Dioxide (SO_2)		Carbon Monoxide (CO)		Hydrogen Sulfide (S^m)		RSH, RSR, RSSR (S^m)	
		kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Digester relief and blow tank	Untreated[b]	ND	ND	ND	ND	ND	ND	0.02	0.03	0.6	1.2
Brown stock washer	Untreated[b]	ND	ND	ND	ND	ND	ND	0.01	0.02	0.2[c]	0.4[c]
Multiple effect evaporator	Untreated[b]	ND	ND	ND	ND	ND	ND	0.55	1.1	0.05	0.1
Recovery boiler and direct evaporator	Untreated[d]	90	180	3.5	7	5.5	11	6[e]	12[e]	1.5[e]	3[e]
	Venturi scrubber[f]	24	48	3.5	7	5.5	11	6[e]	12[e]	1.5[e]	3[e]
	ESP	1	2	3.5	7	5.5	11	6[e]	12[e]	1.5[e]	3[e]
	Auxiliary scrubber	1.5 - 7.5[g]	3 - 15[g]					6[e]	12[e]	1.5[e]	3[e]
Noncontact recovery boiler without direct contact evaporator	Untreated	115	230	ND	ND	5.5	11	0.05[h]	0.1[h]	ND	ND
	ESP	1	2	ND	ND	5.5	11	0.05[h]	0.1[h]	ND	ND
Smelt dissolving tank	Untreated	3.5	7	0.1	0.2	ND	ND	0.1[j]	0.2[j]	0.15[j]	0.3[j]
	Mesh pad	0.5	1	0.1	0.2	ND	ND	0.1[j]	0.2[j]	0.15[j]	0.3[j]
	Scrubber	0.1	0.2	ND	ND	ND	ND	0.1[j]	0.2[j]	0.15[j]	0.3[j]
Lime kiln	Untreated	28	56	0.15	0.3	0.05	0.1	0.25[m]	0.5[m]	0.1[m]	0.2[m]
	Scrubber or ESP	0.25	0.5	ND	ND	0.05	0.1	0.25[m]	0.5[m]	0.1[m]	0.2[m]
Turpentine condenser	Untreated	ND	ND	ND	ND	ND	ND	0.005	0.01	0.25	0.5
Miscellaneous[n]	Untreated	ND	ND	ND	ND	ND	ND	ND	ND	0.25	0.5

Table 10.2-1 (cont.).

[a] References 8-10. Factors expressed in unit weight of air-dried unbleached pulp (ADP). RSH = Methyl mercaptan. RSR = Dimethyl sulfide. RSSR = Dimethyl disulfide. ESP = Electrostatic precipitator. ND = No data.

[b] If noncondensable gases from these sources are vented to lime kiln, recovery furnace, or equivalent, the reduced sulfur compounds are destroyed.

[c] Apply with system using condensate as washing medium. When using fresh water, emissions are 0.05 kg/Mg (0.1 lb/ton).

[d] Apply when cyclonic scrubber or cascade evaporator is used for direct contact evaporation, with no further controls.

[e] Usually reduced by 50% with black liquor oxidation and can be cut 95 - 99% when oxidation is complete and recovery furnace is operated optimally.

[f] Apply when venturi scrubber is used for direct contact evaporation, with no further controls.

[g] Use 7.5 kg/Mg (15 lb/ton) when auxiliary scrubber follows venturi scrubber, and 1.5 kg/Mg (3 lb/ton) when it follows ESP.

[h] Apply when recovery furnace is operated optimally to control total reduced sulfur (TRS) compounds.

[j] Usually reduced to 0.01 g/kg (0.02 lb/ton) ADP when water low in sulfides is used in smelt dissolving tank and associated scrubber.

[m] Usually reduced to 0.015 g/kg (0.03 lb/ton) ADP with efficient mud washing, optimal kiln operation and added caustic in scrubbing water. With only efficient mud washing and optimal process control, TRS compounds reduced to 0.04 g/kg (0.08 lb/ton) ADP.

[n] Includes knotter vents, brownstock seal tanks, etc. When black liquor oxidation is included, emissions are 0.3 kg/Mg (0.6 lb/ton).

Table 10.2-2 (Metric Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR A RECOVERY BOILER WITH A DIRECT-CONTACT EVAPORATOR AND AN ESP[a]

EMISSION FACTOR RATING: C

Particulate Size (μm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor (kg/Mg of Air-Dried Pulp)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
15	95.0	ND	86	ND
10	93.5	ND	84	ND
6	92.2	68.2	83	0.7
2.5	83.5	53.8	75	0.5
1.25	56.5	40.5	51	0.4
1.00	45.3	34.2	41	0.3
0.625	26.5	22.2	24	0.2
Total	100	100	90	1.0

[a] Reference 7. ND = no data.

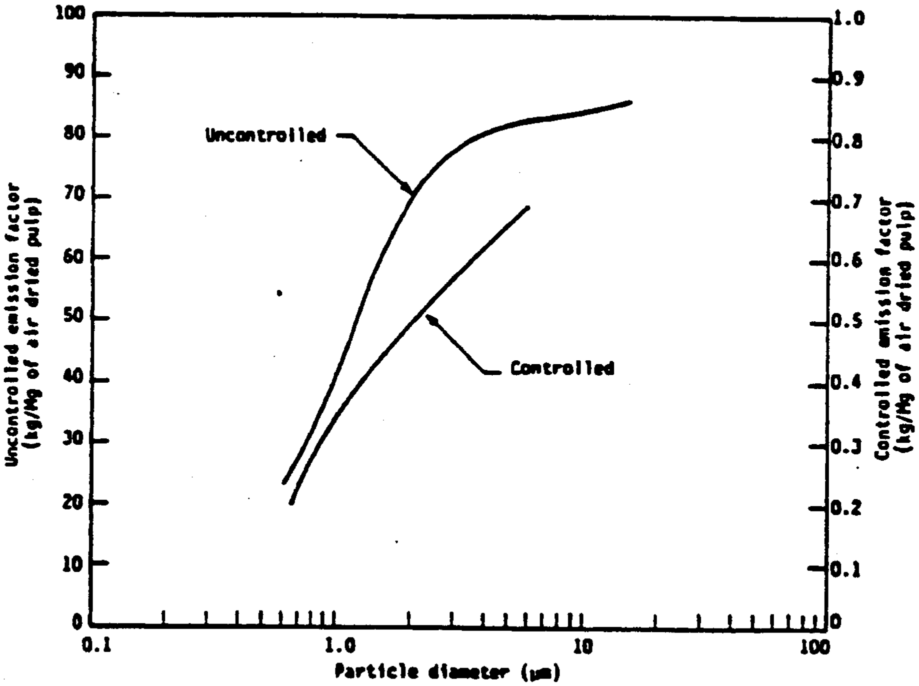

Figure 10.2-2. Cumulative particle size distribution and size-specific emission factors for recovery boiler with direct-contact evaporator and ESP.

Table 10.2-3 (Metric Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR A RECOVERY BOILER WITHOUT A DIRECT-CONTACT EVAPORATOR BUT WITH AN ESP[a]

EMISSION FACTOR RATING: C

Particulate Size (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor (kg/Mg of Air-Dried Pulp)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
15	ND	78.8	ND	0.8
10	ND	74.8	ND	0.7
6	ND	71.9	ND	0.7
2.5	78.0	67.3	90	0.6
1.25	40.0	51.3	46	0.5
1.00	30.0	42.4	35	0.5
0.625	17.0	29.6	20	0.3
Total	100	100	115	1.0

[a]Reference 7. ND = no data.

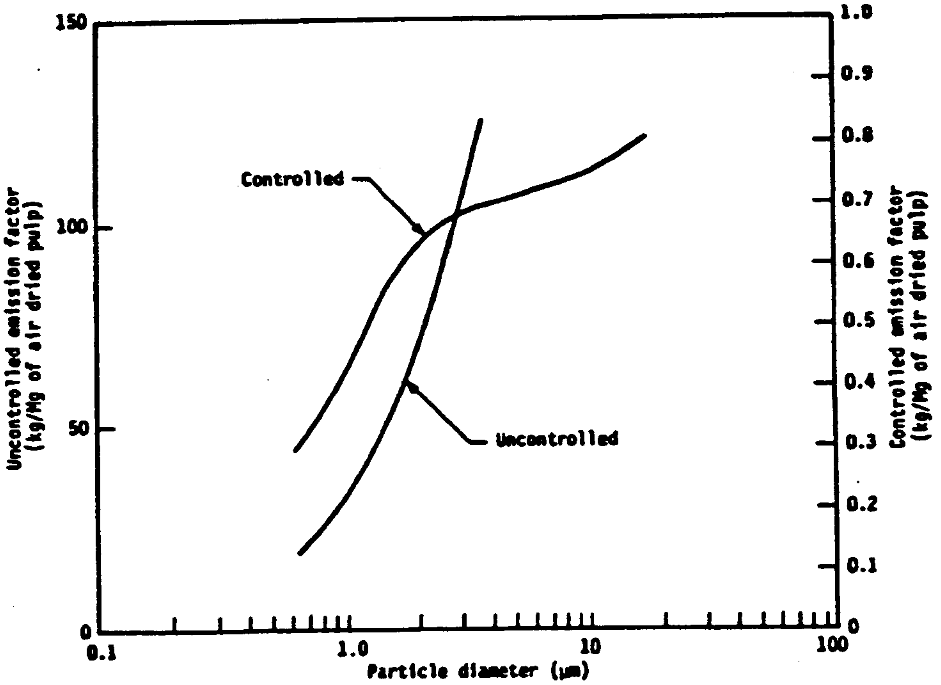

Figure 10.2-3. Cumulative particle size distribution and size-specific emission factors for recovery boiler without direct-contact evaporator but with ESP.

Table 10.2-4 (Metric Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR A LIME KILN WITH A VENTURI SCRUBBER[a]

EMISSION FACTOR RATING: C

Particulate Size (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor (kg/Mg of Air-Dried Pulp)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
15	27.7	98.9	7.8	0.24
10	16.8	98.3	4.7	0.24
6	13.4	98.2	3.8	0.24
2.5	10.5	96.0	2.9	0.24
1.25	8.2	85.0	2.3	0.21
1.00	7.1	78.9	2.0	0.20
0.625	3.9	54.3	1.1	0.14
Total	100	100	28.0	0.25

[a]Reference 7.

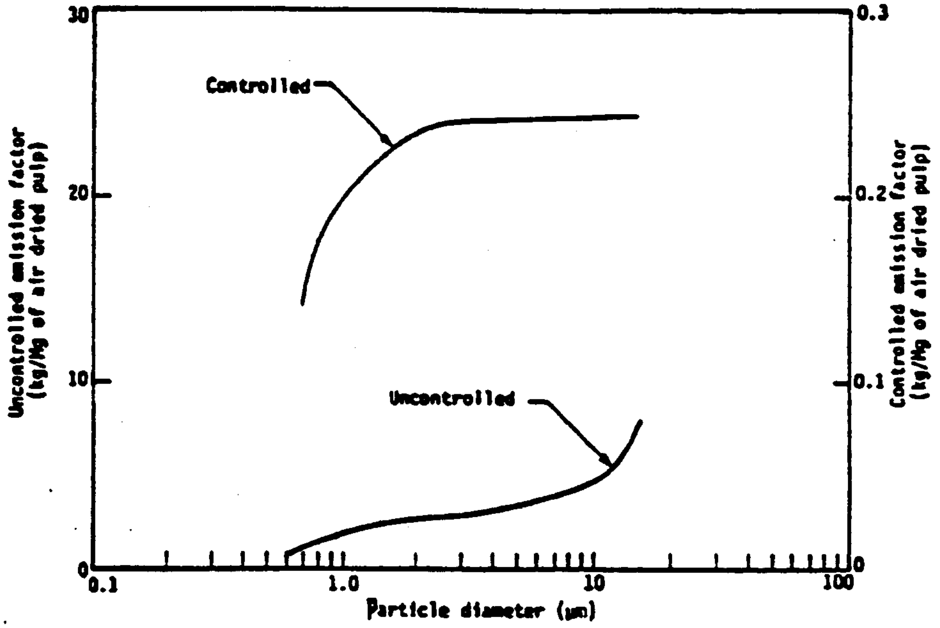

Figure 10.2-4. Cumulative particle size distribution and size-specific emission factors for lime kiln with venturi scrubber.

Table 10.2-5 (Metric Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR A LIME KILN WITH AN ESP[a]

EMISSION FACTOR RATING: C

Particulate Size (μm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor (kg/Mg of Air-Dried Pulp)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
15	27.7	91.2	7.8	0.23
10	16.8	88.5	4.7	0.22
6	13.4	86.5	3.8	0.22
2.5	10.5	83.0	2.9	0.21
1.25	8.2	70.2	2.3	0.18
1.00	7.1	62.9	2.0	0.16
0.625	3.9	46.9	1.1	0.12
Total	100	100	28.0	0.25

[a]Reference 7.

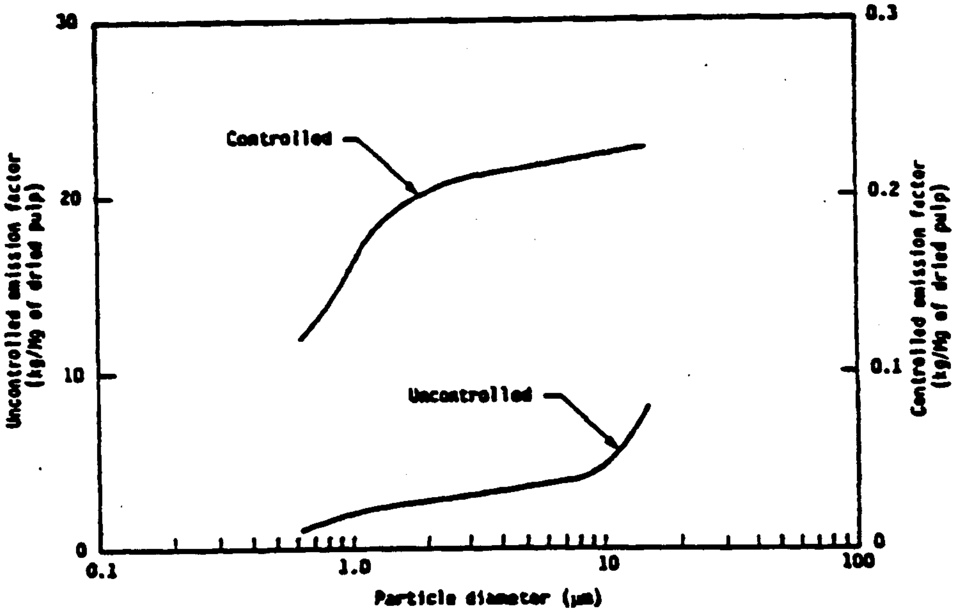

Figure 10.2-5. Cumulative particle size distribution and size-specific emission factors for lime kiln with ESP.

Table 10.2-6 (Metric Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR A SMELT DISSOLVING TANK WITH A PACKED TOWER[a]

EMISSION FACTOR RATING: C

Particulate Size (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor (kg/Mg of Air-Dried Pulp)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
15	90.0	95.3	3.2	0.48
10	88.5	95.3	3.1	0.48
6	87.0	94.3	3.0	0.47
2.5	73.0	85.2	2.6	0.43
1.25	47.5	63.8	1.7	0.32
1.00	40.0	54.2	1.4	0.27
0.625	25.5	34.2	0.9	0.17
Total	100	100	3.5	0.50

[a] Reference 7.

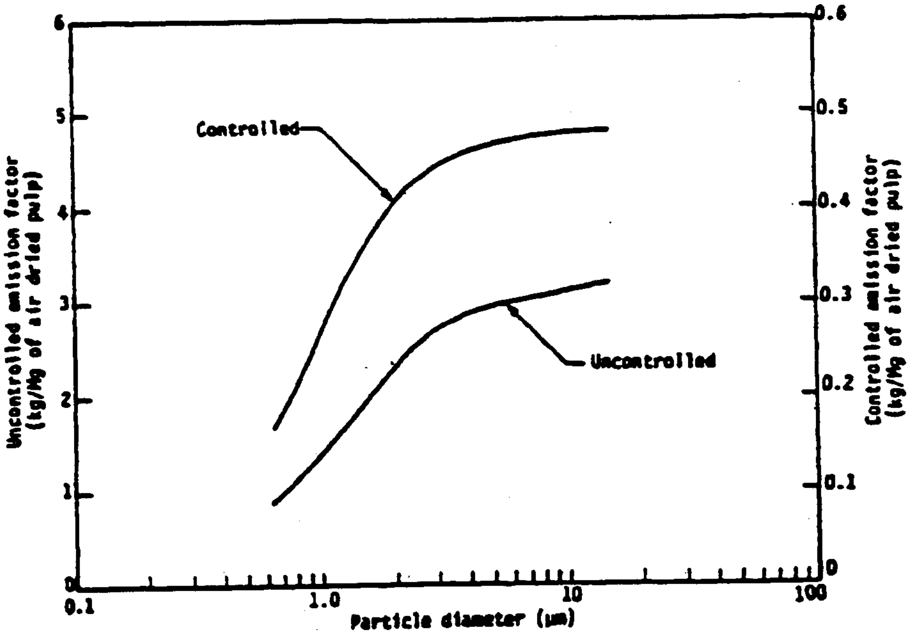

Figure 10.2-6. Cumulative particle size distribution and size-specific emission factors for smelt dissolving tank with packed tower.

Table 10.2-7 (Metric Units). CUMULATIVE PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR A SMELT DISSOLVING TANK WITH A VENTURI SCRUBBER[a]

EMISSION FACTOR RATING: C

Particulate Size (µm)	Cumulative Mass % ≤ Stated Size		Cumulative Emission Factor (kg/Mg of Air-Dried Pulp)	
	Uncontrolled	Controlled	Uncontrolled	Controlled
15	90.0	89.9	3.2	0.09
10	88.5	89.5	3.1	0.09
6	87.0	88.4	3.0	0.09
2.5	73.0	81.3	2.6	0.08
1.25	47.5	63.5	1.7	0.06
1.00	40.0	54.7	1.4	0.06
0.625	25.5	38.7	0.9	0.04
Total	100	100	3.5	0.09

[a] Reference 7.

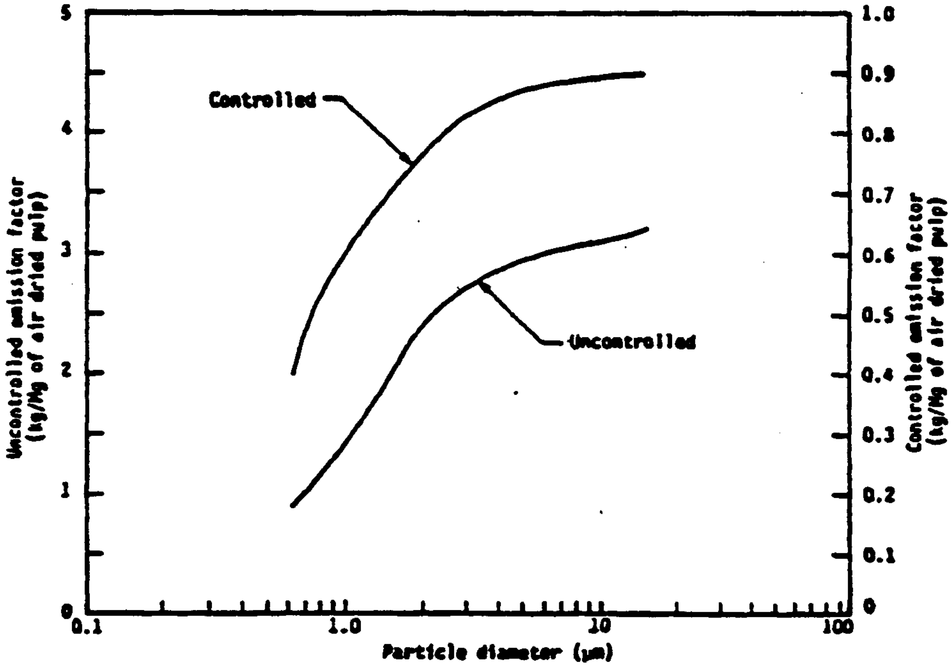

Figure 10.2-7. Cumulative particle size distribution and size-specific emission factors for smelt dissolving tank with venturi scrubber.

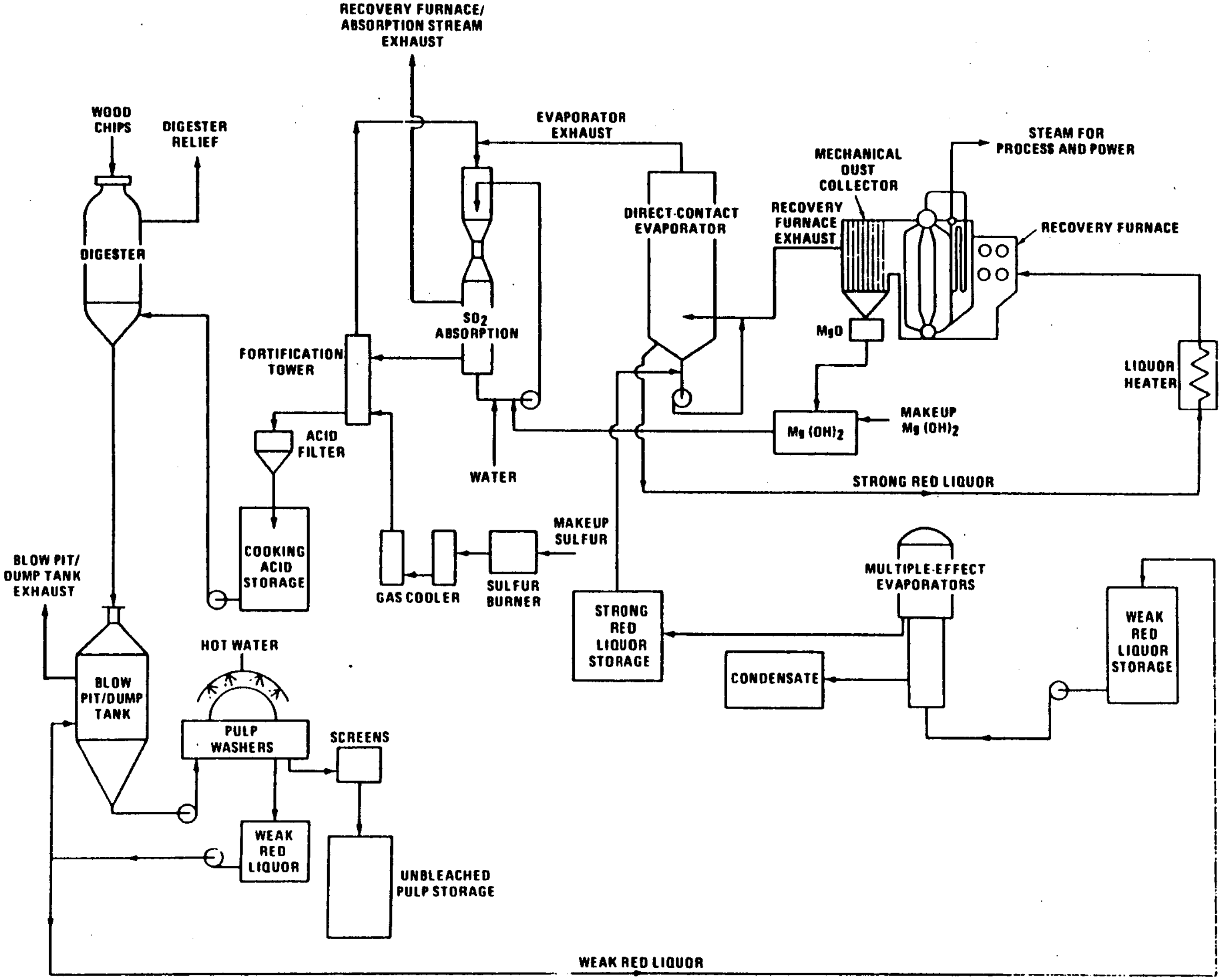

Figure 10.2-8. Simplified process flow diagram of magnesium-base process employing chemical and heat recovery.

If recovery is practiced, the spent (weak) red liquor (which contains more than half of the raw materials as dissolved organic solids) is concentrated in a multiple-effect evaporator and a direct-contact evaporator to 55 to 60 percent solids. This strong liquor is sprayed into a furnace and burned, producing steam to operate the digesters, evaporators, etc. and to meet other power requirements.

When magnesium base liquor is burned, a flue gas is produced from which magnesium oxide is recovered in a multiple cyclone as fine white power. The magnesium oxide is then water slaked and is used as circulating liquor in a series of venturi scrubbers, which are designed to absorb sulfur dioxide from the flue gas and to form a bisulfite solution for use in the cook cycle. When sodium base liquor is burned, the inorganic compounds are recovered as a molten smelt containing sodium sulfide and sodium carbonate. This smelt may be processed further and used to absorb sulfur dioxide from the flue gas and sulfur burner. In some sodium base mills, however, the smelt may be sold to a nearby kraft mill as raw material for producing green liquor.

If liquor recovery is not practiced, an acid plant is necessary of sufficient capacity to fulfill the mill's total sulfite requirement. Normally, sulfur is burned in a rotary or spray burner. The gas produced is then cooled by heat exchangers and a water spray and is then absorbed in a variety of different scrubbers containing either limestone or a solution of the base chemical. Where recovery is practiced, fortification is accomplished similarly, although a much smaller amount of sulfur dioxide must be produced to make up for that lost in the process.

10.2.3.2 Emissions And Controls[11] -

Sulfur dioxide (SO_2) is generally considered the major pollutant of concern from sulfite pulp mills. The characteristic "kraft" odor is not emitted because volatile reduced sulfur compounds are not products of the lignin/bisulfite reaction.

A major SO_2 source is the digester and blow pit (dump tank) system. Sulfur dioxide is present in the intermittent digester relief gases, as well as in the gases given off at the end of the cook when the digester contents are discharged into the blow pit. The quantity of sulfur dioxide evolved and emitted to the atmosphere in these gas streams depends on the pH of the cooking liquor, the pressure at which the digester contents are discharged, and the effectiveness of the absorption systems employed for SO_2 recovery. Scrubbers can be installed that reduce SO_2 from this source by as much as 99 percent.

Another source of sulfur dioxide emissions is the recovery system. Since magnesium, sodium, and ammonium base recovery systems all use absorption systems to recover SO_2 generated in recovery furnaces, acid fortification towers, multiple effect evaporators, etc., the magnitude of SO_2 emissions depends on the desired efficiency of these systems. Generally, such absorption systems recover better than 95 percent of the sulfur so it can be reused.

The various pulp washing, screening, and cleaning operations are also potential sources of SO_2. These operations are numerous and may account for a significant fraction of a mill's SO_2 emissions if not controlled.

The only significant particulate source in the pulping and recovery process is the absorption system handling the recovery furnace exhaust. Ammonium base systems generate less particulate than do magnesium or sodium base systems. The combustion productions are mostly nitrogen, water vapor, and sulfur dioxide.

Auxiliary power boilers also produce emissions in the sulfite pulp mill, and emission factors for these boilers are presented in Chapter 1, "External Combustion Sources". Table 10.2-8 contains emission factors for the various sulfite pulping operations.

10.2.4 Neutral Sulfite Semichemical (NSSC) Pulping

10.2.4.1 Process Description[9,12-14] -

In this method, wood chips are cooked in a neutral solution of sodium sulfite and sodium carbonate. Sulfite ions react with the lignin in wood, and the sodium bicarbonate acts as a buffer to maintain a neutral solution. The major difference between all semichemical techniques and those of kraft and acid sulfite processes is that only a portion of the lignin is removed during the cook, after which the pulp is further reduced by mechanical disintegration. This method achieves yields as high as 60 to 80 percent, as opposed to 50 to 55 percent for other chemical processes.

The NSSC process varies from mill to mill. Some mills dispose of their spent liquor, some mills recover the cooking chemicals, and some, when operated in conjunction with kraft mills, mix their spent liquor with the kraft liquor as a source of makeup chemicals. When recovery is practiced, the involved steps parallel those of the sulfite process.

10.2.4.2 Emissions And Controls[9,12-14] -

Particulate emissions are a potential problem only when recovery systems are involved. Mills that do practice recovery but are not operated in conjunction with kraft operations often utilize fluidized bed reactors to burn their spent liquor. Because the flue gas contains sodium sulfate and sodium carbonate dust, efficient particulate collection may be included for chemical recovery.

A potential gaseous pollutant is sulfur dioxide. Absorbing towers, digester/blower tank systems, and recovery furnaces are the main sources of SO_2, with amounts emitted dependent upon the capability of the scrubbing devices installed for control and recovery.

Hydrogen sulfide can also be emitted from NSSC mills which use kraft type recovery furnaces. The main potential source is the absorbing tower, where a significant quantity of hydrogen sulfite is liberated as the cooking liquor is made. Other possible sources, depending on the operating conditions, include the recovery furnace, and in mills where some green liquor is used in the cooking process, the digester/blow tank system. Where green liquor is used, it is also possible that significant quantities of mercaptans will be produced. Hydrogen sulfide emissions can be eliminated if burned to sulfur dioxide before the absorbing system.

Because the NSSC process differs greatly from mill to mill, and because of the scarcity of adequate data, no emission factors are presented for this process.

Table 10.2-8. (Metric And English Units). EMISSION FACTORS FOR SULFITE PULPING

Source	Base	Control	Emission Factor[b]				EMISSION FACTOR RATING
			Particulate		Sulfur Dioxide		
			kg/ADUMg	lb/ADUT	kg/ADUMg	lb/ADUT	
Digester/blow pit or dump tank[c]	All	None	Neg	Neg	5 to 35	10 to 70	C
	MgO	Process change[d]	Neg	Neg	1 to 3	2 to 6	C
	MgO	Scrubber	Neg	Neg	0.5	1	B
	MgO	Process change and scrubber	Neg	Neg	0.1	0.2	B
	MgO	All exhaust vented through recovery system	Neg	Neg	0	0	A
	NH_3	Process change	Neg	Neg	12.5	25	D
	NH_3	Process change and scrubber	Neg	Neg	0.2	0.4	B
	Na	Process change and scrubber	Neg	Neg	1	2	C
	Ca	Unknown	Neg	Neg	33.5	67	C
Recovery system[e]	MgO	Multicyclone and venturi scrubbers	1	2	4.5	9	A
	NH_3	Ammonia absorption and mist eliminator	0.35	0.7	3.5	7	B
	Na	Sodium carbonate scrubber	2	4	1	2	C
Acid plant[f]	NH_3	Scrubber	Neg	Neg	0.2	0.3	C
	Na	Unknown[g]	Neg	Neg	0.1	0.2	D
	Ca	Jensen scrubber	Neg	Neg	4	8	C
Other[h]	All	None	Neg	Neg	6	12	D

[a] Reference 11. All factors represent long term average emissions. ADUMg = Air-dried unbleached megagram. ADUT = Air-dried unbleached ton. Neg = negligible.

[b] Expressed as kg (lb) of pollutant/air dried unbleached Mg (ton) of pulp.

Table 10.2-8 (cont.).

[c] Factors represent emissions after cook is completed and when digester contents are discharged into blow pit or dump tank. Some relief gases are vented from digester during cook cycle, but these are usually transferred to pressure accumulators and SO_2 herein reabsorbed for use in cooking liquor. In some mills, actual emissions will be intermittent and for short periods.

[d] May include such measures as raising cooking liquor pH (thereby lowering free SO_2), relieving digester pressure before contents discharge, and pumping out digester contents instead of blowing out.

[e] Recovery system at most mills is closed and includes recovery furnace, direct contact evaporator, multiple effect evaporator, acid fortification tower, and SO_2 absorption scrubbers. Generally only one emission point for entire system. Factors include high SO_2 emissions during periodic purging of recovery systems.

[f] Necessary in mills with insufficient or nonexistent recovery systems.

[g] Control is practiced, but type of system is unknown.

[h] Includes miscellaneous pulping operations such as knotters, washers, screens, etc.

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10.3 Pulp Bleaching

[Work In Progress]

10.4 Papermaking

[Work In Progress]

10.5 Plywood

[Work In Progress]

10.6 Reconstituted Wood Products

10.6.1 Waferboard And Oriented Strand Board

10.6.2 Particleboard

10.6.3 Medium Density Fiberboard

10.6.1 Waferboard And Oriented Strand Board

[Work In Progress]

10.6.2 Particleboard

[Work In Progress]

10.6.3 Medium Density Fiberboard

[Work In Progess]

10.7 Charcoal

[Work In Progress]

10.8 Wood Preserving

[Work In Progress]

11. MINERAL PRODUCTS INDUSTRY

The production, processing, and use of various minerals are characterized by particulate emissions in the form of dust. Frequently, as in the case of crushing and screening, this dust is identical in composition to the material being handled. Emissions occur also from handling and storing the finished product because this material is often dry and fine. Particulate emissions from some of the processes such as quarrying, yard storage, and dust from transport are difficult to control, but most can be reduced by conventional particulate control equipment such as cyclones, scrubbers, and fabric filters. Because of the wide variety in processing equipment and final products, emission levels will range widely.

11.1 Hot Mix Asphalt Plants

11.1.1 General[1-2,23,42-43]

Hot mix asphalt (HMA) paving materials are a mixture of well-graded, high-quality aggregate (which can include reclaimed asphalt pavement [RAP]) and liquid asphalt cement, which is heated and mixed in measured quantities to produce HMA. Aggregate and RAP (if used) constitute over 92 percent by weight of the total mixture. Aside from the amount and grade of asphalt cement used, mix characteristics are determined by the relative amounts and types of aggregate and RAP used. A certain percentage of fine aggregate (less than 74 micrometers [μm] in physical diameter) is required for the production of good quality HMA.

Hot mix asphalt paving materials can be manufactured by: (1) batch mix plants, (2) continuous mix (mix outside drum) plants, (3) parallel flow drum mix plants, and (4) counterflow drum mix plants. This order of listing generally reflects the chronological order of development and use within the HMA industry.

There are approximately 3,600 active asphalt plants in the United States. Of these, approximately 2,300 are batch plants, 1,000 are parallel flow drum mix plants, and 300 are counterflow drum mix plants. About 85 percent of plants being manufactured today are of the counterflow drum mix design, while batch plants and parallel flow drum mix plants account for 10 percent and 5 percent, respectively. Continuous mix plants represent a very small fraction of the plants in use ($\leq$0.5 percent) and, therefore, are not discussed further.

An HMA plant can be constructed as a permanent plant, a skid-mounted (easily relocated) plant, or a portable plant. All plants can have RAP processing capabilities. Virtually all plants being manufactured today have RAP processing capability.

Batch Mix Plants -

Figure 11.1-1 shows the batch mix HMA production process. Raw aggregate normally is stockpiled near the plant. The bulk aggregate moisture content typically stabilizes between 3 to 5 percent by weight.

Processing begins as the aggregate is hauled from the storage piles and is placed in the appropriate hoppers of the cold feed unit. The material is metered from the hoppers onto a conveyer belt and is transported into a rotary dryer (typically gas- or oil-fired). Dryers are equipped with flights designed to shower the aggregate inside the drum to promote drying efficiency.

As the hot aggregate leaves the dryer, it drops into a bucket elevator and is transferred to a set of vibrating screens where it is classified into as many as 4 different grades (sizes), and is dropped into individual "hot" bins according to size. To control aggregate size distribution in the final batch mix, the operator opens various hot bins over a weigh hopper until the desired mix and weight are obtained. Reclaimed asphalt pavement may be added at this point, also. Concurrent with the aggregate being weighed, liquid asphalt cement is pumped from a heated storage tank to an asphalt bucket, where it is weighed to achieve the desired aggregate-to-asphalt cement ratio in the final mix.

The aggregate from the weigh hopper is dropped into the mixer (pug mill) and dry-mixed for 6 to 10 seconds. The liquid asphalt is then dropped into the pug mill where it is mixed for an

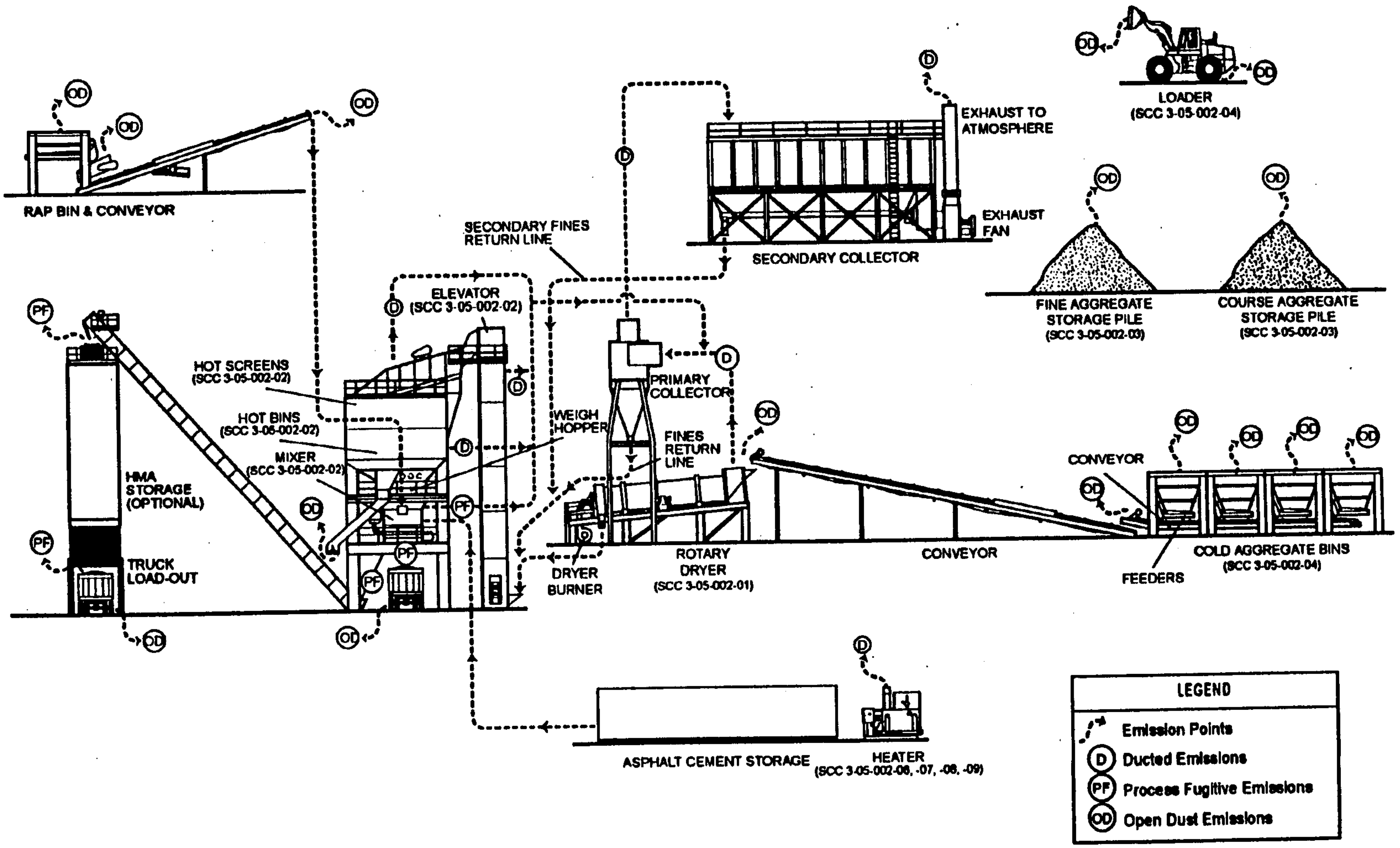

Figure 11.1-1. General process flow diagram for batch mix asphalt plants.[43] (Source Classification Codes in parentheses.)

additional period of time. Total mixing time is usually less than 60 seconds. Then the hot mix is conveyed to a hot storage silo or is dropped directly into a truck and hauled to the job site.

Parallel Flow Drum Mix Plants -

Figure 11.1-2 shows the parallel flow drum mix process. This process is a continuous mixing type process, using proportioning cold feed controls for the process materials. The major difference between this process and the batch process is that the dryer is used not only to dry the material but also to mix the heated and dried aggregates with the liquid asphalt cement. Aggregate, which has been proportioned by size gradations, is introduced to the drum at the burner end. As the drum rotates, the aggregates, as well as the combustion products, move toward the other end of the drum in parallel. Liquid asphalt cement flow is controlled by a variable flow pump electronically linked to the new (virgin) aggregate and RAP weigh scales. The asphalt cement is introduced in the mixing zone midway down the drum in a lower temperature zone, along with any RAP and particulate matter (PM) from collectors.

The mixture is discharged at the end of the drum and is conveyed to either a surge bin or HMA storage silos. The exhaust gases also exit the end of the drum and pass on to the collection system.

Parallel flow drum mixers have an advantage, in that mixing in the discharge end of the drum captures a substantial portion of the aggregate dust, therefore lowering the load on the downstream collection equipment. For this reason, most parallel flow drum mixers are followed only by primary collection equipment (usually a baghouse or venturi scrubber). However, because the mixing of aggregate and liquid asphalt cement occurs in the hot combustion product flow, organic emissions (gaseous and liquid aerosol) may be greater than in other processes.

Counterflow Drum Mix Plants -

Figure 11.1-3 shows a counterflow drum mix plant. In this type of plant, the material flow in the drum is opposite or counterflow to the direction of exhaust gases. In addition, the liquid asphalt cement mixing zone is located behind the burner flame zone so as to remove the materials from direct contact with hot exhaust gases.

Liquid asphalt cement flow is controlled by a variable flow pump which is electronically linked to the virgin aggregate and RAP weigh scales. It is injected into the mixing zone along with any RAP and particulate matter from primary and secondary collectors.

Because the liquid asphalt cement, virgin aggregate, and RAP are mixed in a zone removed from the exhaust gas stream, counterflow drum mix plants will likely have organic emissions (gaseous and liquid aerosol) that are lower than parallel flow drum mix plants. A counterflow drum mix plant can normally process RAP at ratios up to 50 percent with little or no observed effect upon emissions. Today's counterflow drum mix plants are designed for improved thermal efficiencies.

Recycle Processes -

In recent years, the use of RAP has been initiated in the HMA industry. Reclaimed asphalt pavement significantly reduces the amount of virgin rock and asphalt cement needed to produce HMA.

In the reclamation process, old asphalt pavement is removed from the road base. This material is then transported to the plant, and is crushed and screened to the appropriate size for further processing. The paving material is then heated and mixed with new aggregate (if applicable), and the proper amount of new asphalt cement is added to produce a high-quality grade of HMA.

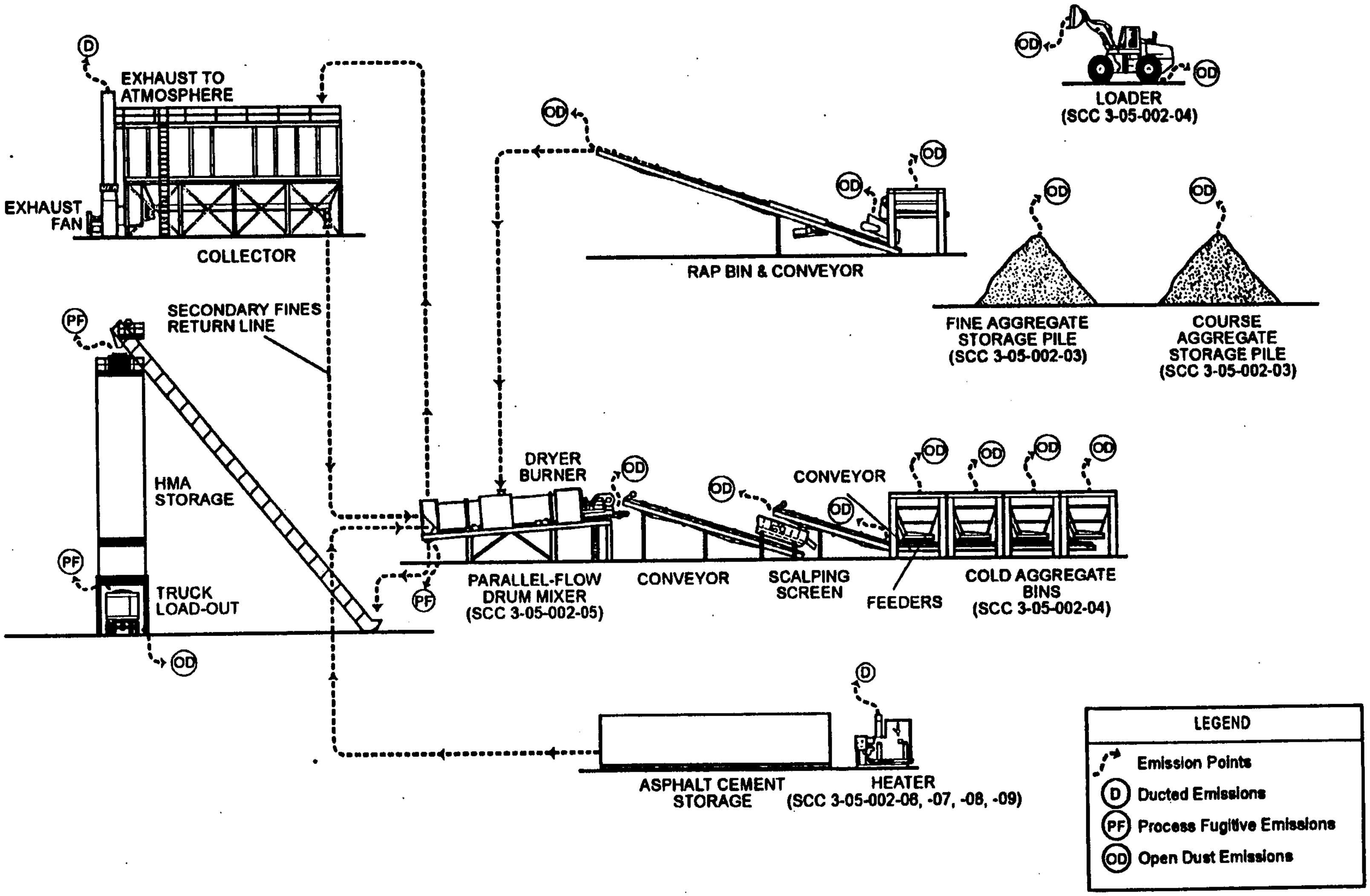

Figure 11.1-2. General process flow diagram for drum mix asphalt plants.[43] (Source Classification Coes in parentheses.)

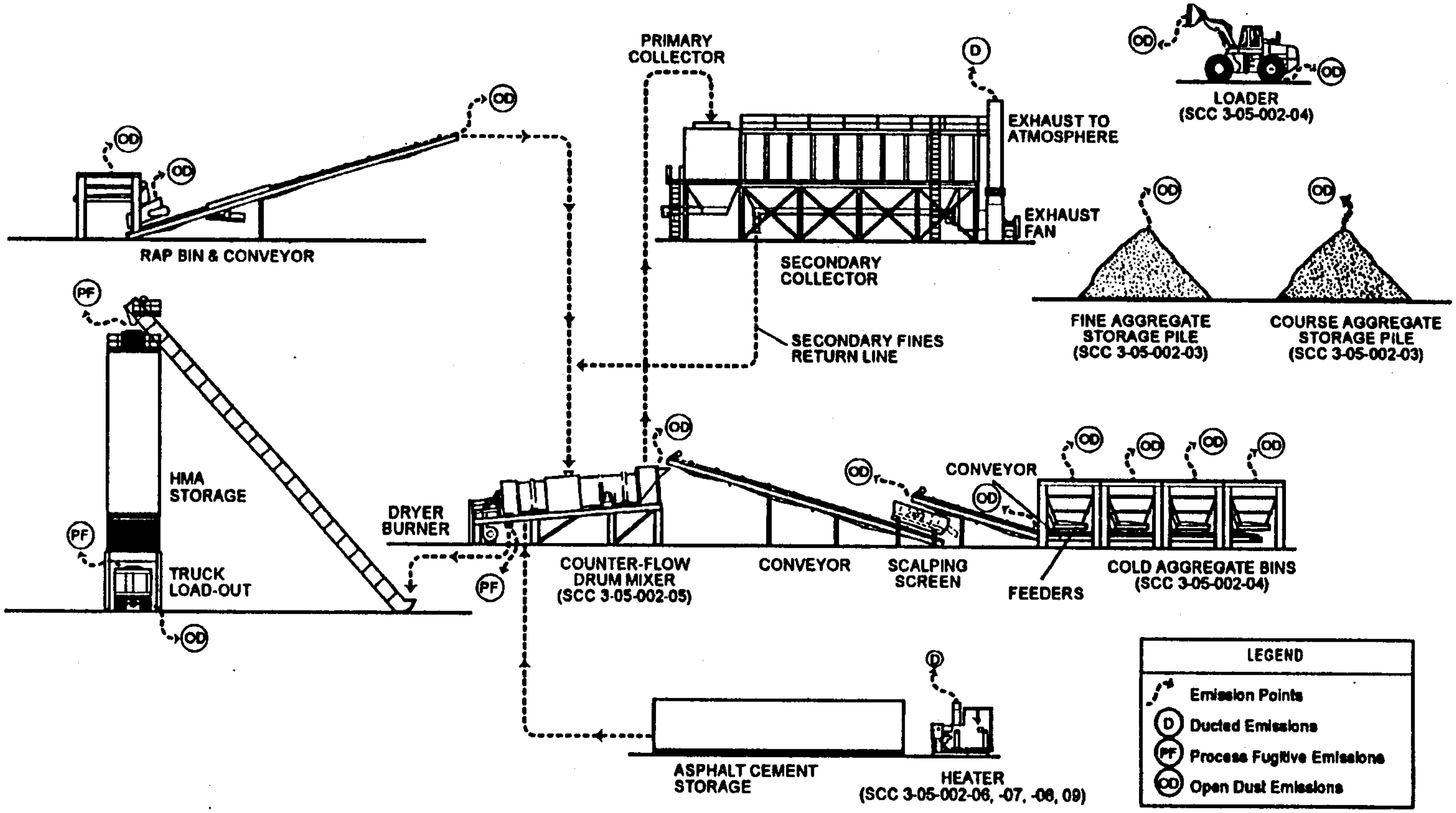

Figure 11.1-3. General process flow diagram for counterflow drum mix asphalt plants.[43] (Source Classification Codes in parentheses.)

11.1.2 Emissions And Controls[23,42-43]

Emission points discussed below refer to Figure 11.1-1 for batch mix asphalt plants, and to Figure 11.1-2 and Figure 11.1-3 for drum mix plants.

Batch Mix Plants -

As with most facilities in the mineral products industry, batch mix HMA plants have 2 major categories of emissions: ducted sources (those vented to the atmosphere through some type of stack, vent, or pipe), and fugitive sources (those not confined to ducts and vents but emitted directly from the source to the ambient air). Ducted emissions are usually collected and transported by an industrial ventilation system having 1 or more fans or air movers, eventually to be emitted to the atmosphere through some type of stack. Fugitive emissions result from process and open sources and consist of a combination of gaseous pollutants and PM.

The most significant source of ducted emissions from batch mix HMA plants is the rotary drum dryer. Emissions from the dryer consist of water as steam evaporated from the aggregate, PM, and small amounts of volatile organic compounds (VOC) of various species (including hazardous air pollutants [HAP]) derived from combustion exhaust gases.

Other potential process sources include the hot-side conveying, classifying, and mixing equipment, which are vented to either the primary dust collector (along with the dryer gas) or to a separate dust collection system. The vents and enclosures that collect emissions from these sources are commonly called "fugitive air" or "scavenger" systems. The scavenger system may or may not have its own separate air mover device, depending on the particular facility. The emissions captured and transported by the scavenger system are mostly aggregate dust, but they may also contain gaseous VOCs and a fine aerosol of condensed liquid particles. This liquid aerosol is created by the condensation of gas into particles during cooling of organic vapors volatilized from the asphalt cement in the mixer (pug mill). The amount of liquid aerosol produced depends to a large extent on the temperature of the asphalt cement and aggregate entering the pug mill. Organic vapor and its associated aerosol are also emitted directly to the atmosphere as process fugitives during truck loadout, from the bed of the truck itself during transport to the job site, and from the asphalt storage tank. In addition to low molecular weight VOCs, these organic emission streams may contain small amounts of polycyclic compounds. Both the low molecular weight VOCs and the polycyclic organic compounds can include HAPs. The ducted emissions from the heated asphalt storage tanks may include VOCs and combustion products from the tank heater.

The choice of applicable control equipment for the dryer exhaust and vent line ranges from dry mechanical collectors to scrubbers and fabric collectors. Attempts to apply electrostatic precipitators have met with little success. Practically all plants use primary dust collection equipment with large diameter cyclones, skimmers, or settling chambers. These chambers are often used as classifiers to return collected material to the hot elevator and to combine it with the drier aggregate. To capture remaining PM, the primary collector effluent is ducted to a secondary collection device. Most plants use either a baghouse or a venturi scrubber for secondary emissions control.

There are also a number of fugitive dust sources associated with batch mix HMA plants, including vehicular traffic generating fugitive dust on paved and unpaved roads, aggregate material handling, and other aggregate processing operations. Fugitive dust may range from 0.1 μm to more than 300 μm in aerodynamic diameter. On average, 5 percent of cold aggregate feed is less than 74 μm (minus 200 mesh). Fugitive dust that may escape collection before primary control generally consists of PM with 50 to 70 percent of the total mass less than 74 μm. Uncontrolled PM emission factors for various types of fugitive sources in HMA plants are addressed in Section 13.2.3, "Heavy Construction Operations".

Parallel Flow Drum Mix Plants -

The most significant ducted source of emissions is the rotary drum dryer. Emissions from the drum consist of water as steam evaporated from the aggregate, PM, and small amounts of VOCs of various species (including HAPs) derived from combustion exhaust gases, liquid asphalt cement, and RAP, if utilized. The VOCs result from incomplete combustion and from the heating and mixing of liquid asphalt cement inside the drum. The processing of RAP materials may increase VOC emissions because of an increase in mixing zone temperature during processing.

Once the VOCs cool after discharge from the process stack, some condense to form a fine liquid aerosol or "blue smoke" plume. A number of process modifications or restrictions have been introduced to reduce blue smoke including installation of flame shields, rearrangement of flights inside the drum, adjustments of the asphalt injection point, and other design changes.

Counterflow Drum Mix Plants -

The most significant ducted source of emissions is the rotary drum dryer in a counterflow drum mix plant. Emissions from the drum consist of water as steam evaporated from the aggregate, PM, and small amounts of VOCs of various species (including HAPs) derived from combustion exhaust gases, liquid asphalt cement, and RAP, if used.

Because liquid asphalt cement, aggregate, and sometimes RAP, are mixed in a zone not in contact with the hot exhaust gas stream, counterflow drum mix plants will likely have lower VOC emissions than parallel flow drum mix plants. The organic compounds that are emitted from counterflow drum mix plants are likely to be products of a slight inefficient combustion and can include HAP.

Parallel and Counterflow Drum Mix Plants -

Process fugitive emissions associated with batch plant hot screens, elevators, and the mixer (pug mill) are not present in the drum mix processes. However, there may be slight fugitive VOC emissions from transport and handling of the hot mix from the drum mixer to the storage silo and also from the load-out operations to the delivery trucks. Since the drum process is continuous, these plants must have surge bins or storage silos. The fugitive dust sources associated with drum mix plants are similar to those of batch mix plants with regard to truck traffic and to aggregate material feed and handling operations.

Tables 11.1-1 and 11.1-2 present emission factors for filterable PM and PM-10, condensable PM, and total PM for batch mix HMA plants. The emission factors are based on both the type of control technology employed and the type of fuel used to fire the dryer. Particle size data for batch mix HMA plants, also based on the control technology used, are shown in Table 11.1-3. Tables 11.1-4 and 11.1-5 present filterable PM and PM-10, condensable PM, and total PM emission factors for drum mix HMA plants. The emission factors are based on both the type of control technology employed and the type of fuel used to fire the dryer. Particle size data for drum mix HMA plants, also based on the control technology used, are shown in Table 11.1-6. Tables 11.1-7 and 11.1-8 present emission factors for carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and total organic compounds (TOC) from batch and drum mix plants. Table 11.1-9 presents organic pollutant emission factors for batch plants. Tables 11.1-10 and 11.1-11 present organic pollutant emission factors for drum mix plants. Tables 11.1-12 and 11.1-13 present metal emission factors for batch and drum mix plants, respectively.

Table 11.1-1 (Metric Units). EMISSION FACTORS FOR BATCH MIX HOT MIX ASPHALT PLANTS[a]

Process	Filterable PM				Condensable PM						Total PM			
	PM	EMISSION FACTOR RATING	PM-10[b]	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING	Total	EMISSION FACTOR RATING	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Natural gas-fired dryer (SCC 3-05-002-01)														
Uncontrolled	16[c]	E	2.2	E	0.0017[d]	D	0.00039[d]	D	0.0021	D	16	E	2.2	E
Low-energy scrubber[e]	0.039	D	ND		0.0017	D	ND		ND		ND		ND	
Venturi scrubber[e]	0.026	E	ND		ND		ND		ND		ND		ND	
Fabric filter	0.020[f]	D	0.0080	D	0.0014[g]	D	0.00039[h]	D	0.0018[h]	D	0.022[j]	D	0.0098	D
Oil-fired dryer (SCC 3-05-002-01)														
Uncontrolled	16[c]	E	2.2	E	0.0083[d]	D	ND		0.022[d]	D	16	E	2.2	E
Venturi scrubber[e]	0.026	E	ND		0.0083	E	ND		ND		ND		ND	
Fabric filter	0.020[e]	D	0.0080	D	ND		ND		0.022[k]	D	0.042[m]	D	0.030	D

[a] Factors are kg/Mg of product. Filterable PM emission factors were developed from tests on dryers fired with several different fuels. SCC = Source Classification Code. ND = no data.

[b] Particle size data from Reference 23 were used in conjunction with the filterable PM emission factors shown.

[c] Reference 5.

[d] Although no data are available for uncontrolled condensable PM, values are assumed to be equal to the maximum controlled value measured.

[e] Reference 15.

[f] References 15,24,40-41.

[g] Reference 24.

[h] References 24,39.

[j] References 15,24,39-41.

[k] Reference 39.

[m] Reference 40.

Table 11.1-2 (English Units). EMISSION FACTORS FOR BATCH MIX HOT MIX ASPHALT PLANTS[a]

	Filterable PM				Condensable PM						Total PM			
Process	PM	EMISSION FACTOR RATING	PM-10[b]	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING	Total	EMISSION FACTOR RATING	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Natural gas-fired dryer (SCC 3-05-002-01)														
Uncontrolled	32[c]	E	4.5	E	0.0033[d]	D	0.00078[d]	D	0.0041	D	32	E	4.5	E
Low-energy scrubber[e]	0.077	D	ND		0.0033	D	ND		ND		ND		ND	
Venturi scrubber[e]	0.052	E	ND		ND		ND		ND		ND		ND	
Fabric filter	0.040[f]	D	0.016	D	0.0027[g]	D	0.00078[g]	D	0.0035[h]	D	0.044[j]	D	0.020	D
Oil-fired dryer (SCC 3-05-002-01)														
Uncontrolled	32[c]	E	4.5	E	0.017[d]	E	ND		0.045[d]	D	32	E	4.5	E
Venturi scrubber[e]	0.052	E	ND		0.017	E	ND		ND		ND		ND	
Fabric filter	0.040[e]	D	0.016	D	ND		ND		0.045[k]	D	0.085[m]	D	0.061	D

[a] Factors are lb/ton of product. Filterable PM emission factors were developed from tests on dryers fired with several different fuels. SCC = Source Classification Code. ND = no data.

[b] Particle size data from Reference 23 were used in conjunction with the filterable PM emission factors shown.

[c] Reference 5.

[d] Although no data are available for uncontrolled condensable PM, values are assumed to be equal to the maximum controlled value measured.

[e] Reference 15.

[f] References 15,24,40-41.

[g] Reference 24.

[h] References 24,39.

[j] References 15,24,39-41.

[k] Reference 39.

[m] Reference 40.

Table 11.1-3. SUMMARY OF PARTICLE SIZE DISTRIBUTION FOR BATCH MIX HOT MIX ASPHALT PLANTS[a]

Particle Size, μm[b]	Cumulative Mass Less Than Or Equal To Stated Size (%)[c]				
	Uncontrolled	Cyclone Collectors	Multiple Centrifugal Scrubbers	Gravity Spray Towers	Fabric Filters
2.5	0.83	5.0	67	21	33
5.0	3.5	11	74	27	36
10.0	14	21	80	37	40
15.0	23	29	83	39	47
20.0	30	36	84	41	54

[a] Reference 23, Table 3-36. Rounded to two significant figures.

[b] Aerodynamic diameter.

[c] Applies only to the mass of filterable PM.

Table 11.1-4 (Metric Units). EMISSION FACTORS FOR DRUM MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Filterable PM		Condensable PM			Total PM[b]	
	PM	PM-10[c]	Inorganic	Organic	Total	PM	PM-10
Natural gas-fired dryer (SCC 3-05-002-05)							
Uncontrolled	9.4[d]	2.2	0.014[e]	0.027[f]	0.041	9.4	2.2
Venturi scrubber	0.017[g]	ND	ND	0.010[f]	ND	ND	ND
Fabric filter	0.0070[h]	0.0022	ND	ND	0.0019[j]	0.0089	0.0041
Oil-fired dryer (SCC 3-05-002-05)							
Uncontrolled	9.4[d]	2.2	0.012[e]	0.0013[e]	0.013[e]	9.4	2.2
Venturi scrubber	0.017[g]	ND	ND	ND	ND	ND	ND
Fabric filter	0.0070[h]	0.0022	0.012[k]	0.0013[k]	0.013[k]	0.020	0.015

[a] Factors are kg/Mg of product. Tests included dryers that were processing reclaimed asphalt pavement (RAP). Because of the limited data available, the effect of RAP processing on emissions could not be determined. Filterable PM emission factors were developed from tests on dryers firing several different fuels. SCC = Source Classification Code. ND = no data.

[b] Total PM emission factors are the sum of filterable PM and total condensable PM emission factors. Total PM-10 emission factors are the sum of filterable PM-10 and total condensable PM emission factors.

[c] Particle size data from Reference 23 were used in conjunction with the filterable PM emission factors shown.

[d] References 31,36-38.

[e] Although no emission test data are available for uncontrolled condensible PM, values are assumed to be equal to the maximum controlled value measured.

[f] References 36-37.

[g] References 29,32,36-37,40.

[h] References 25-28,31,33,40. EMISSION FACTOR RATING: C.

[j] Reference 39.

[k] References 25,39.

Table 11.1-5 (English Units). EMISSION FACTORS FOR DRUM MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D (except as noted)

	Filterable PM		Condensable PM			Total PM[b]	
Process	PM	PM-10[c]	Inorganic	Organic	Total	PM	PM-10
Natural gas-fired dryer (SCC 3-05-002-05)							
Uncontrolled	19[d]	4.3	0.027[e]	0.054[f]	0.081	19	4.4
Venturi scrubber	0.033[g]	ND	ND	0.020[f]	ND	ND	ND
Fabric filter	0.014[h]	0.0045	ND	ND	0.0037[j]	0.018	0.0082
Dryer (oil-fired) (SCC 3-05-002-05)							
Uncontrolled	19[d]	4.3	0.023[e]	0.0026[e]	0.026[e]	19	4.3
Venturi scrubber	0.033[g]	ND	ND	ND	ND	ND	ND
Fabric filter	0.014[h]	0.0045	0.023[k]	0.0026[k]	0.026[k]	0.040	0.031

[a] Factors are lb/ton of product. Tests included dryers that were processing reclaimed asphalt pavement (RAP). Because of the limited data available, the effect of RAP processing on emissions could not be determined. Filterable PM emission factors were developed from tests on dryers firing several different fuels. SCC = Source Classification Code. ND = no data.

[b] Total PM emission factors are the sum of filterable PM and total condensable PM emission factors. Total PM-10 emission factors are the sum of filterable PM-10 and total condensable PM emission factors.

[c] Particle size data from Reference 23 were used in conjunction with the filterable PM emission factors shown.

[d] References 31,36-38.

[e] Although no emission test data are available for uncontrolled condensable PM, values are assumed to be equal to the maximum controlled value measured.

[f] References 36-37.

[g] References 29,32,36-37,40.

[h] References 25-28,31,33,40. EMISSION FACTOR RATING: C.

[j] Reference 39.

[k] References 25,39.

Table 11.1-6. SUMMARY OF PARTICLE SIZE DISTRIBUTION FOR DRUM MIX HOT MIX ASPHALT PLANTS[a]

	Cumulative Mass Less Than Or Equal To Stated Size (%)[c]	
Particle Size, μm[b]	Uncontrolled	Fabric Filters[d]
2.5	5.5	11
10.0	23	32
15.0	27	35

[a] Reference 23, Table 3-35. Rounded to two significant figures.

[b] Aerodynamic diameter.

[c] Applies only to the mass of filterable PM.

[d] Includes data from two out of eight tests where about 30% reclaimed asphalt pavement was processed using a split feed process.

Table 11.1-7 (Metric And English Units). EMISSION FACTORS FOR BATCH MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D

	CO		CO_2		NO_x		SO_2		TOC[b]	
Process	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Natural gas-fired dryer (SCC 3-05-002-01)	0.17[c]	0.34[c]	17[d]	35[d]	0.013[e]	0.025[c]	0.0025[e]	0.0050[e]	0.0084[f]	0.017[f]
Oil-fired dryer (SCC 3-05-002-01)	0.035[e]	0.069[e]	19[g]	39[g]	0.084[e]	0.17[e]	0.12[e]	0.24[e]	0.023[f]	0.046[f]

[a] Factors are kg/Mg and lb/ton of product. Factors are for uncontrolled emissions, unless noted. SCC = Source Classification Code.

[b] Factors represent TOC as methane, based on EPA Method 25A test data.

[c] References 24,34,39.

[d] References 15,24,39.

[e] Reference 39. Dryer tested was fired with #6 fuel oil. Dryers fired with other fuel oils will have different SO_2 emission factors.

[f] References 24,39.

[g] References 15,39.

Table 11.1-8 (Metric And English Units). EMISSION FACTORS FOR DRUM MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D

	CO		CO_2		NO_x		SO_2		TOC[b]	
Process	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Natural gas-fired dryer (SCC 3-05-002-01)	0.028[c]	0.056[c]	14[d]	27[d]	0.015[c]	0.030[c]	0.0017[c]	0.0033[c]	0.025[c]	0.051[c]
Oil-fired dryer (SCC 3-05-002-01)	0.018[e]	0.036[e]	19[f]	37[f]	0.038[g]	0.075[g]	0.028[g]	0.056[g]	0.035[g]	0.069[g]

[a] Factors are kg/Mg and lb/ton of product. Factors represent uncontrolled emissions, unless noted. Tests included dryers that were processing reclaimed asphalt pavement (RAP). Because of limited data, the effect of RAP processing on emissions could not be determined.
SCC = Source Classification Code.

[b] Factors represent TOC as methane, based on EPA Method 25A test data.

[c] Reference 39. Includes data from both parallel flow and counterflow drum mix dryers. Organic compound emissions from counterflow systems are expected to be smaller than from parallel flow systems. However, the available data are insufficient to accurately quantify the difference in these emissions.

[d] References 30,39.

[e] Reference 25.

[f] References 25-27,29,32-33,39.

[g] References 25,39. Includes data from both parallel flow and counterflow drum mix dryers. Organic compound emissions from counterflow systems are expected to be smaller than from parallel flow systems. However, the available data are insufficient to accurately quantify the difference in these emissions. One of the dryers tested was fired with #2 fuel oil (0.003 kg/Mg [0.006 lb/ton]) and the other dryer was fired with waste oil (0.05 kg/Mg [0.1 lb/ton]). Dryers fired with other fuel oils will have different SO_2 emission factors.

Table 11.1-9 (Metric And English Units). EMISSION FACTORS FOR ORGANIC POLLUTANT EMISSIONS FROM BATCH MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Pollutant		Emission Factor		Ref. Nos.
	CASRN	Name	kg/Mg	lb/ton	
Natural gas-fired dryer (SCC 3-05-002-01)	91-57-6	2-Methylnaphthalene[b]	3.8×10^{-5}	7.7×10^{-5}	24,39
	83-32-9	Acenaphthene[b]	6.2×10^{-7}	1.2×10^{-6}	34,39
	208-96-8	Acenaphthylene[b]	4.3×10^{-7}	8.6×10^{-7}	34,39
	75-07-0	Acetaldehyde	0.00032	0.00064	24
	67-64-1	Acetone	0.0032	0.0064	24
	120-12-7	Anthracene[b]	1.5×10^{-7}	3.1×10^{-7}	34,39
	100-52-7	Benzaldehyde	6.4×10^{-5}	0.00013	24
	71-43-2	Benzene	0.00017	0.00035	24,39
	56-55-3	Benzo(a)anthracene[b]	2.3×10^{-9}	4.5×10^{-9}	39
	205-99-2	Benzo(b)fluoranthene[b]	2.3×10^{-9}	4.5×10^{-9}	39
	207-08-9	Benzo(k)fluoranthene[b,c]	1.2×10^{-8}	2.4×10^{-8}	34
	78-84-2	Butyraldehyde/ Isobutyraldehyde	1.5×10^{-5}	3.0×10^{-5}	24
	218-01-9	Chrysene[b]	3.1×10^{-9}	6.1×10^{-9}	39
	4170-30-3	Crotonaldehyde	1.5×10^{-5}	2.9×10^{-5}	24
	100-41-4	Ethyl benzene	0.0016	0.0033	24,39
	206-44-0	Fluoranthene[b]	1.6×10^{-7}	3.1×10^{-7}	34,39
	86-73-7	Fluorene[b]	9.8×10^{-7}	2.0×10^{-6}	34,39
	50-00-0	Formaldehyde	0.00043	0.00086	24,39
	66-25-1	Hexanal	1.2×10^{-5}	2.4×10^{-5}	24
	74-82-8	Methane	0.0060	0.012	39
	91-20-3	Naphthalene[b]	2.1×10^{-5}	4.2×10^{-5}	34,39
	85-01-8	Phenanthrene[b]	1.6×10^{-6}	3.3×10^{-6}	34,39
	129-00-0	Pyrene[b]	3.1×10^{-8}	6.2×10^{-8}	34,39
	106-51-4	Quinone	0.00014	0.00027	24
	108-88-3	Toluene	0.00088	0.0018	24,39
	1330-20-7	Xylene	0.0021	0.0043	24,39
Oil-fired dryer (SCC 3-05-002-01)	91-57-6	2-Methylnaphthalene[b]	3.0×10^{-5}	6.0×10^{-5}	39
	206-44-0	Fluoranthene[b]	1.2×10^{-5}	2.4×10^{-5}	39
	50-00-0	Formaldehyde[c]	0.0016	0.0032	39,40
		Methane	0.0022	0.0043	39
	91-20-3	Naphthalene[b]	2.2×10^{-5}	4.5×10^{-5}	39
	85-01-8	Phenanthrene[b,c]	1.8×10^{-5}	3.7×10^{-5}	39
	129-00-0	Pyrene[b]	2.7×10^{-5}	5.5×10^{-5}	39

[a] Factors are kg/Mg and lb/ton of hot mix asphalt produced. Factors represent uncontrolled emissions, unless noted. CASRN = Chemical Abstracts Service Registry Number. SCC = Source Classification Code.

[b] Controlled by a fabric filter. Compound is classified as polycyclic organic matter (POM), as defined in the 1990 Clean Air Act Amendments (CAAA).

[c] EMISSION FACTOR RATING: E.

Table 11.1-10 (Metric And English Units). EMISSION FACTORS FOR ORGANIC POLLUTANT EMISSIONS FROM DRUM MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Pollutant		Emission Factor		Ref. Nos.
	CASRN	Name	kg/Mg	lb/ton	
Natural gas- or propane-fired dryer[b] (SCC 3-05-002-05)	91-58-7	2-Chloronaphthalene[c]	8.9×10^{-7}	1.8×10^{-6}	39
	91-57-6	2-Methylnaphthalene[c]	3.7×10^{-5}	7.4×10^{-5}	39
	83-32-9	Acenaphthene[c]	6.4×10^{-7}	1.3×10^{-6}	35,39
	208-96-8	Acenaphthylene[c]	4.2×10^{-6}	8.4×10^{-6}	35,39
	120-12-7	Anthracene[c]	1.0×10^{-7}	2.1×10^{-7}	35,39
	71-43-2	Benzene	0.00060	0.0012	39
	56-55-3	Benzo(a)anthracene[c]	1.0×10^{-7}	2.0×10^{-7}	39
	50-32-8	Benzo(a)pyrene[c]	4.6×10^{-9}	9.2×10^{-9}	39
	205-99-2	Benzo(b)fluoranthene[c]	5.1×10^{-8}	1.0×10^{-7}	35,39
	192-97-2	Benzo(e)pyrene[c]	5.2×10^{-8}	1.0×10^{-7}	39
	191-24-2	Benzo(g,h,i)perylene[c]	1.9×10^{-8}	3.9×10^{-8}	39
	207-08-9	Benzo(k)fluoranthene[c]	2.6×10^{-8}	5.3×10^{-8}	39
	218-01-9	Chrysene[c]	1.8×10^{-7}	3.5×10^{-7}	39
	53-70-3	Dibenz(a,h)anthracene[c,e]	1.3×10^{-9}	2.7×10^{-9}	39
	100-41-4	Ethylbenzene[e]	0.00015	0.00029	39
	206-44-0	Fluoranthene[c]	3.0×10^{-7}	5.9×10^{-7}	35,39
	86-73-7	Fluorene[c]	2.7×10^{-6}	5.3×10^{-6}	35,39
	50-00-0	Formaldehyde	0.0018	0.0036	35,39
	50-00-0	Formaldehyde[d,e]	0.00079	0.0016	40
	193-39-5	Indeno(1,2,3-cd)pyrene[c]	3.6×10^{-9}	7.3×10^{-9}	39
	74-82-8	Methane	0.010	0.021	39
	71-55-6	Methyl chloroform[e]	2.4×10^{-5}	4.8×10^{-5}	35
	91-20-3	Naphthalene[c]	2.4×10^{-5}	4.8×10^{-5}	35,39
	198-55-0	Perylene[c,e]	6.2×10^{-9}	1.2×10^{-8}	39
	85-01-8	Phenanthrene[c]	4.2×10^{-6}	8.4×10^{-6}	35,39
	129-00-0	Pyrene[c]	2.3×10^{-7}	4.6×10^{-7}	35,39
	108-88-3	Toluene	0.00010	0.00020	35,39
	1330-20-7	Xylene	0.00020	0.00040	39
Oil-fired dryer[c] (SCC 3-05-002-05)	91-57-6	2-Methylnaphthalene[c]	8.5×10^{-5}	0.00017	39
	208-96-8	Acenaphthylene[c]	1.1×10^{-5}	2.2×10^{-5}	39
	75-07-0	Acetaldehyde	0.00065	0.0013	25
	67-64-1	Acetone	0.00042	0.00083	25

Table 11.1-10 (cont.).

Process	Pollutant		Emission Factor		Ref. Nos.
	CASRN	Name	kg/Mg	lb/ton	
	107-02-8	Acrolein	1.3×10^{-5}	2.6×10^{-5}	25
	120-12-7	Anthracene[c]	1.8×10^{-6}	3.6×10^{-6}	39
	100-52-7	Benzaldehyde	5.5×10^{-5}	0.00011	25
	71-43-2	Benzene	0.00020	0.00041	25
	78-84-2	Butyraldehyde/Isobutyraldehyde	8.0×10^{-5}	0.00016	25
	4170-30-3	Crotonaldehyde	4.3×10^{-5}	8.6×10^{-5}	25
	100-41-4	Ethylbenzene	0.00019	0.00038	25
	86-73-7	Fluorene[c]	8.5×10^{-6}	1.7×10^{-5}	39
	50-00-0	Formaldehyde	0.0012	0.0024	25,39
	50-00-0	Formaldehyde[d,e]	0.00026	0.00052	40
	66-25-1	Hexanal	5.5×10^{-5}	0.00011	25
	590-86-3	Isovaleraldehyde	1.6×10^{-5}	3.2×10^{-5}	25
	74-82-8	Methane	0.0096	0.020	25,39
	78-93-3	Methyl ethyl ketone	1.0×10^{-5}	2.0×10^{-5}	25
	91-20-3	Naphthalene[c]	0.00016	0.00031	25,39
	85-01-8	Phenanthrene[c]	2.8×10^{-5}	5.5×10^{-5}	39
	123-38-6	Propionaldehyde	6.5×10^{-5}	0.00013	25
	129-00-0	Pyrene[c,e]	1.5×10^{-6}	3.0×10^{-6}	39
	106-51-4	Quinone	8.0×10^{-5}	0.00016	25
	108-88-3	Toluene	0.00037	0.00075	25
	110-62-3	Valeraldehyde	3.4×10^{-5}	6.7×10^{-5}	25
	1330-20-7	Xylene	8.2×10^{-5}	0.00016	25

[a] Factors are kg/Mg and lb/ton of hot mix asphalt produced. Table includes data from both parallel flow and counterflow drum mix dryers. Organic compound emissions from counterflow systems are expected to be less than from parallel flow systems, but the available data are insufficient to quantify accurately the difference in these emissions. CASRN = Chemical Abstracts Service Registry Number. SCC = Source Classification Code.

[b] Tests included dryers that were processing reclaimed asphalt pavement (RAP). Because of limited data, the effect of RAP processing on emissions could not be determined.

[c] Controlled by a fabric filter. Compound is classified as polycyclic organic matter (POM), as defined in the 1990 Clean Air Act Amendments (CAAA).

[d] Controlled by a wet scrubber.

[e] EMISSION FACTOR RATING: E

Table 11.1-11 (Metric And English Units). EMISSION FACTORS FOR ORGANIC POLLUTANT EMISSIONS FROM HOT MIX ASPHALT HOT OIL HEATERS[a]

EMISSION FACTOR RATING: E

Process	Pollutant		Emission Factor	
	CASRN	Name	kg/L	lb/gal
Hot oil heater fired with No.2 fuel oil (SCC 3-05-002-08)	83-32-9	Acenaphthene[b]	6.4x10^{-8}	5.3x10^{-7}
	208-96-8	Acenaphthylene[b]	2.4x10^{-8}	2.0x10^{-7}
	120-12-7	Anthracene[b]	2.2x10^{-8}	1.8x10^{-7}
	205-99-2	Benzo(b)fluoranthene[b]	1.2x10^{-8}	1.0x10^{-7}
	206-44-0	Fluoranthene[b]	5.3x10^{-9}	4.4x10^{-8}
	86-73-7	Fluorene[b]	3.8x10^{-9}	3.2x10^{-8}
	50-00-0	Formaldehyde	0.0032	0.027
	91-20-3	Naphthalene[b]	2.0x10^{-6}	1.7x10^{-5}
	85-01-8	Phenanthrene[b]	5.9x10^{-7}	4.9x10^{-6}
	129-00-0	Pyrene[b]	3.8x10^{-9}	3.2x10^{-8}
	19408-74-3	1,2,3,7,8,9-HxCDD	9.1x10^{-14}	7.6x10^{-13}
	39227-28-6	1,2,3,4,7,8-HxCDD	8.3x10^{-14}	6.9x10^{-13}
		HxCDD	7.4x10^{-13}	6.2x10^{-12}
	35822-46-9	1,2,3,4,6,7,8-HpCDD	1.8x10^{-12}	1.5x10^{-11}
		HpCDD	2.4x10^{-12}	2.0x10^{-11}
	3268-87-9	OCDD	1.9x10^{-11}	1.6x10^{-10}
		TCDF[b]	4.0x10^{-13}	3.3x10^{-12}
		PeCDF[b]	5.8x10^{-14}	4.8x10^{-13}
		HxCDF[b]	2.4x10^{-13}	2.0x10^{-12}
		HpCDF[b]	1.2x10^{-12}	9.7x10^{-12}
	67562-39-4	1,2,3,4,6,7,8-HpCDF	4.2x10^{-13}	3.5x10^{-12}
	39001-02-0	OCDF	1.4x10^{-12}	1.2x10^{-11}

[a] Reference 34. Factors are kg/L and lb/gal of fuel consumed. Table includes data from both parallel flow and counterflow drum mix dryers. Organic compound emissions from counterflow systems are expected to be less than from parallel flow systems, but available data are insufficient to quantify accurately the difference in these emissions. CASRN = Chemical Abstracts Service Registry Number. SCC = Source Classification Code.

[b] Compound is classified as polycyclic organic matter (POM), as defined in the 1990 Clean Air Act Amendments (CAAA).

Table 11.1-12 (Metric And English Units). EMISSION FACTORS FOR METAL EMISSIONS FROM BATCH MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Pollutant	Emission Factor		Ref. Nos.
		kg/Mg	lb/ton	
Dryer (SCC 3-05-002-01)	Arsenic[b]	$3.3x10^{-7}$	$6.6x10^{-7}$	34,40
	Barium	$7.3x10^{-7}$	$1.5x10^{-6}$	24
	Beryllium[b]	$1.1x10^{-7}$	$2.2x10^{-7}$	34
	Cadmium	$4.2x10^{-7}$	$8.4x10^{-7}$	24,34
	Chromium	$4.5x10^{-7}$	$8.9x10^{-7}$	24
	Copper	$1.8x10^{-6}$	$3.7x10^{-6}$	24,34
	Hexavalent chromium[b]	$4.9x10^{-9}$	$9.7x10^{-9}$	34
	Lead	$3.7x10^{-7}$	$7.4x10^{-7}$	24,34
	Manganese	$5.0x10^{-6}$	$9.9x10^{-6}$	24,34
	Mercury	$2.3x10^{-7}$	$4.5x10^{-7}$	34
	Nickel	$2.1x10^{-6}$	$4.2x10^{-6}$	24,34
	Selenium[b]	$4.6x10^{-8}$	$9.2x10^{-8}$	34
	Zinc	$3.4x10^{-6}$	$6.8x10^{-6}$	24,34

[a] Factors are kg/Mg and lb/ton of hot mix asphalt produced. Emissions controlled by a fabric filter. SCC = Source Classification Code.

[b] EMISSION FACTOR RATING: E.

Table 11.1-13 (Metric And English Units). EMISSION FACTORS FOR METAL EMISSIONS FROM DRUM MIX HOT MIX ASPHALT PLANTS[a]

EMISSION FACTOR RATING: D

Process	Pollutant	Emission Factor		Ref. Nos.
		kg/Mg	lb/ton	
Dryer[b] (SCC 3-05-002-05)	Arsenic	$5.5x10^{-7}$	$1.1x10^{-6}$	25,35
	Barium	$2.4x10^{-6}$	$4.8x10^{-6}$	25
	Cadmium	$2.2x10^{-7}$	$4.4x10^{-7}$	25,35
	Chromium	$6.0x10^{-6}$	$1.2x10^{-5}$	25
	Copper	$3.1x10^{-6}$	$6.1x10^{-6}$	25
	Lead	$1.7x10^{-6}$	$3.3x10^{-6}$	25,35
	Manganese	$5.5x10^{-6}$	$1.1x10^{-5}$	25
	Mercury	$3.7x10^{-9}$	$7.3x10^{-9}$	35
	Nickel	$7.5x10^{-6}$	$1.5x10^{-5}$	25
	Phosphorus	$2.8x10^{-5}$	$5.5x10^{-5}$	25
	Silver	$7.0x10^{-7}$	$1.4x10^{-6}$	25
	Zinc	$2.1x10^{-5}$	$4.2x10^{-5}$	25,35

[a] Factors are kg/Mg and lb/ton of hot mix asphalt produced. Emissions controlled by a fabric filter. SCC = Source Classification Code.

[b] Feed material includes RAP.

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11.2 Asphalt Roofing

11.2.1 General[1-2]

The asphalt roofing industry manufactures asphalt-saturated felt rolls, fiberglass and organic (felt-based) shingles, and surfaced and smooth roll roofing. Most of these products are used in roof construction, but small quantities are used in walls and other building applications.

11.2.2 Process Description[1-4]

The production of asphalt roofing products consists of six major operations: (1) felt saturation, (2) coating, (3) mineral surfacing (top and bottom), (4) cooling and drying, (5) product finishing (seal-down strip application, cutting and trimming, and laminating of laminated shingles), and (6) packaging. There are six major production support operations: (1) asphalt storage, (2) asphalt blowing, (3) back surfacing and granule storage, (4) filler storage, (5) filler heating, and (6) filler and coating asphalt mixing. There are two primary roofing substrates: organic (paper felt) and fiberglass. Production of roofing products from the two substrates differ mainly in the elimination of the saturation process when using fiberglass.

Preparation of the asphalt is an integral part of the production of asphalt roofing. This preparation, called "blowing," involves the oxidation of asphalt flux by bubbling air through liquid asphalt flux at 260°C (500°F) for 1 to 10 hours. The amount of time depends on the desired characteristics of the roofing asphalt, such as softening point and penetration rate. Blowing results in an exothermic reaction that requires cooling. Water sprays are applied either internally or externally to the shell of the blowing vessel. A typical plant blows four to six batches per 24-hour day. Blowing may be done in either vertical vessels or in horizontal chambers (both are frequently referred to as "blowing stills"). Inorganic salts such as ferric chloride ($FeCl_3$) may be used as catalysts to achieve desired properties and to increase the rate of reaction in the blowing still, decreasing the time required for each blow. Blowing operations may be located at oil refineries, asphalt processing plants, or asphalt roofing plants. Figure 11.2-1 illustrates an asphalt blowing operation.

The most basic asphalt roofing product is asphalt-saturated felt. Figure 11.2-2 shows a typical line for the manufacture of asphalt-saturated felt. It consists of a dry felt feed roll, a dry looper section, a saturator spray section (seldom used today), a saturator dipping section, heated drying-in drums, a wet looper, cooling drums, a finish floating looper, and a roll winder.

Organic felt may weigh from approximately 20 to 55 pounds (lb) per 480 square feet (ft^2) (a common unit in the paper industry), depending upon the intended product. The felt is unrolled from the unwind stand onto the dry looper, which maintains a constant tension on the material. From the dry looper, the felt may pass into the spray section of the saturator (not used in all plants), where asphalt at 205 to 250°C (400 to 480°F) is sprayed onto one side of the felt through several nozzles. In the saturator dip section, the saturated felt is drawn over a series of rollers, with the bottom rollers submerged in hot asphalt at 205 to 250°C (400 to 480°F). During the next step, heated drying-in drums and the wet looper provide the heat and time, respectively, for the asphalt to penetrate the felt. The saturated felt then passes through water-cooled rolls onto the finish floating looper, and then is rolled and cut to product size on the roll winder. Three common weights of asphalt felt are approximately 12, 15, and 30 lb per 108 ft^2 (108 ft^2 of felt covers exactly 100 ft^2 of roof).

EMISSION SOURCE	SCC
ASPHALT BLOWING: SATURANT	3-05-001-01
ASPHALT BLOWING: COATING	3-05-001-02
ASPHALT BLOWING: (GENERAL)	3-05-001-10
FIXED ROOF ASPHALT STORAGE TANKS	3-05-001-30, -31
FLOATING ROOF ASPHALT STORAGE TANKS	3-05-001-32, -33

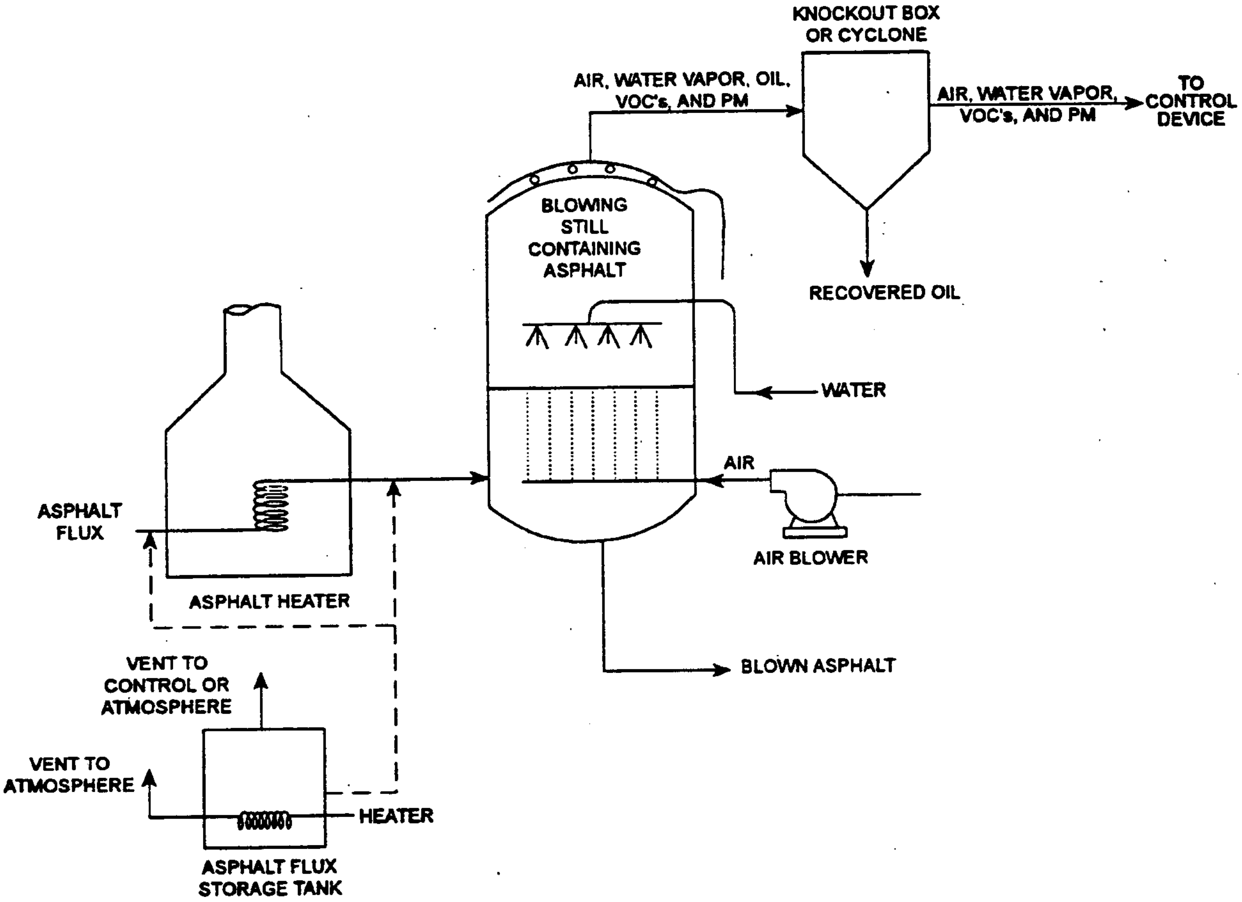

Figure 11.2-1. Asphalt blowing process flow diagram.[1,4]
(SCC = Source Classification Code)

EMISSION SOURCE	SCC
DIPPING ONLY	3-05-001-11
SPRAYING ONLY	3-05-001-12
DIPPING/SPRAYING	3-05-001-13
DIP SATURATOR, DRYING-IN DRUM, WET LOOPER, AND COATER	3-05-001-16
DIP SATURATOR, DRYING-IN DRUM, AND COATER	3-05-001-17
DIP SATURATOR, DRYING-IN DRUM, AND WET LOOPER	3-05-001-18
SPRAY/DIP SATURATOR, DRYING-IN DRUM, WET LOOPER, COATER, AND STORAGE TANKS	3-05-001-19
FIXED ROOF ASPHALT STORAGE TANKS	3-05-001-30, -31
FLOATING ROOF ASPHALT STORAGE TANKS	3-05-001-32, -33

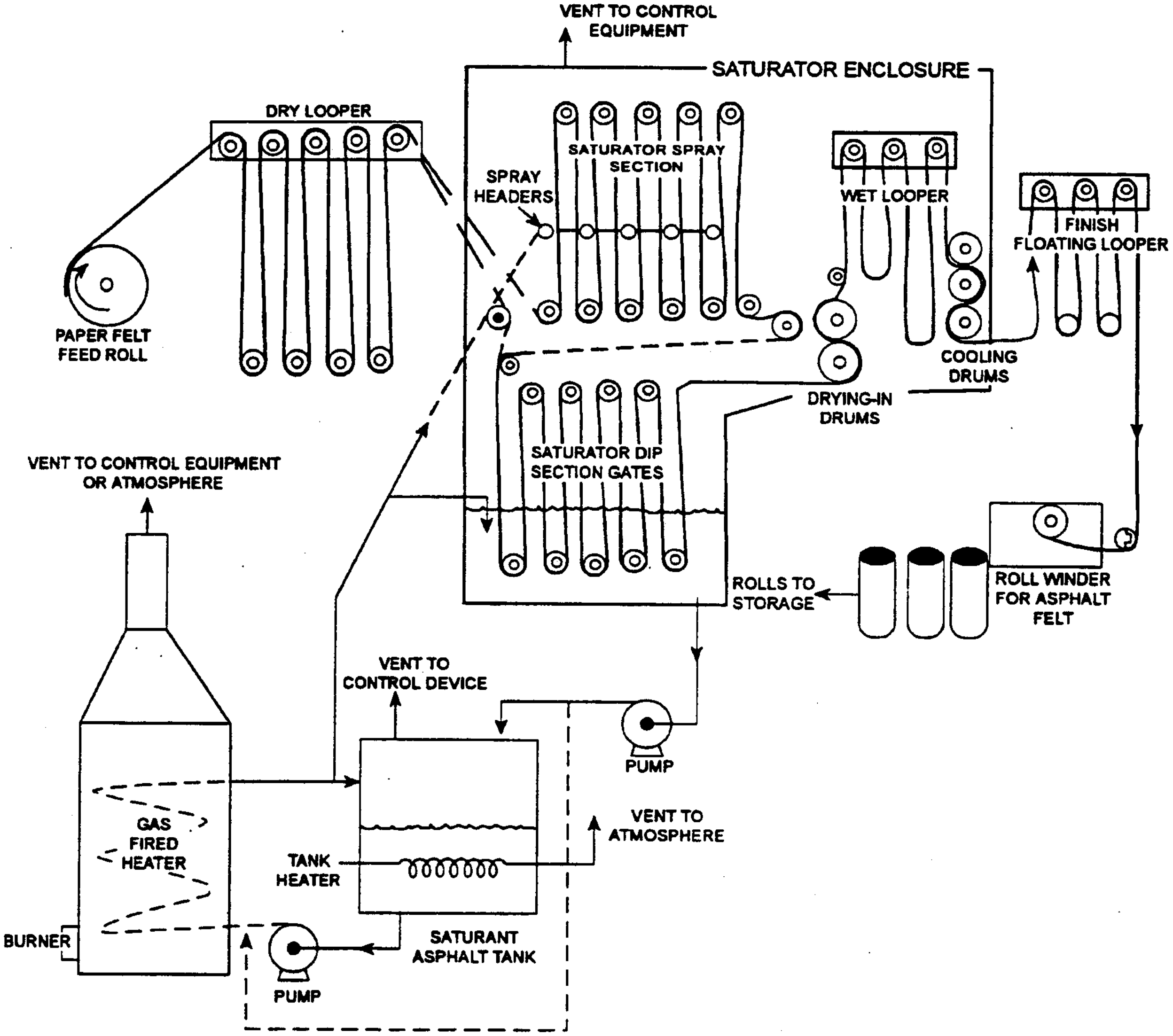

Figure 11.2-2. Asphalt-saturated felt manufacturing process.[1,2]
(SCC = Source Classification Code)

The typical process arrangement for manufacturing asphalt shingles, mineral-surfaced rolls, and smooth rolls is illustrated in Figure 11.2-3. For organic products, the initial production steps are similar to the asphalt-saturated felt line. For fiberglass (polyester) products, the initial saturation operation is eliminated although the dry looper is utilized. A process flow diagram for fiberglass shingle and roll manufacturing is presented in Figure 11.2-4. After the saturation process, both organic and fiberglass (polyester) products follow essentially the same production steps, which include a coater, a granule and sand or backing surface applicator, a press section, water-cooled rollers and/or water spray cooling, finish floating looper, and a roll winder (for roll products), or a seal-down applicator and a shingle cutter (for shingles), or a laminating applicator and laminating operation (for laminated shingles), a shingle stacker, and a packaging station.

Saturated felt (from the saturator) or base fiberglass (polyester) substrate enters the coater. Filled asphalt coating at 180 to 205°C (355 to 425°F) is released through a valve onto the top of the mat just as it passes into the coater. Squeeze rollers in the coater apply filled coating to the backside and distribute it evenly to form a thick base coating to which surfacing materials will adhere. Filled asphalt coating is prepared by mixing coating asphalt or modified asphalt at approximately 250°C (480°F) and a mineral stabilizer (filler) in approximately equal proportions. Typically, the filler is dried and preheated at about 120°C (250°F) in a filler heater before mixing with the coating asphalt. Asphalt modifiers can include rubber polymers or olefin polymers. When modified asphalt is used to produce fiberglass roll roofing, the process is similar to the process depicted in Figure 11.2-4 with the following exception: instead of a coater, an impregnation vat is used, and preceding this vat, asphalt, polymers, and mineral stabilizers are combined in mixing tanks.

After leaving the coater, the coated sheet to be made into shingles or mineral-surfaced rolls passes through the granule applicator where granules are fed onto the hot, coated surface. The granules are pressed into the coating as the mat passes around a press roll where it is reversed, exposing the bottom side. Sand, talc, or mica is applied to the back surface and is also pressed into the coating.

After application of the mineral surfacing, the mat is cooled rapidly by water-cooled rolls and/or water sprays and is passed through air pressure-operated press rolls used to embed the granules firmly into the filled coating. The mat then passes through a drying section where it is air dried. After drying, a strip of adhesive (normally asphalt) is applied to the roofing surface. The strip will act to seal the loose edge of the roofing after application to a roof. A finish looper in the line allows continuous movement of the sheet through the preceding operations and serves to further cool and dry the roofing sheet. Roll roofing is completed at this point is and moves to a winder where rolls are formed. Shingles are passed through a cutter, which cuts the sheet into individual shingles. (Some shingles are formed into laminated products by layering the shingle pieces and binding them together with a laminating material, normally a modified asphalt. The laminant is applied in narrow strips to the backside of the sheet.) The finished shingles are stacked and packaged for shipment.

There are several operations that support the asphalt roofing production line. Asphalt (coating and saturant) is normally delivered to the facility by truck and rail and stored in heated storage tanks. Filler (finely divided mineral) is delivered by truck and normally is pneumatically conveyed to storage bins that supply the filler heater. Granules and back surfacing material are brought in by truck or rail and mechanically or pneumatically conveyed to storage bins.

11.2.3 Emissions And Controls

Emissions from the asphalt roofing industry consist primarily of particulate matter (PM) and volatile organic compounds (VOC). Both are emitted from asphalt storage tanks, blowing stills,

EMISSION SOURCE	SCC
FELT SATURATION: DIPPING ONLY	3-05-001-03
FELT SATURATION: DIPPING/SPRAYING	3-05-001-04
DIPPING ONLY	3-05-001-11
SPRAYING ONLY	3-05-001-12
DIPPING/SPRAYING	3-05-001-13
DIP SATURATOR, DRYING-IN DRUM, WET LOOPER, AND COATER	3-05-001-16
DIP SATURATOR, DRYING-IN DRUM, AND COATER	3-05-001-17
DIP SATURATOR, DRYING-IN DRUM, AND WET LOOPER	3-05-001-18
SPRAY/DIP SATURATOR, DRYING-IN DRUM, WET LOOPER, COATER, AND STORAGE TANKS	3-05-001-19
FIXED ROOF ASPHALT STORAGE TANKS	3-05-001-30, 31
FLOATING ROOF ASPHALT STORAGE TANKS	3-05-001-32, -33

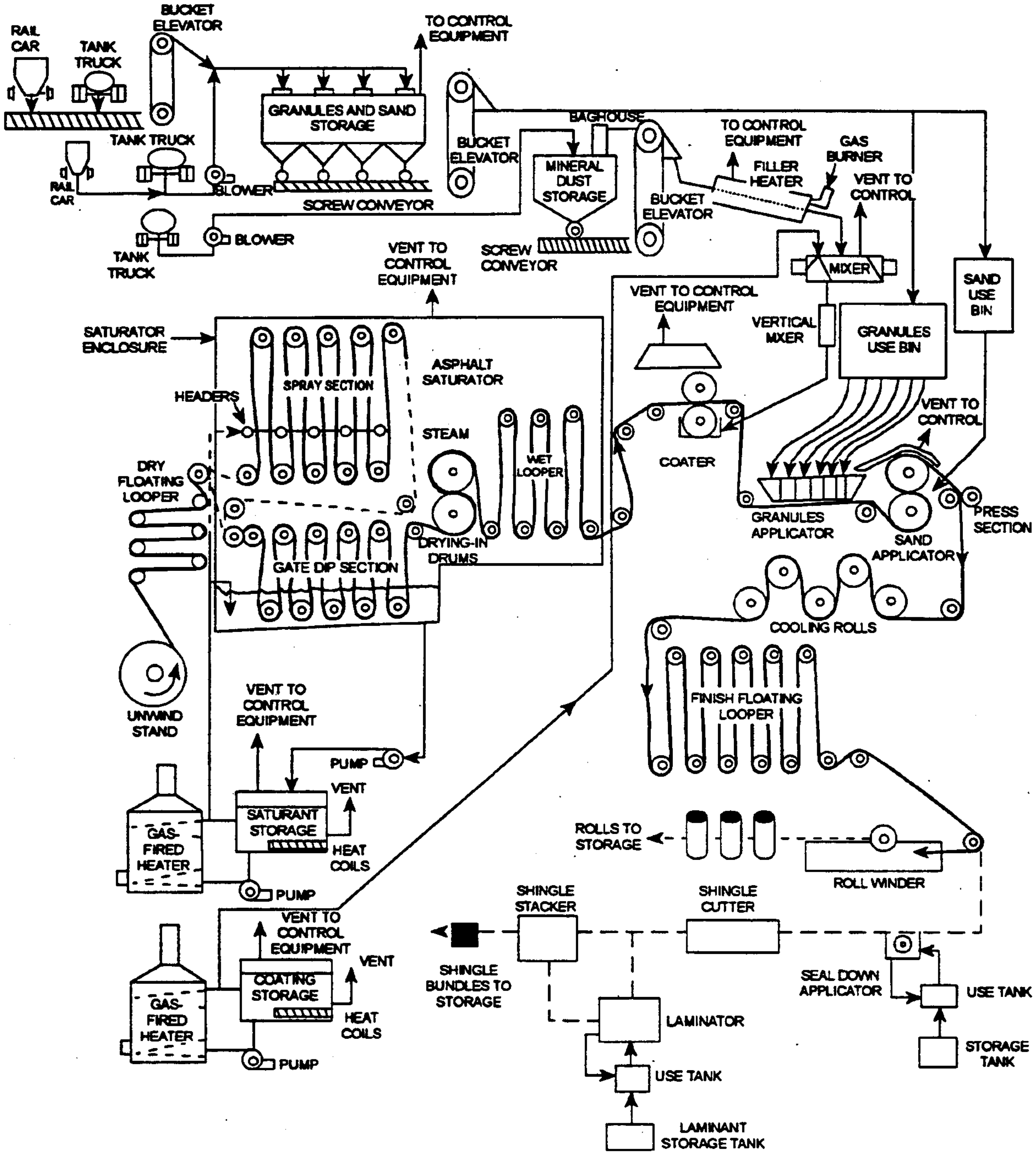

Figure 11.2-3. Organic shingle and roll manufacturing process flow diagram.[1,2] (SCC = Source Classification Code)

EMISSION SOURCE	SCC
FELT SATURATION: DIPPING ONLY	3-05-001-03
FELT SATURATION: DIPPING/SPRAYING	3-05-001-04
DIPPING ONLY	3-05-001-11
SPRAYING ONLY	3-05-001-12
DIPPING/SPRAYING	3-05-001-13
DIP SATURATOR, DRYING-IN DRUM, WET LOOPER, AND COATER	3-05-001-16
DIP SATURATOR, DRYING-IN DRUM, AND COATER	3-05-001-17
DIP SATURATOR, DRYING-IN DRUM, AND WET LOOPER	3-05-001-18
SPRAY/DIP SATURATOR, DRYING-IN DRUM, WET LOOPER, COATER, AND STORAGE TANKS	3-05-001-19
FIXED ROOF ASPHALT STORAGE TANKS	3-05-001-30-31
FLOATING ROOF ASPHALT STORAGE TANKS	3-05-001-32, 33

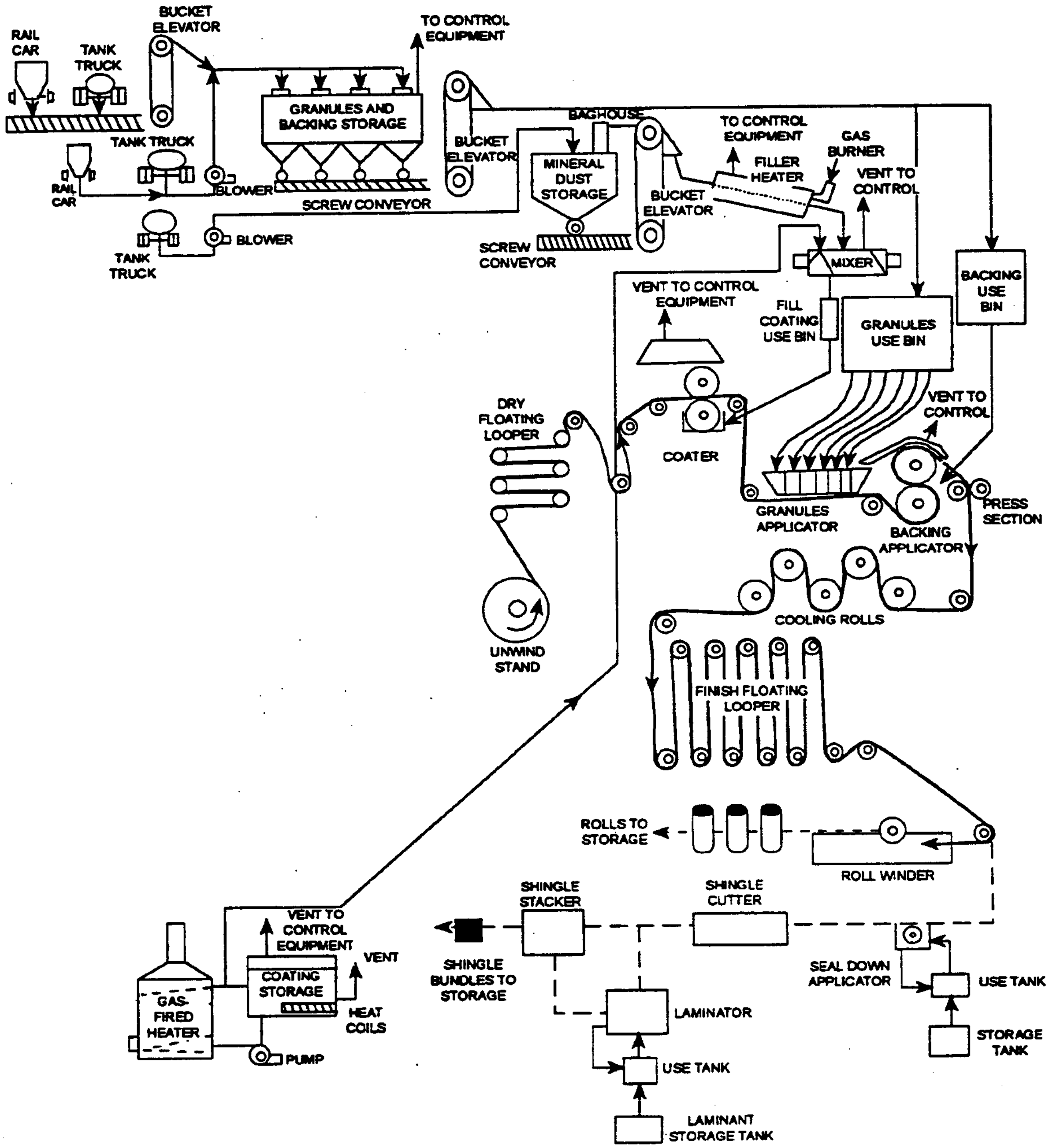

Figure 11.2-4. Fiberglass shingle and roll manufacturing process flow diagram.[1,2]
(SCC = Source Classification Code)

saturators, coater-mixer tanks, and coaters. The PM from these operations is primarily recondensed asphalt fume. Sealant strip and laminant applicators are also sources of small amounts of PM and VOCs. Mineral surfacing operations and materials handling are additional sources of PM. Small amounts of polycyclic organic matter (POM) are also emitted from blowing stills and saturators. Asphalt and filler heaters are sources of typical products of combustion from natural gas or the fuel in use.

A common method for controlling emissions from the saturator, including the wet looper, is to enclose them completely and vent the enclosure to a control device. The coater may be partially enclosed, normally with a canopy-type hood that is vented to a control device. Full enclosure is not always practical due to operating constraints. Fugitive emissions from the saturator or coater may pass through roof vents and other building openings if not captured by enclosures or hoods. Control devices for saturator/coater emissions include low-voltage electrostatic precipitators (ESP), high-energy air filters (HEAF), coalescing filters (mist eliminators), afterburners (thermal oxidation), fabric filters, and wet scrubbers. Blowing operations are controlled by thermal oxidation (afterburners).

Emission factors for filterable PM from the blowing and saturation processes are summarized in Tables 11.2-1 and 11.2-2. Emission factors for total organic compounds (TOC) and carbon monoxide (CO) are shown in Tables 11.2-3 and 11.2-4.

Particulate matter associated with mineral handling and storage operations is captured by enclosures, hoods, or pickup pipes and controlled by fabric filtration (baghouses) with removal efficiencies of approximately 95 to 99 percent. Other control devices that may be used with mineral handling and storage operations are wet scrubbers and cyclones.

In the industry, closed silos and bins are used for mineral storage, so open storage piles are not an emission source. To protect the minerals from moisture pickup, all conveyors that are outside the buildings are covered or enclosed. Fugitive mineral emissions may occur at unloading points depending on the type of equipment used and the mineral handled. The discharge from the conveyor to the silos and bins is normally controlled by a fabric filter (baghouse).

Table 11.2-1 (Metric Units). EMISSION FACTORS FOR ASPHALT ROOFING[a]

Process	Filterable PM[b]	EMISSION FACTOR RATING
Asphalt blowing: saturant asphalt[c] (SCC 3-05-001-01)	3.3	E
Asphalt blowing: coating asphalt[d] (SCC 3-05-001-02)	12	E
Asphalt blowing: saturant asphalt with afterburner[c] (SCC 3-05-001-01)	0.14	D
Asphalt blowing: coating asphalt with afterburner[d] (SCC 3-05-001-02)	0.41	D
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater[e] (SCC 3-05-001-16)	0.60	D
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater with ESP[f] (SCC 3-05-001-16)	0.016	D
Shingle saturation: dip saturator, drying-in drum section, and wet looper with HEAF[g] (SCC 3-05-001-18)	0.035	D
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks[h] (SCC 3-05-001-19)	1.6	D
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks with HEAF[h] (SCC 3-05-001-19)	0.027	D

[a] Factors represent uncontrolled emissions unless noted. Emission factors in kg/Mg of shingles produced unless noted. Polycyclic organic matter emissions comprise approximately 0.03% of PM for blowing stills and 1.1% of PM for saturators. SCC = Source Classification Code. ESP = electrostatic precipitator. HEAF = high-energy air filter.

[b] As measured using EPA Method 5A. Filterable PM is that PM collected on or prior to the filter, which is heated to 42.2°C (108°F).

[c] Reference 10. Saturant blow of 1.5 hours. Expressed as kg/Mg of asphalt processed.

[d] Reference 10. Coating blow of 4.5 hours. Expressed as kg/Mg of asphalt processed.

[e] References 6-7,9.

[f] Reference 6.

[g] Reference 9.

[h] Reference 8.

Table 11.2-2 (English Units). EMISSION FACTORS FOR ASPHALT ROOFING[a]

Process	Filterable PM[b]	EMISSION FACTOR RATING
Asphalt blowing: saturant asphalt[c] (SCC 3-05-001-01)	6.6	E
Asphalt blowing: coating asphalt[d] (SCC 3-05-001-02)	24	E
Asphalt blowing: saturant asphalt with afterburner[c] (SCC 3-05-001-01)	0.27	D
Asphalt blowing: coating asphalt with afterburner[d] (SCC 3-05-001-02)	0.81	D
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater[e] (SCC 3-05-001-16)	1.2	D
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater with ESP[f] (SCC 3-05-001-16)	0.032	D
Shingle saturation: dip saturator, drying-in drum section, and wet looper with HEAF[g] (SCC 3-05-001-18)	0.071	D
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks[h] (SCC 3-05-001-19)	3.2	D
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks with HEAF[h] (SCC 3-05-001-19)	0.053	D

[a] Factors represent uncontrolled emissions unless noted. Emission factors in lb/ton of shingles produced unless noted. Polycyclic organic matter emissions comprise approximately 0.03% of PM for blowing stills and 1.1% of PM for saturators. SCC = Source Classification Code. ESP = electrostatic precipitator. HEAF = high-energy air filter.

[b] As measured using EPA Method 5A. Filterable PM is that PM collected on or prior to the filter, which is heated to 42.2°C (108°F).

[c] Reference 10. Saturant blow of 1.5 hours. Expressed as lb/ton of asphalt processed.

[d] Reference 10. Coating blow of 4.5 hours. Expressed as lb/ton of asphalt processed.

[e] References 6-7,9.

[f] Reference 6.

[g] Reference 9.

[h] Reference 8.

Table 11.2-3 (Metric Units). EMISSION FACTORS FOR ASPHALT ROOFING[a]

Process	TOC[b]	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING
Asphalt blowing: saturant asphalt[d] (SCC 3-05-001-01)	0.66	E	ND	
Asphalt blowing: coating asphalt[d] (SCC 3-05-001-02)	1.7	E	ND	
Asphalt blowing: saturant asphalt with afterburner[c] (SCC 3-05-001-01)	0.0022	D	ND	
Asphalt blowing: coating asphalt with afterburner[d] (SCC 3-05-001-02)	0.085	D	ND	
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater[e] (SCC 3-05-001-16)	0.046	D	ND	
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater with ESP[f] (SCC 3-05-001-16)	0.049	D	ND	
Shingle saturation: dip saturator, drying-in drum section, and coater[g] (SCC 3-05-001-17)	ND		0.0095	D
Shingle saturation: dip saturator, drying-in drum section, and wet looper with HEAF[h] (SCC 3-05-001-18)	0.047	D	ND	
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks[j] (SCC 3-05-001-19)	0.13	D	ND	
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks with HEAF[j] (SCC 3-05-001-19)	0.16	D	ND	
Asphalt blowing[k] (SCC 3-05-001-10)	ND		0.14	E
Asphalt blowing with afterburner[k] (SCC 3-05-001-10)	ND		1.9	E

[a] Factors represent uncontrolled emissions unless otherwise noted. Emission factors in kg/Mg of shingles produced unless noted. SCC = Source Classification Code. ND = no data. ESP = electrostatic precipitator. HEAF = high-energy air filter.

[b] Total organic compounds as measured with an EPA Method 25A (or equivalent) sampling train.

[c] Reference 10. Saturant blow of 1.5 hours. Expressed as kg/Mg of asphalt processed.

[d] Reference 10. Coating blow of 4.5 hours. Expressed as kg/Mg of asphalt processed.

[e] References 6-7.

[f] Reference 6.

[g] Reference 7.

[h] Reference 9.

[j] Reference 8.

[k] Reference 3. Emission factors in kg/Mg of saturated felt produced.

Table 11.2-4 (English Units). EMISSION FACTORS FOR ASPHALT ROOFING[a]

Process	TOC[b]	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING
Asphalt blowing: saturant asphalt[c] (SCC 3-05-001-01)	1.3	E	ND	
Asphalt blowing: coating asphalt[d] (SCC 3-05-001-02)	3.4	E	ND	
Asphalt blowing: saturant asphalt with afterburner[d] (SCC 3-05-001-01)	0.0043	D	ND	
Asphalt blowing: coating asphalt with afterburner[d] (SCC 3-05-001-02)	0.017	D	ND	
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater[e] (SCC 3-05-001-16)	0.091	D	ND	
Shingle saturation: dip saturator, drying-in drum section, wet looper, and coater with ESP[f] (SCC 3-05-001-16)	0.098	D	ND	
Shingle saturation: dip saturator, drying-in drum section, and coater[g] (SCC 3-05-001-17)	ND		0.0019	D
Shingle saturation: dip saturator, drying-in drum section, and wet looper with HEAF[h] (SCC 3-05-001-18)	0.094	D	ND	
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks[j] (SCC 3-05-001-19)	0.26	D	ND	
Shingle saturation: spray/dip saturator, drying-in drum section, wet looper, coater, and storage tanks with HEAF[j] (SCC 3-05-001-19)	0.32	D	ND	
Asphalt blowing[k] (SCC 3-05-001-10)	ND		0.27	E
Asphalt blowing with afterburner[k] (SCC 3-05-001-10)	ND		3.7	E

[a] Factors represent uncontrolled emissions unless otherwise noted. Emission factors in lb/ton of shingles produced unless noted. SCC = Source Classification Code. ND = no data. ESP = electrostatic precipitator. HEAF = high-energy air filter.

[b] Total organic compounds as measured with an EPA Method 25A (or equivalent) sampling train.

[c] Reference 10. Saturant blow of 1.5 hours. Expressed as lb/ton of asphalt processed.

[d] Reference 10. Coating blow of 4.5 hours. Expressed as lb/ton of asphalt processed.

[e] References 6-7.

[f] Reference 6.

[g] Reference 7.

[h] Reference 9.

[j] Reference 8.

[k] Reference 3. Emission factors in lb/ton of saturated felt produced.

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11.3 Bricks And Related Clay Products

11.3.1 Process Description

The manufacture of brick and related products such as clay pipe, pottery, and some types of refractory brick involves the mining, grinding, screening, and blending of the raw materials, and the forming, cutting or shaping, drying or curing, and firing of the final product.

Surface clays and shales are mined in open pits. Most fine clays are found underground. After mining, the material is crushed to remove stones and is stirred before it passes onto screens for segregation by particle size.

To start the forming process, clay is mixed with water, usually in a pug mill. The 3 principal processes for forming bricks are stiff mud, sort mud, and dry press. In the stiff mud process, sufficient water is added to give the clay plasticity, and bricks are formed by forcing the clay through a die. Wire is used in separating bricks. All structural tile and most brick are formed by this process. The soft mud process is usually used with clay too wet for the stiff mud process. The clay is mixed with water to a moisture content of 20 to 30 percent, and the bricks are formed in molds. In the dry press process, clay is mixed with a small amount of water and formed in steel molds by applying pressure of 3.43 to 10.28 megapascals (500 to 1500 pounds per square inch). A typical brick manufacturing process is shown in Figure 11.3-1.

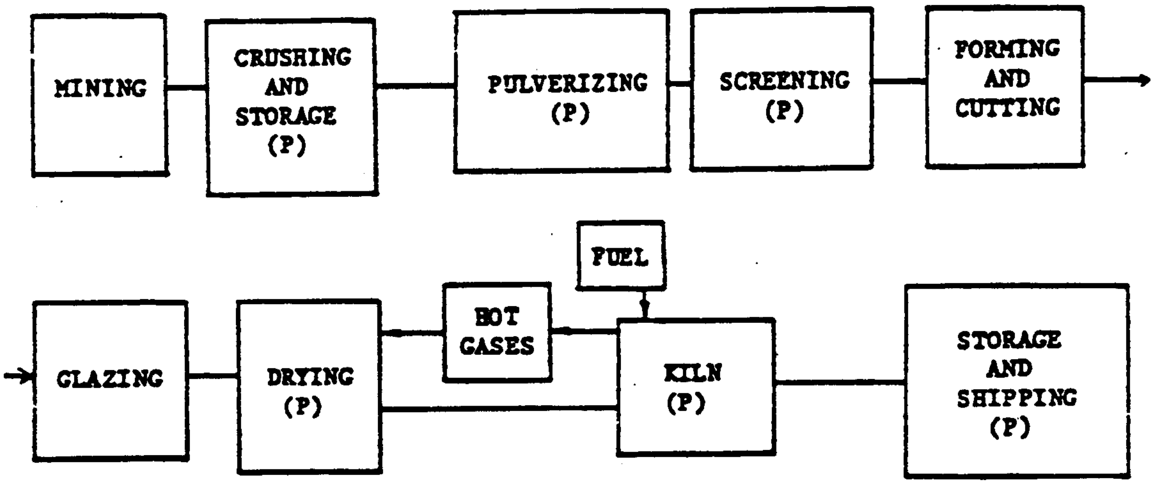

Figure 11.3-1. Basic flow diagram of brick manufacturing process.
(P = a major source of particulate emissions.)

Wet clay units that have been formed are almost completely dried before firing, usually with waste heat from kilns. Many types of kilns are used for firing brick, but the most common are the downdraft periodic kiln and the tunnel kiln. The periodic kiln is a permanent brick structure with a number of fireholes where fuel enters the furnace. Hot gases from the fuel are drawn up over the bricks, down through them by underground flues, and out of the oven to the chimney. Although lower heat recovery makes this type less efficient than the tunnel kiln, the uniform temperature distribution leads to a good quality product. In most tunnel kilns, cars carrying about 1200 bricks travel on rails through the kiln at the rate of one 1.83-meter (6-foot) car per hour. The fire zone is located near the middle of the kiln and is stationary.

In all kilns, firing takes place in 6 steps: evaporation of free water, dehydration, oxidation, vitrification, flashing, and cooling. Normally, gas or residual oil is used for heating, but coal may be used. Total heating time varies with the type of product; for example, 22.9-centimeter (9-inch) refractory bricks usually require 50 to 100 hours of firing. Maximum temperatures of about 1090°C (2000°F) are used in firing common brick.

11.3.2 Emissions And Controls[1,3]

Particulate matter is the primary emission in the manufacture of bricks. The main source of dust is the materials handling procedure, which includes drying, grinding, screening, and storing the raw material. Combustion products are emitted from the fuel consumed in the dryer and the kiln. Fluorides, largely in gaseous form, are also emitted from brick manufacturing operations. Sulfur dioxide may be emitted from the bricks when temperatures reach or exceed 1370°C (2500°F), but no data on such emissions are available.[4]

A variety of control systems may be used to reduce both particulate and gaseous emissions. Almost any type of particulate control system will reduce emissions from the material handling process, but good plant design and hooding are also required to keep emissions to an acceptable level.

The emissions of fluorides can be reduced by operating the kiln at temperatures below 1090°C (2000°F) and by choosing clays with low fluoride content. Satisfactory control can be achieved by scrubbing kiln gases with water, since wet cyclonic scrubbers can remove fluorides with an efficiency of 95 percent or higher.

Tables 11.3-1 and 11.3-2 present emission factors for brick manufacturing without controls. Table 11.3-3 presents data on particle size distribution and emission factors for uncontrolled sawdust-fired brick kilns. Table 11.3-4 presents data on particle size distribution and emission factors for uncontrolled coal-fired tunnel brick kilns. Table 11.3-5 presents data on particle size distribution and emission factors for uncontrolled screening and grinding of raw materials for brick and related clay products. Figure 11.3-2, Figure 11.3-3, and Figure 11.3-4 present a particle size distribution for Tables 11.3-3, 11.3-4, and 11.3-5 expressed as the cumulative weight percent of particles less than a specified aerodynamic diameter (cut point), in micrometers (μm).

Table 11.3-1 (Metric Units). EMISSION FACTORS FOR BRICK MANUFACTURING WITHOUT CONTROLS[a]

EMISSION FACTOR RATING: C

Process	Particulates	Sulfur Oxides	Carbon Monoxide	Volatile Organic Compounds		Nitrogen Oxides	Fluorides[b]
				Nonmethane	Methane		
Raw material handling[c]							
Drying	35	ND	ND	ND	ND	ND	ND
Grinding	38	ND	ND	ND	ND	ND	ND
Storage	17	ND	ND	ND	ND	ND	ND
Brick dryer[d]							
Coal/gas fired	0.006A	0.55S	ND	ND	ND	0.33	ND
Curing and firing[e]							
Tunnel kiln							
Gas fired	0.012	Neg	0.03	0.0015	0.003	0.09	0.5
Oil fired	0.29	1.98S	0.06	0.0035	0.013	0.525	0.5
Coal fired	0.34A	3.65S	0.71	0.005	0.003	0.73	0.5
Coal/gas fired	0.16A	0.31S	ND	ND	ND	0.81	ND
Sawdust fired	0.12	ND	ND	ND	ND	ND	ND
Periodic kiln							
Gas fired	0.033	Neg	0.075	0.005	0.01	0.25	0.5
Oil fired	0.44	2.93S	0.095	0.005	0.02	0.81	0.5
Coal fired	9.42	6.06S	1.19	0.01	0.005	1.18	0.5

[a] Expressed as units per unit weight of brick produced, kilograms per megagram (kg/Mg). One brick weighs about 2.95 kg. ND = no data. A = % ash in coal. S = % sulfur in fuel. Neg = negligible.

[b] References 3,6-10.

[c] Based on data from Section 11.7, "Ceramic Clay Manufacturing" in this publication. Because of process variation, some steps may be omitted. Storage losses apply only to that quantity of material stored.

[d] Reference 12.

[e] References 1,5,12-16.

Table 11.3-2 (English Units). EMISSION FACTORS FOR BRICK MANUFACTURING WITHOUT CONTROLS[a]

EMISSION FACTOR RATING: C

Process	Particulates	Sulfur Oxides	Carbon Monoxide	Volatile Organic Compounds		Nitrogen Oxides	Fluorides[b]
				Nonmethane	Methane		
Raw material handling[c]							
Drying	70	ND	ND	ND	ND	ND	ND
Grinding	76	ND	ND	ND	ND	ND	ND
Storage	34	ND	ND	ND	ND	ND	ND
Brick dryer[d]							
Coal/gas fired	0.012A	1.10S	ND	ND	ND	0.66	ND
Curing and firing[e]							
Tunnel kiln							
Gas fired	0.023	Neg	0.06	0.003	0.006	0.18	1.0
Oil fired	0.59	3.95S	0.12	0.007	0.025	1.05	1.0
Coal fired	0.67A	7.31S	1.43	0.01	0.006	1.45	1.0
Coal/gas fired	0.31A	0.62S	ND	ND	ND	1.61	ND
Sawdust fired	0.24	ND	ND	ND	ND	ND	ND
Periodic kiln							
Gas fired	0.065	Neg	0.15	0.01	0.02	0.50	1.0
Oil fired	0.88	5.86S	0.19	0.01	0.04	1.62	1.0
Coal fired	18.84	12.13S	2.39	0.02	0.015	2.35	1.0

[a] Expressed as units per unit weight of brick produced, pounds per ton (lb/ton). One brick weighs about 6.5 pounds. ND = no data. A = % ash in coal. S = % sulfur in fuel. Neg = negligible.

[b] References 3,6-10.

[c] Based on data from Section 11.7, "Ceramic Clay Manufacturing" in this publication. Because of process variation, some steps may be omitted. Storage losses apply only to that quantity of material stored.

[d] Reference 12.

[e] References 1,5,12-16.

Table 11.3-3 (Metric Units). PARTICLE SIZE DISTRIBUTION AND EMISSION FACTORS FOR UNCONTROLLED SAWDUST-FIRED BRICK KILNS[a]

EMISSION FACTOR RATING: E

Aerodynamic Particle Diameter (μm)	Cumulative Weight % ≤ Stated Size	Emission Factor[b] (kg/Mg)
2.5	36.5	0.044
6.0	63.0	0.076
10.0	82.5	0.099
	Total particulate emission factor	0.12[c]

[a] Reference 13.

[b] Expressed as cumulative weight of particulate ≤ corresponding particle size/unit weight of brick produced.

[c] Total mass emission factor from Table 11.3-1.

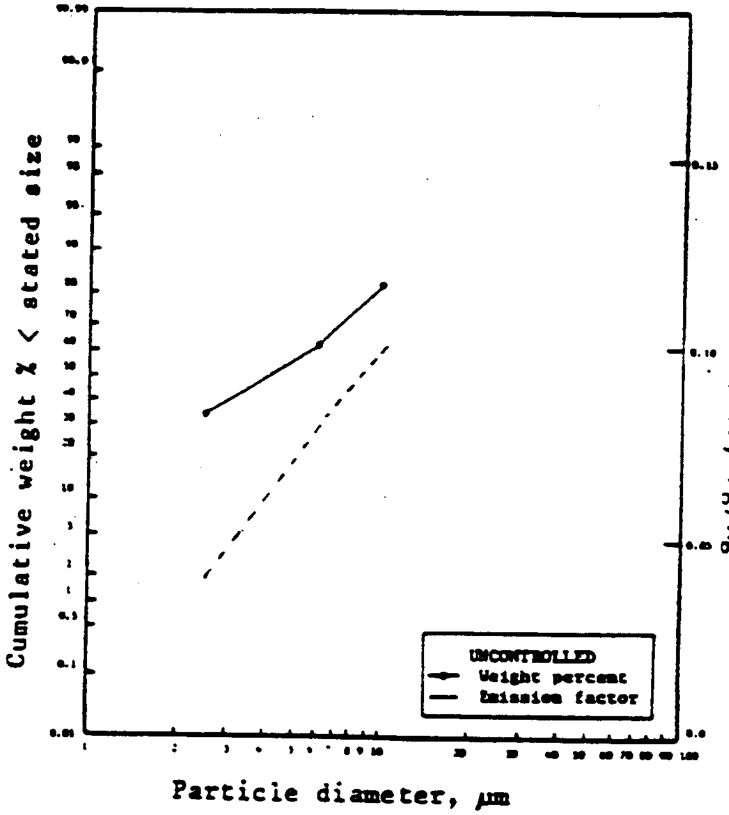

Figure 11.3-2. Cumulative weight percent of particles less than stated particle diameters for uncontrolled sawdust-fired brick kilns.

Table 11.3-4 (Metric Units). PARTICLE SIZE DISTRIBUTION AND EMISSION FACTORS FOR UNCONTROLLED COAL-FIRED TUNNEL BRICK KILNS[a]

EMISSION FACTOR RATING: E

Aerodynamic Particle Diameter (μm)	Cumulative Weight % ≤ Stated Size	Emission Factor[b] (kg/Mg)
2.5	24.7	0.08A
6.0	50.4	0.17A
10.0	71.0	0.24A
	Total particulate emission factor	0.34A[c]

[a] References 12,17.

[b] Expressed as cumulative weight of particulate ≤ corresponding particle size/unit weight of brick produced. A = % ash in coal. (Use 10% if ash content is not known.)

[c] Total mass emission factor from Table 11.3-1.

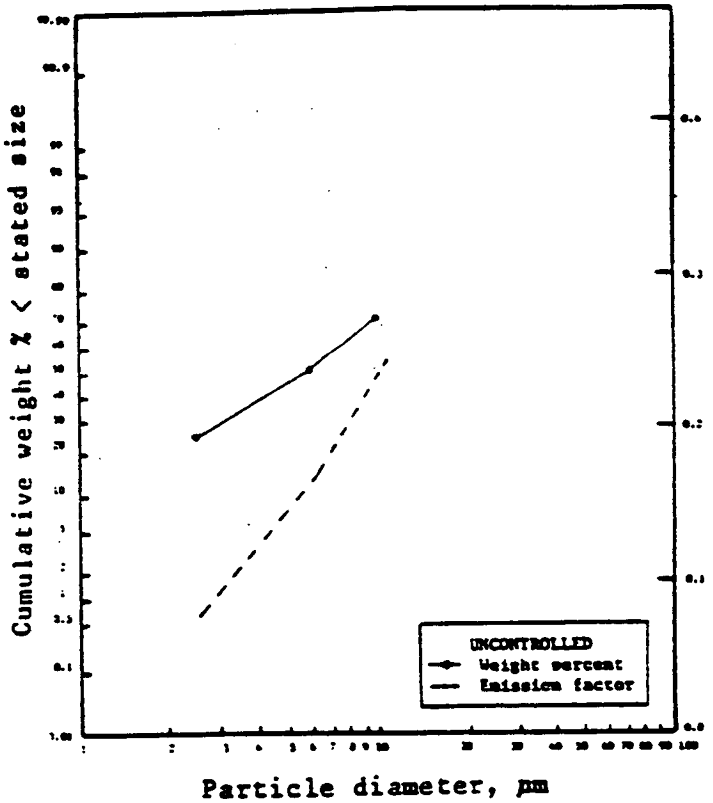

Figure 11.3-3. Cumulative weight percent of particles less than stated particle diameters for uncontrolled coal-fired tunnel brick kilns.

Table 11.3-5 (Metric Units). PARTICLE SIZE DISTRIBUTION AND EMISSION FACTORS FOR UNCONTROLLED SCREENING AND GRINDING OF RAW MATERIALS FOR BRICK AND RELATED CLAY PRODUCTS[a]

EMISSION FACTOR RATING: E

Aerodynamic Particle Diameter (μm)	Cumulative Weight % ≤ Stated Size	Emission Factor[b] (kg/Mg)
2.5	0.2	0.08
6.0	0.4	0.15
10.0	7.0	2.66
	Total particulate emission factor	38[c]

[a] References 11,18.

[b] Expressed as cumulative weight of particulate ≤ corresponding particle size/unit weight of raw material processed.

[c] Total mass emission factor from Table 11.3-1.

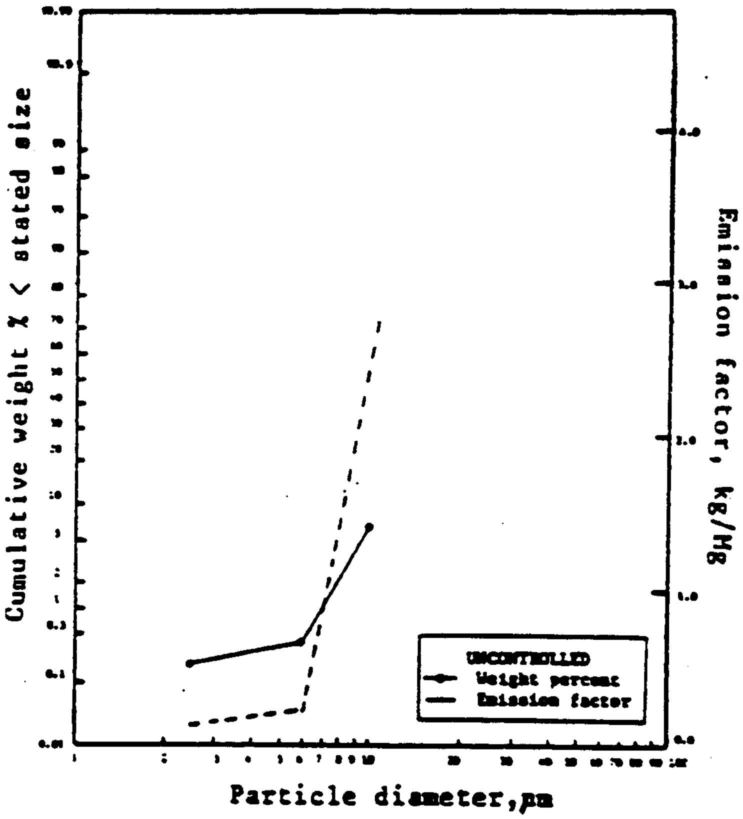

Figure 11.3-4. Cumulative weight percent of particles less than stated particle diameters for uncontrolled screening and grinding of raw materials for brick and related clay products.

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11.4 Calcium Carbide Manufacturing

11.4.1 General

Calcium carbide (CaC_2) is manufactured by heating a lime and carbon mixture to 2000 to 2100°C (3632 to 3812°F) in an electric arc furnace. At those temperatures, the lime is reduced by carbon to calcium carbide and carbon monoxide (CO), according to the following reaction:

$$CaO + 3C \rightarrow CaC_2 + CO$$

Lime for the reaction is usually made by calcining limestone in a kiln at the plant site. The sources of carbon for the reaction are petroleum coke, metallurgical coke, and anthracite coal. Because impurities in the furnace charge remain in the calcium carbide product, the lime should contain no more than 0.5 percent each of magnesium oxide, aluminum oxide, and iron oxide, and 0.004 percent phosphorus. Also, the coke charge should be low in ash and sulfur. Analyses indicate that 0.2 to 1.0 percent ash and 5 to 6 percent sulfur are typical in petroleum coke. About 991 kilograms (kg) (2,185 pounds [lb]) of lime, 683 kg (1,506 lb) of coke, and 17 to 20 kg (37 to 44 lb) of electrode paste are required to produce 1 megagram (Mg) (2,205 lb) of calcium carbide.

The process for manufacturing calcium carbide is illustrated in Figure 11.4-1. Moisture is removed from coke in a coke dryer, while limestone is converted to lime in a lime kiln. Fines from coke drying and lime operations are removed and may be recycled. The two charge materials are then conveyed to an electric arc furnace, the primary piece of equipment used to produce calcium carbide. There are three basic types of electric arc furnaces: the open furnace, in which the CO burns to carbon dioxide (CO_2) when it contacts the air above the charge; the closed furnace, in which the gas is collected from the furnace and is either used as fuel for other processes or flared; and the semi-covered furnace, in which mix is fed around the electrode openings in the primary furnace cover resulting in mix seals. Electrode paste composed of coal tar pitch binder and anthracite coal is fed into a steel casing where it is baked by heat from the electric arc furnace before being introduced into the furnace. The baked electrode exits the steel casing just inside the furnace cover and is consumed in the calcium carbide production process. Molten calcium carbide is tapped continuously from the furnace into chills and is allowed to cool and solidify. Then, the solidified calcium carbide goes through primary crushing by jaw crushers, followed by secondary crushing and screening for size. To prevent explosion hazards from acetylene generated by the reaction of calcium carbide with ambient moisture, crushing and screening operations may be performed in either an air-swept environment before the calcium carbide has completely cooled, or in an inert atmosphere. The calcium carbide product is used primarily in generating acetylene and in desulfurizing iron.

11.4.2 Emissions And Controls

Emissions from calcium carbide manufacturing include particulate matter (PM), sulfur oxides (SO_x), CO, CO_2, and hydrocarbons. Particulate matter is emitted from a variety of equipment and operations in the production of calcium carbide including the coke dryer, lime kiln, electric furnace, tap fume vents, furnace room vents, primary and secondary crushers, and conveying equipment. (Lime kiln emission factors are presented in Section 11.17). Particulate matter emitted from a process source such as an electric furnace is ducted to a PM control device, usually a fabric filter or wet scrubber. Fugitive PM from sources such as tapping operations, the furnace room, and conveyors is captured and sent to a PM control device. The composition of the PM varies according

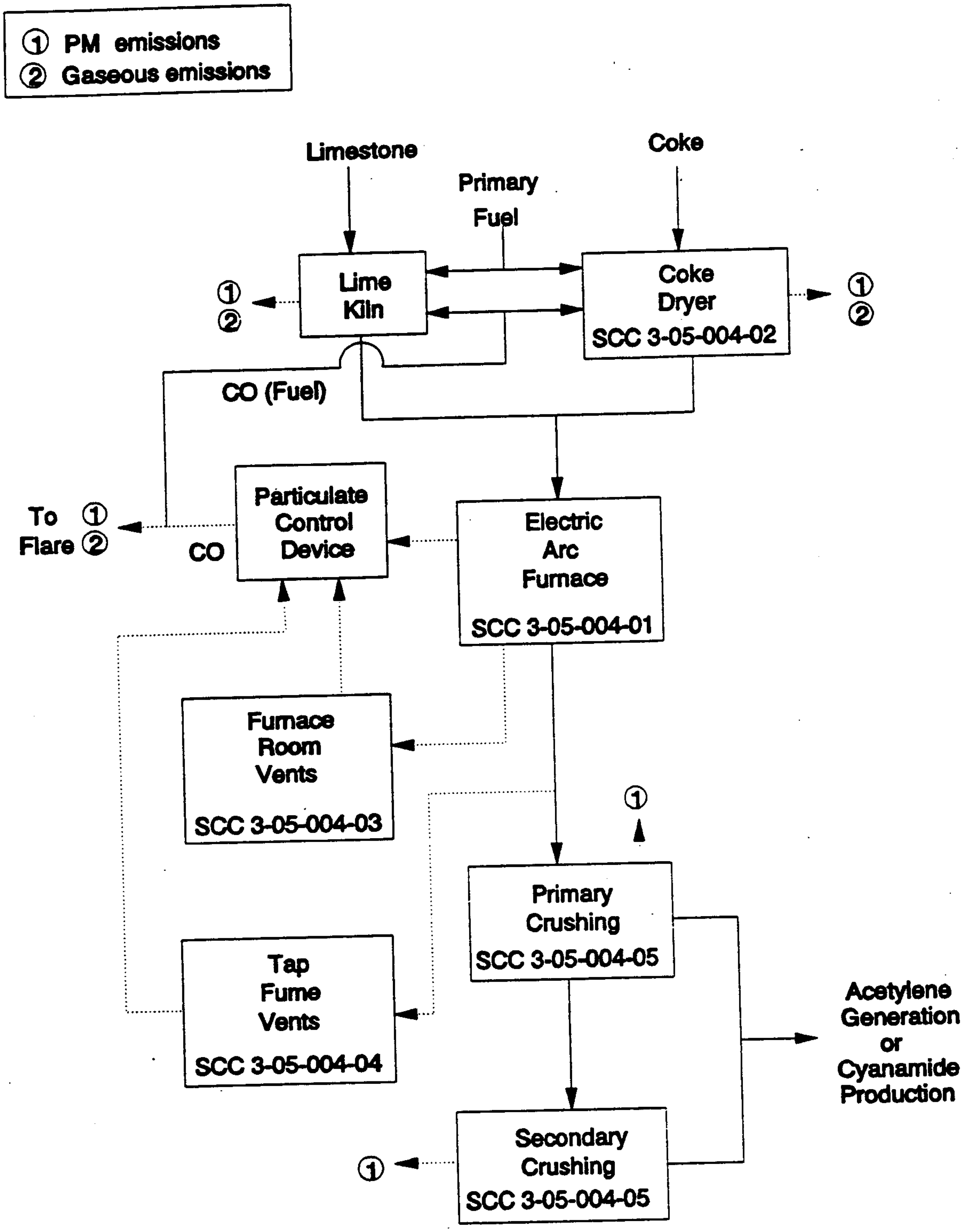

Figure 11.4-1. Process flow diagram for calcium carbide manufacturing.
(SCC = Source Classification Code).

to the specific equipment or operation, but the primary components are calcium and carbon compounds, with significantly smaller amounts of magnesium compounds.

Sulfur oxides may be emitted both by the electric furnace from volatilization and oxidation of sulfur in the coke feed, and by the coke dryer and lime kiln from fuel combustion. These process sources are not controlled specifically for SO_x emissions. Carbon monoxide is a byproduct of calcium carbide production in the electric furnace. Carbon monoxide emissions to the atmosphere are usually negligible. In open furnaces, CO is oxidized to CO_2, thus eliminating CO emissions. In closed furnaces, a portion of the generated CO is burned in the flames surrounding the furnace charge holes, and the remaining CO is either used as fuel for other processes or is flared. In semi-covered furnaces, the CO that is generated is either used as fuel for the lime kiln or other processes, or is flared.

The only potential source of hydrocarbon emissions from the manufacture of calcium carbide is the coal tar pitch binder in the furnace electrode paste. Since the maximum volatiles content in the electrode paste is about 18 percent, the electrode paste represents only a small potential source of hydrocarbon emissions. In closed furnaces, actual hydrocarbon emissions from the consumption of electrode paste typically are negligible because of high furnace operating temperature and flames surrounding the furnace charge holes. In open furnaces, hydrocarbon emissions are expected to be negligible because of high furnace operating temperatures and the presence of excess oxygen above the furnace. Hydrocarbon emissions from semi-covered furnaces are also expected to be negligible because of high furnace operating temperatures.

Tables 11.4-1 and 11.4-2 give controlled and uncontrolled emission factors in metric and English units, respectively, for various processes in the manufacture of calcium carbide. Controlled factors are based on test data and permitted emissions for operations with the fabric filters and wet scrubbers that are typically used to control PM emissions in calcium carbide manufacturing.

Table 11.4-1 (Metric Units). EMISSION FACTORS FOR CALCIUM CARBIDE MANUFACTURING[a]

EMISSION FACTOR RATING: E (except as noted)

Process	Filterable PM[b] (kg/Mg feed)	Condensable Inorganic PM[c] (kg/Mg feed)	Sulfur Oxides (kg/Mg feed)	CO_2 (kg/Mg feed)
Electric arc furnace main stack (SCC 3-05-004-01)[d]	13[e]	ND	1.5[f]	ND
Electric arc furnace main stack with fabric filter (SCC 3-05-004-01)[d]	0.32[g]	0.37[g]	ND	Neg[h]
Electric arc furnace main stack with scrubber (SCC 3-05-004-01)[d]	0.25[e]	ND	ND	ND
Electric arc furnace and calcium carbide cooling conveyor with fabric filter (SCC 3-05-004-__)[d]	0.035[j,k]	ND	ND	Neg[m]
Coke dryer (SCC 3-05-004-02)	1.0[f]	ND	1.5[f]	ND
Coke dryer with fabric filter (SCC 3-05-004-02)	0.13[n]	ND	NA	ND
Furnace room vents (SCC 3-05-004-03)	13[f]	ND	ND	ND
Furnace room vents with fabric filter (SCC 3-05-004-03)	0.07[n]	ND	ND	ND
Tap fume vents with fabric filter (SCC 3-05-004-04)	0.07[n]	ND	ND	ND
Primary and secondary crushing with fabric filter (SCC 3-05-004-05)	0.055[n]	ND	NA	NA
Circular charging conveyor with fabric filter (SCC 3-05-004-06)	0.11[n]	ND	NA	NA

[a] Factors are for uncontrolled emissions, unless otherwise noted. Factors are kg/Mg of feed unless noted. Feed materials: electric furnace - coke and lime; coke dryer - coke; tap fume vent - coke and lime; furnace room vent - coke and lime; crusher - calcium carbide; charging conveyor - coke and lime. NA = not applicable. ND = no data. Neg = negligible. SCC = Source Classification Code.

[b] Filterable PM is that collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that collected in the impinger portion of a PM sampling train.

[d] Emission factors applicable to open furnaces using petroleum coke.

[e] Reference 4.

[f] From previous AP-42 section; reference not specified.

[g] References 8,13. EMISSION FACTOR RATING: C.

[h] Reference 13.

[j] Reference 12; emission factor in kg/Mg of calcium carbide produced.

[k] EMISSION FACTOR RATING: D.

[m] Reference 12.

[n] Reference 1.

Table 11.4-2 (English Units). EMISSION FACTORS FOR CALCIUM CARBIDE MANUFACTURING[a]

EMISSION FACTOR RATING: E (except as noted)

Process	Filterable PM[b] (lb/ton)	Condensable Inorganic PM[c] (lb/ton)	Sulfur Oxides (lb/ton)	CO_2 (lb/ton)
Electric arc furnace main stack (SCC 3-05-004-01)[d]	26[e]	ND	3.0[f]	ND
Electric arc furnace main stack with fabric filter (SCC 3-05-004-01)[d]	0.63[g]	0.73[g]	ND	Neg[h]
Electric arc furnace main stack with scrubber (SCC 3-05-004-01)[d]	0.50[e]	ND	ND	ND
Electric arc furnace and calcium carbide cooling conveyor with fabric filter (SCC 3-05-004-__)[d]	0.70[j,k]	ND	ND	Neg[m]
Coke dryer (SCC 3-05-004-02)	2.0[f]	ND	3.0[f]	ND
Coke dryer with fabric filter (SCC 3-05-004-02)	0.26[n]	ND	NA	ND
Furnace room vents (SCC 3-05-004-03)	26[f]	ND	ND	ND
Furnace room vents with fabric filter (SCC 3-05-004-03)	0.14[n]	ND	ND	ND
Tap fume vents with fabric filter (SCC 3-05-004-04)	0.14[n]	ND	ND	ND
Primary and secondary crushing with fabric filter (SCC 3-05-004-05)	0.11[n]	ND	NA	NA
Circular charging conveyor with fabric filter (SCC 3-05-004-06)	0.22[n]	ND	NA	NA

[a] Factors are for uncontrolled emissions, unless otherwise noted. Factors in lb/ton of feed unless noted. Feed materials: electric furnace - coke and lime; coke dryer - coke; tap fume vent - coke and lime; furnace room vent - coke and lime; crusher - calcium carbide; charging conveyor - coke and lime. NA = not applicable. ND = no data. Neg = negligible. SCC = Source Classification Code.

[b] Filterable PM is that collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that collected in the impinger portion of a PM sampling train.

[d] Emission factors applicable to open furnaces using petroleum coke.

[e] Reference 4.

[f] From previous AP-42 section; reference not specified.

[g] References 8,13. EMISSION FACTOR RATING: C

[h] Reference 13.

[j] Reference 12; emission factor in kg/Mg of calcium carbide produced.

[k] EMISSION FACTOR RATING: D.

[m] Reference 12.

[n] Reference 1.

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11.5 Refractory Manufacturing

11.5.1 Process Description[1-2]

Refractories are materials that provide linings for high-temperature furnaces and other processing units. Refractories must be able to withstand physical wear, high temperatures (above 538°C [1000°F]), and corrosion by chemical agents. There are two general classifications of refractories, clay and nonclay. The six-digit source classification code (SCC) for refractory manufacturing is 3-05-005. Clay refractories are produced from fireclay (hydrous silicates of aluminum) and alumina (57 to 87.5 percent). Other clay minerals used in the production of refractories include kaolin, bentonite, ball clay, and common clay. Nonclay refractories are produced from a composition of alumina (<87.5 percent), mullite, chromite, magnesite, silica, silicon carbide, zircon, and other nonclays.

Refractories are produced in two basic forms, formed objects, and unformed granulated or plastic compositions. The preformed products are called bricks and shapes. These products are used to form the walls, arches, and floor tiles of various high-temperature process equipment. Unformed compositions include mortars, gunning mixes, castables (refractory concretes), ramming mixes, and plastics. These products are cured in place to form a monolithic, internal structure after application.

Refractory manufacturing involves four processes: raw material processing, forming, firing, and final processing. Figure 11.5-1 illustrates the refractory manufacturing process. Raw material processing consists of crushing and grinding raw materials, followed if necessary by size classification and raw materials calcining and drying. The processed raw material then may be dry-mixed with other minerals and chemical compounds, packaged, and shipped as product. All of these processes are not required for some refractory products.

Forming consists of mixing the raw materials and forming them into the desired shapes. This process frequently occurs under wet or moist conditions. Firing involves heating the refractory material to high temperatures in a periodic (batch) or continuous tunnel kiln to form the ceramic bond that gives the product its refractory properties. The final processing stage involves milling, grinding, and sandblasting of the finished product. This step keeps the product in correct shape and size after thermal expansion has occurred. For certain products, final processing may also include product impregnation with tar and pitch, and final packaging.

Two other types of refractory processes also warrant discussion. The first is production of fused products. This process involves using an electric arc furnace to melt the refractory raw materials, then pouring the melted materials into sand-forming molds. Another type of refractory process is ceramic fiber production. In this process, calcined kaolin is melted in an electric arc furnace. The molten clay is either fiberized in a blowchamber with a centrifuge device or is dropped into an air jet and immediately blown into fine strands. After the blowchamber, the ceramic fiber may then be conveyed to an oven for curing, which adds structural rigidity to the fibers. During the curing process, oils are used to lubricate both the fibers and the machinery used to handle and form the fibers. The production of ceramic fiber for refractory material is very similar to the production of mineral wool.

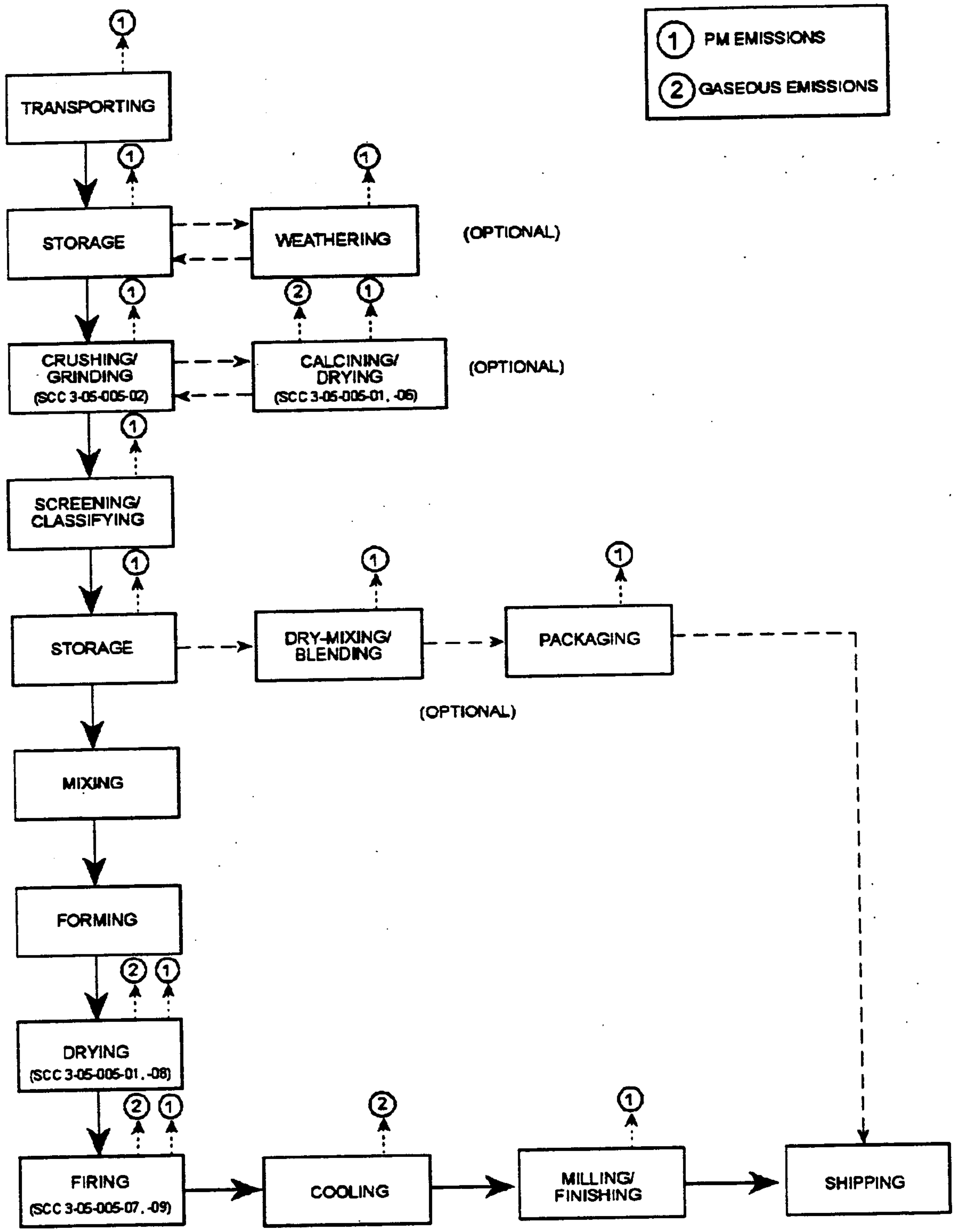

Figure 11.5-1. Refractory manufacturing process flow diagram.[1]
(Source Classification Codes in parentheses.)

11.5.2 Emissions And Controls[2-6]

The primary pollutant of concern in refractory manufacturing is particulate matter (PM). Particulate matter emissions occur during the crushing, grinding, screening, calcining, and drying of the raw materials; the drying and firing of the unfired "green" refractory bricks, tar and pitch operations; and finishing of the refractories (grinding, milling, and sandblasting).

Emissions from crushing and grinding operations generally are controlled with fabric filters. Product recovery cyclones followed by wet scrubbers are used on calciners and dryers to control PM emissions from these sources. The primary sources of PM emissions are the refractory firing kilns and electric arc furnaces. Particulate matter emissions from kilns generally are not controlled. However, at least one refractory manufacturer currently uses a multiple-stage scrubber to control kiln emissions. Particulate matter emissions from electric arc furnaces generally are controlled by a baghouse. Particulate removal of 87 percent and fluoride removal of greater than 99 percent have been reported at one facility that uses an ionizing wet scrubber.

Pollutants emitted as a result of combustion in the calcining and kilning processes include sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and volatile organic compounds (VOC). The emission of SO_x is also a function of the sulfur content of certain clays and the plaster added to refractory materials to induce brick setting. Fluoride emissions occur during the kilning process because of fluorides in the raw materials. Emission factors for filterable PM, PM-10, SO_2, NO_x, and CO_2 emissions from rotary dryers and calciners processing fire clay are presented in Tables 11.5-1 and 11.5-2. Particle size distributions for filterable particulate emissions from rotary dryers and calciners processing fire clay are presented in Table 11.5-3.

Volatile organic compounds emitted from tar and pitch operations generally are controlled by incineration, when inorganic particulates are not significant. Based on the expected destruction of organic aerosols, a control efficiency in excess of 95 percent can be achieved using incinerators.

Chromium is used in several types of nonclay refractories, including chrome-magnesite, (chromite-magnesite), magnesia-chrome, and chrome-alumina. Chromium compounds are emitted from the ore crushing, grinding, material drying and storage, and brick firing and finishing processes used in producing these types of refractories. Tables 11.5-4 and 11.5-5 present emission factors for emissions of filterable PM, filterable PM-10, hexavalent chromium, and total chromium from the drying and firing of chromite-magnesite ore. The emission factors are presented in units of kilograms of pollutant emitted per megagram of chromite ore processed (kg/Mg CrO_3) (pounds per ton of chromite ore processed [lb/ton CrO_3]). Particle size distributions for the drying and firing of chromite-magnesite ore are summarized in Table 11.5-6.

A number of elements in trace concentrations including aluminum, beryllium, calcium, chromium, iron, lead, mercury, magnesium, manganese, nickel, titanium, vanadium, and zinc also are emitted in trace amounts by the drying, calcining, and firing operations of all types of refractory materials. However, data are inadequate to develop emission factors for these elements.

Emissions of PM from electric arc furnaces producing fused cast refractory material are controlled with baghouses. The efficiency of the fabric filters often exceeds 99.5 percent. Emissions of PM from the ceramic fiber process also are controlled with fabric filters, at an efficiency similar to that found in the fused cast refractory process. To control blowchamber emissions, a fabric filter is used to remove small pieces of fine threads formed in the fiberization stage. The efficiency of fabric filters in similar control devices exceeds 99 percent. Small particles of ceramic fiber are broken off or separated during the handling and forming of the fiber blankets in the curing oven. An oil is used in this process, and higher molecular weight organics may be emitted. However, these emissions generally are controlled with a fabric filter followed by incineration, at an expected overall efficiency in excess of 95 percent.

Table 11.5-1 (Metric Units). EMISSION FACTORS FOR REFRACTORY MANUFACTURING: FIRE CLAY[a]

EMISSION FACTOR RATING: D

Process	SO_2	NO_x	CO_2	Filterable[b]	
				PM	PM-10
Rotary dryer[c] (SCC 3-05-005-01)	ND	ND	15	33	8.1
Rotary dryer with cyclone (SCC 3-05-005-01)	ND	ND	15	5.6	2.6
Rotary dryer with cyclone and wet scrubber[c] (SCC 3-05-005-01)	ND	ND	15	0.052	ND
Rotary calciner (SCC 3-05-005-06)	ND	ND	300[c]	62[d]	14[e]
Rotary calciner with multiclone (SCC 3-05-005-06)	ND	ND	300[c]	31[f]	ND
Rotary calciner with multiclone and wet scrubber (SCC 3-05-005-06)	3.8[d]	0.87[d]	300[c]	0.15[d]	0.031[e]

[a] Factors represent uncontrolled emissions, unless noted. All emission factors in kg/Mg of raw material feed. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Reference 3.

[d] References 4-5.

[e] Reference 4.

[f] Reference 5.

Table 11.5-2 (English Units). EMISSION FACTORS FOR REFRACTORY MANUFACTURING: FIRE CLAY[a]

EMISSION FACTOR RATING: D

Process	SO_2	NO_x	CO_2	Filterable[b]	
				PM	PM-10
Rotary dryer[c] (SCC 3-05-005-01)	ND	ND	30	65	16
Rotary dryer with cyclone[c] (SCC 3-05-005-01)	ND	ND	30	11	5.1
Rotary dryer with cyclone and wet scrubber[c] (SCC 3-05-005-01)	ND	ND	30	0.11	ND
Rotary calciner (SCC 3-05-005-06)	ND	ND	600[c]	120[d]	30[e]
Rotary calciner with multiclone (SCC 3-05-005-06)	ND	ND	600[c]	61[f]	ND
Rotary calciner with multiclone and wet scrubber (SCC 3-05-005-06)	7.6[d]	1.7[d]	ND	0.30[d]	0.062[e]

[a] Factors represent uncontrolled emissions, unless noted. All emission factors in lb/ton of raw material feed. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Reference 3.

[d] References 4-5.

[e] Reference 4.

[f] Reference 5.

Table 11.5-3. PARTICLE SIZE DISTRIBUTIONS FOR REFRACTORY MANUFACTURING: FIRE CLAY[a]

EMISSION FACTOR RATING: D

Diameter (μm)	Uncontrolled	Multiclone Controlled	Cyclone Controlled	Cyclone/Scrubber Controlled
	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter
Rotary Dryers (SCC 3-05-005-01)[b]				
2.5	2.5	ND	14	ND
6.0	10	ND	31	ND
10.0	24	ND	46	ND
15.0	37	ND	60	ND
20.0	51	ND	68	ND
Rotary Calciners (SCC 3-05-005-06)[c]				
1.0	3.1	13	ND	31
1.25	4.1	14	ND	43
2.5	6.9	23	ND	46
6.0	17	39	ND	55
10.0	34	50	ND	69
15.0	50	63	ND	81
20.0	62	81	ND	91

[a] For filterable PM only. ND = no data. SCC = Source Classification Code.

[b] Reference 3.

[c] References 4-5 (uncontrolled). Reference 4 (multiclone-controlled). Reference 5 (cyclone/scrubber-controlled).

Table 11.5-4 (Metric Units). EMISSION FACTORS FOR REFRACTORY MANUFACTURING: CHROMITE-MAGNESITE ORE[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Filterable[b]		Chromium[c]	
	PM	PM-10	Hexavalent	Total
Rotary dryer (SCC 3-05-005-08)	0.83	0.20	3.8×10^{-5}	0.035
Rotary dryer with cyclone and fabric filter (SCC 3-05-005-08)	0.15	ND	1.9×10^{-5}	0.064
Tunnel kiln (SCC 3-05-005-09)	0.41	0.34	0.0087	0.13

[a] Reference 6. Factors represent uncontrolled emissions. Factors for filterable PM are kg/Mg of material processed. Factors for chrominum are kg/Mg of chromite ore processed. SCC = Source Classification Code for chromium. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution and filterable PM emission factor.

[c] EMISSION FACTOR RATING: E.

Table 11.5-5 (English Units). EMISSION FACTORS FOR REFRACTORY MANUFACTURING: CHROMITE-MAGNESITE ORE[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Filterable[b]		Chromium[c]	
	PM	PM-10	Hexavalent	Total
Rotary dryer (SCC 3-05-005-08)	1.7	0.41	7.6×10^{-5}	0.70
Rotary dryer with cyclone and fabric filter (SCC 3-05-005-08)	0.30	ND	3.7×10^{-5}	0.13
Tunnel kiln (SCC 3-05-005-09)	0.82	0.69	0.017	0.27

[a] Reference 6. Factors represent uncontrolled emissions. Factors for filterable PM are lb/ton of material processed. Factors for chromium are lb/ton of chromite ore processed. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution and filterable PM emission factor.

[c] EMISSION FACTOR RATING: E.

Table 11.5-6. PARTICLE SIZE DISTRIBUTIONS FOR REFRACTORY MANUFACTURING: CHROMITE-MAGNESITE ORE DRYING AND FIRING[a]

Diameter (μm)	Filterable PM[b]	Hexavalent Chromium[c]	Total Chromium[c]
	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter
Uncontrolled rotary dryer (SCC 3-05-005-01)			
1	1.2	3.5	0.8
2	13	39	9
10	24	64	19
Uncontrolled tunnel kiln (SCC 3-05-005-07)			
1	71	71	84
5	78	81	91
10	84	84	93

[a] Reference 6. For filterable PM only. SCC = Source Classification Code.
[b] EMISSION FACTOR RATING: D.
[c] EMISSION FACTOR RATING: E.

or separated during the handling and forming of the fiber blankets in the curing oven. An oil is used in this process, and higher molecular weight organics may be emitted. However, these emissions generally are controlled with a fabric filter followed by incineration, at an expected overall efficiency in excess of 95 percent.

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11.6 Portland Cement Manufacturing

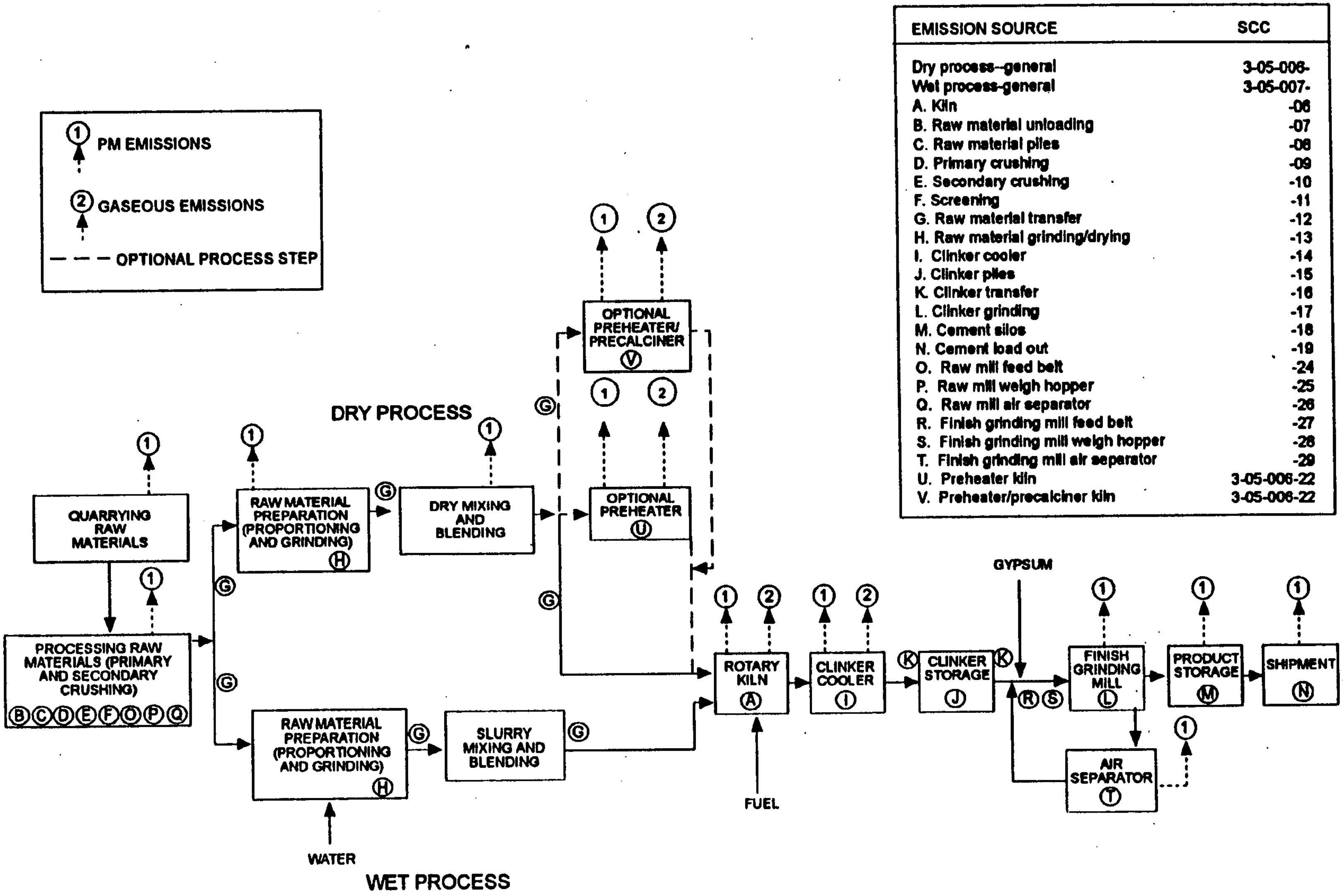
11.6.1 Process Description[1-7]

Portland cement is a fine powder, gray or white in color, that consists of a mixture of hydraulic cement materials comprising primarily calcium silicates, aluminates and aluminoferrites. More than 30 raw materials are known to be used in the manufacture of portland cement, and these materials can be divided into four distinct categories: calcareous, siliceous, argillaceous, and ferrifrous. These materials are chemically combined through pyroprocessing and subjected to subsequent mechanical processing operations to form gray and white portland cement. Gray portland cement is used for structural applications and is the more common type of cement produced. White portland cement has lower iron and manganese contents than gray portland cement and is used primarily for decorative purposes. Portland cement manufacturing plants are part of hydraulic cement manufacturing, which also includes natural, masonry, and pozzolanic cement. The six-digit Source Classification Code (SCC) for portland cement plants with wet process kilns is 3-05-006, and the six-digit SCC for plants with dry process kilns is 3-05-007.

Portland cement accounts for 95 percent of the hydraulic cement production in the United States. The balance of domestic cement production is primarily masonry cement. Both of these materials are produced in portland cement manufacturing plants. A diagram of the process, which encompasses production of both portland and masonry cement, is shown in Figure 11.6-1. As shown in the figure, the process can be divided into the following primary components: raw materials acquisition and handling, kiln feed preparation, pyroprocessing, and finished cement grinding. Each of these process components is described briefly below. The primary focus of this discussion is on pyroprocessing operations, which constitute the core of a portland cement plant.

The initial production step in portland cement manufacturing is raw materials acquisition. Calcium, the element of highest concentration in portland cement, is obtained from a variety of calcareous raw materials, including limestone, chalk, marl, sea shells, aragonite, and an impure limestone known as "natural cement rock". Typically, these raw materials are obtained from open-face quarries, but underground mines or dredging operations are also used. Raw materials vary from facility to facility. Some quarries produce relatively pure limestone that requires the use of additional raw materials to provide the correct chemical blend in the raw mix. In other quarries, all or part of the noncalcarious constituents are found naturally in the limestone. Occasionally, pockets of pyrite, which can significantly increase emissions of sulfur dioxide (SO_2), are found in deposits of limestone, clays, and shales used as raw materials for portland cement. Because a large fraction (approximately one third) of the mass of this primary material is lost as carbon dioxide (CO_2) in the kiln, portland cement plants are located close to a calcareous raw material source whenever possible. Other elements included in the raw mix are silicon, aluminum, and iron. These materials are obtained from ores and minerals such as sand, shale, clay, and iron ore. Again, these materials are most commonly from open-pit quarries or mines, but they may be dredged or excavated from underwater deposits.

Either gypsum or natural anhydrite, both of which are forms of calcium sulfate, is introduced to the process during the finish grinding operations described below. These materials, also excavated from quarries or mines, are generally purchased from an external source, rather than obtained directly from a captive operation by the cement plant. The portland cement manufacturing industry is relying increasingly on replacing virgin materials with waste materials or byproducts from other manufacturing operations, to the extent that such replacement can be implemented without adversely



EMISSION SOURCE	SCC
Dry process--general	3-05-006-
Wet process-general	3-05-007-
A. Kiln	-06
B. Raw material unloading	-07
C. Raw material piles	-08
D. Primary crushing	-09
E. Secondary crushing	-10
F. Screening	-11
G. Raw material transfer	-12
H. Raw material grinding/drying	-13
I. Clinker cooler	-14
J. Clinker piles	-15
K. Clinker transfer	-16
L. Clinker grinding	-17
M. Cement silos	-18
N. Cement load out	-19
O. Raw mill feed belt	-24
P. Raw mill weigh hopper	-25
Q. Raw mill air separator	-26
R. Finish grinding mill feed belt	-27
S. Finish grinding mill weigh hopper	-28
T. Finish grinding mill air separator	-29
U. Preheater kiln	3-05-006-22
V. Preheater/precalciner kiln	3-05-006-22

Figure 11.6-1. Process flow diagram for portland cement manufacturing. (SCC = Source Classification Code.)

affecting plant operations, product quality or the environment. Materials that have been used include fly ash, mill scale, and metal smelting slags.

The second step in portland cement manufacture is preparing the raw mix, or kiln feed, for the pyroprocessing operation. Raw material preparation includes a variety of blending and sizing operations that are designed to provide a feed with appropriate chemical and physical properties. The raw material processing operations differ somewhat for wet and dry processes, as described below.

Cement raw materials are received with an initial moisture content varying from 1 to more than 50 percent. If the facility uses dry process kilns, this moisture is usually reduced to less than 1 percent before or during grinding. Drying alone can be accomplished in impact dryers, drum dryers, paddle-equipped rapid dryers, air separators, or autogenous mills. However, drying can also be accomplished during grinding in ball-and-tube mills or roller mills. While thermal energy for drying can be supplied by exhaust gases from separate, direct-fired coal, oil, or gas burners, the most efficient and widely used source of heat for drying is the hot exit gases from the pyroprocessing system.

Materials transport associated with dry raw milling systems can be accomplished by a variety of mechanisms, including screw conveyors, belt conveyors, drag conveyors, bucket elevators, air slide conveyors, and pneumatic conveying systems. The dry raw mix is pneumatically blended and stored in specially constructed silos until it is fed to the pyroprocessing system.

In the wet process, water is added to the raw mill during the grinding of the raw materials in ball or tube mills, thereby producing a pumpable slurry, or slip, of approximately 65 percent solids. The slurry is agitated, blended, and stored in various kinds and sizes of cylindrical tanks or slurry basins until it is fed to the pyroprocessing system.

The heart of the portland cement manufacturing process is the pyroprocessing system. This system transforms the raw mix into clinkers, which are gray, glass-hard, spherically shaped nodules that range from 0.32 to 5.1 centimeters (cm) (0.125 to 2.0 inches [in.]) in diameter. The chemical reactions and physical processes that constitute the transformation are quite complex, but they can be viewed conceptually as the following sequential events:

1. Evaporation of free water;
2. Evolution of combined water in the argillaceous components;
3. Calcination of the calcium carbonate ($CaCO_3$) to calcium oxide (CaO);
4. Reaction of CaO with silica to form dicalcium silicate;
5. Reaction of CaO with the aluminum and iron-bearing constituents to form the liquid phase;
6. Formation of the clinker nodules;
7. Evaporation of volatile constituents (e. g., sodium, potassium, chlorides, and sulfates); and
8. Reaction of excess CaO with dicalcium silicate to form tricalcium silicate.

This sequence of events may be conveniently divided into four stages, as a function of location and temperature of the materials in the rotary kiln.

1. Evaporation of uncombined water from raw materials, as material temperature increases to 100°C (212°F);
2. Dehydration, as the material temperature increases from 100°C to approximately 430°C (800°F) to form oxides of silicon, aluminum, and iron;
3. Calcination, during which carbon dioxide (CO_2) is evolved, between 900°C (1650°F) and 982°C (1800°F), to form CaO; and
4. Reaction, of the oxides in the burning zone of the rotary kiln, to form cement clinker at temperatures of approximately 1510°C (2750°F).

Rotary kilns are long, cylindrical, slightly inclined furnaces that are lined with refractory to protect the steel shell and retain heat within the kiln. The raw material mix enters the kiln at the elevated end, and the combustion fuels generally are introduced into the lower end of the kiln in a countercurrent manner. The materials are continuously and slowly moved to the lower end by rotation of the kiln. As they move down the kiln, the raw materials are changed to cementitious or hydraulic minerals as a result of the increasing temperature within the kiln. The most commonly used kiln fuels are coal, natural gas, and occasionally oil. The use of supplemental fuels such as waste solvents, scrap rubber, and petroleum coke has expanded in recent years.

Five different processes are used in the portland cement industry to accomplish the pyroprocessing step: the wet process, the dry process (long dry process), the semidry process, the dry process with a preheater, and the dry process with a preheater/precalciner. Each of these processes accomplishes the physical/chemical steps defined above. However, the processes vary with respect to equipment design, method of operation, and fuel consumption. Generally, fuel consumption decreases in the order of the processes listed. The paragraphs below briefly describe the process, starting with the wet process and then noting differences in the other processes.

In the wet process and long dry process, all of the pyroprocessing activity occurs in the rotary kiln. Depending on the process type, kilns have length-to-diameter ratios in the range of 15:1 to 40:1. While some wet process kilns may be as long as 210 m (700 ft), many wet process kilns and all dry process kilns are shorter. Wet process and long dry process pyroprocessing systems consist solely of the simple rotary kiln. Usually, a system of chains is provided at the feed end of the kiln in the drying or preheat zones to improve heat transfer from the hot gases to the solid materials. As the kiln rotates, the chains are raised and exposed to the hot gases. Further kiln rotation causes the hot chains to fall into the cooler materials at the bottom of the kiln, thereby transferring the heat to the load.

Dry process pyroprocessing systems have been improved in thermal efficiency and productive capacity through the addition of one or more cyclone-type preheater vessels in the gas stream exiting the rotary kiln. This system is called the preheater process. The vessels are arranged vertically, in series, and are supported by a structure known as the preheater tower. Hot exhaust gases from the rotary kiln pass countercurrently through the downward-moving raw materials in the preheater vessels. Compared to the simple rotary kiln, the heat transfer rate is significantly increased, the degree of heat utilization is greater, and the process time is markedly reduced by the intimate contact of the solid particles with the hot gases. The improved heat transfer allows the length of the rotary kiln to be reduced. The hot gases from the preheater tower are often used as a source of heat for drying raw materials in the raw mill. Because the catch from the mechanical collectors, fabric filters, and/or electrostatic precipitators (ESP) that follow the raw mill is returned to the process, these devices are considered to be production machines as well as pollution control devices.

Additional thermal efficiencies and productivity gains have been achieved by diverting some fuel to a calciner vessel at the base of the preheater tower. This system is called the preheater/precalciner process. While a substantial amount of fuel is used in the precalciner, at least 40 percent of the thermal energy is required in the rotary kiln. The amount of fuel that is introduced to the calciner is determined by the availability and source of the oxygen for combustion in the calciner. Calciner systems sometimes use lower-quality fuels (e. g., less-volatile matter) as a means of improving process economics.

Preheater and precalciner kiln systems often have an alkali bypass system between the feed end of the rotary kiln and the preheater tower to remove the undesirable volatile constituents. Otherwise, the volatile constituents condense in the preheater tower and subsequently recirculate to the kiln. Buildup of these condensed materials can restrict process and gas flows. The alkali content of portland cement is often limited by product specifications because excessive alkali metals (i. e., sodium and potassium) can cause deleterious reactions in concrete. In a bypass system, a portion of the kiln exit gas stream is withdrawn and quickly cooled by air or water to condense the volatile constituents to fine particles. The solid particles, containing the undesirable volatile constituents, are removed from the gas stream and thus the process by fabric filters and ESPs.

The semidry process is a variation of the dry process. In the semidry process, the water is added to the dry raw mix in a pelletizer to form moist nodules or pellets. The pellets then are conveyed on a moving grate preheater before being fed to the rotary kiln. The pellets are dried and partially calcined by hot kiln exhaust gases passing through the moving grate.

Regardless of the type of pyroprocess used, the last component of the pyroprocessing system is the clinker cooler. This process step recoups up to 30 percent of the heat input to the kiln system, locks in desirable product qualities by freezing mineralogy, and makes it possible to handle the cooled clinker with conventional conveying equipment. The more common types of clinker coolers are (1) reciprocating grate, (2) planetary, and (3) rotary. In these coolers, the clinker is cooled from about 1100°C to 93°C (2000°F to 200°F) by ambient air that passes through the clinker and into the rotary kiln for use as combustion air. However, in the reciprocating grate cooler, lower clinker discharge temperatures are achieved by passing an additional quantity of air through the clinker. Because this additional air cannot be utilized in the kiln for efficient combustion, it is vented to the atmosphere, used for drying coal or raw materials, or used as a combustion air source for the precalciner.

The final step in portland cement manufacturing involves a sequence of blending and grinding operations that transforms clinker to finished portland cement. Up to 5 percent gypsum or natural anhydrite is added to the clinker during grinding to control the cement setting time, and other specialty chemicals are added as needed to impart specific product properties. This finish milling is accomplished almost exclusively in ball or tube mills. Typically, finishing is conducted in a closed-circuit system, with product sizing by air separation.

11.6.2 Emissions And Controls[1,3-7]

Particulate matter (PM and PM-10), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and CO_2 are the primary emissions in the manufacture of portland cement. Small quantities of volatile organic compounds (VOC), ammonia (NH_3), chlorine, and hydrogen chloride

(HCl), also may be emitted. Emissions may also include residual materials from the fuel and raw materials or products of incomplete combustion that are considered to be hazardous. Because some facilities burn waste fuels, particularly spent solvents in the kiln, these systems also may emit small quantities of additional hazardous organic pollutants. Also, raw material feeds and fuels typically contain trace amounts of heavy metals that may be emitted as a particulate or vapor.

Sources of PM at cement plants include (1) quarrying and crushing, (2) raw material storage, (3) grinding and blending (in the dry process only), (4) clinker production, (5) finish grinding, and (6) packaging and loading. The largest emission source of PM within cement plants is the pyroprocessing system that includes the kiln and clinker cooler exhaust stacks. Often, dust from the kiln is collected and recycled into the kiln, thereby producing clinker from the dust. However, if the alkali content of the raw materials is too high, some or all of the dust is discarded or leached before being returned to the kiln. In many instances, the maximum allowable cement alkali content of 0.6 percent (calculated as sodium oxide) restricts the amount of dust that can be recycled. Bypass systems sometimes have a separate exhaust stack. Additional sources of PM are raw material storage piles, conveyors, storage silos, and unloading facilities. Emissions from portland cement plants constructed or modified after August 17, 1971 are regulated to limit PM emissions from portland cement kilns to 0.15 kg/Mg (0.30 lb/ton) of feed (dry basis), and to limit PM emissions from clinker coolers to 0.050 kg/Mg (0.10 lb/ton) of feed (dry basis).

Oxides of nitrogen are generated during fuel combustion by oxidation of chemically-bound nitrogen in the fuel and by thermal fixation of nitrogen in the combustion air. As flame temperature increases, the amount of thermally generated NO_x increases. The amount of NO_x generated from fuel increases with the quantity of nitrogen in the fuel. In the cement manufacturing process, NO_x is generated in both the burning zone of the kiln and the burning zone of a precalcining vessel. Fuel use affects the quantity and type of NO_x generated. For example, in the kiln, natural gas combustion with a high flame temperature and low fuel nitrogen generates a larger quantity of NO_x than does oil or coal, which have higher fuel nitrogen but which burn with lower flame temperatures. The opposite may be true in a precalciner. Types of fuels used vary across the industry. Historically, some combination of coal, oil, and natural gas was used, but over the last 15 years, most plants have switched to coal, which generates less NO_x than does oil or gas. However, in recent years a number of plants have switched to systems that burn a combination of coal and waste fuel. The effect of waste fuel use on NO_x emissions is not clearly established.

Sulfur dioxide may be generated both from the sulfur compounds in the raw materials and from sulfur in the fuel. The sulfur content of both raw materials and fuels varies from plant to plant and with geographic location. However, the alkaline nature of the cement provides for direct absorption of SO_2 into the product, thereby mitigating the quantity of SO_2 emissions in the exhaust stream. Depending on the process and the source of the sulfur, SO_2 absorption ranges from about 70 percent to more than 95 percent.

The CO_2 emissions from portland cement manufacturing are generated by two mechanisms. As with most high-temperature, energy-intensive industrial processes, combusting fuels to generate process energy releases substantial quantities of CO_2. Substantial quantities of CO_2 also are generated through calcining of limestone or other calcareous material. This calcining process thermally decomposes $CaCO_3$ to CaO and CO_2. Typically, portland cement contains the equivalent of about 63.5 percent CaO. Consequently, about 1.135 units of $CaCO_3$ are required to produce 1 unit of cement, and the amount of CO_2 released in the calcining process is about 500 kilograms (kg) per Mg of portland cement produced (1,000 pounds [lb] per ton of cement). Total CO_2 emissions from the pyroprocess depend on energy consumption and generally fall in the range of 0.85 to 1.35 Mg of CO_2 per Mg of clinker.

In addition to CO_2 emissions, fuel combustion at portland cement plants can emit a wide range of pollutants in smaller quantities. If the combustion reactions do not reach completion, CO and volatile organic pollutants, typically measured as total organic compounds (TOC), VOC, or organic condensable particulate, can be emitted. Incomplete combustion also can lead to emissions of specific hazardous organic air pollutants, although these pollutants are generally emitted at substantially lower levels than CO or TOC.

Emissions of metal compounds from portland cement kilns can be grouped into three general classes: volatile metals, including mercury (Hg) and thallium (Tl); semivolatile metals, including antimony (Sb), cadmium (Cd), lead (Pb), selenium (Se), zinc (Zn), potassium (K), and sodium (Na); and refractory or nonvolatile metals, including barium (Ba), chromium (Cr), arsenic (As), nickel (Ni), vanadium (V), manganese (Mn), copper (Cu), and silver (Ag). Although the partitioning of these metal groups is affected by kiln operating conditions, the refractory metals tend to concentrate in the clinker, while the volatile and semivolatile metals tend to be discharged through the primary exhaust stack and the bypass stack, respectively.

Fugitive dust sources in the industry include quarrying and mining operations, vehicle traffic during mineral extraction and at the manufacturing site, raw materials storage piles, and clinker storage piles. The measures used to control emissions from these fugitive dust sources are comparable to those used throughout the mineral products industries. Vehicle traffic controls include paving and road wetting. Controls that are applied to other open dust sources include water sprays with and without surfactants, chemical dust suppressants, wind screens, and process modifications to reduce drop heights or enclose storage operations. Additional information on these control measures can be found in Chapter 13 of AP-42, "Miscellaneous Sources".

Process fugitive emission sources include materials handling and transfer, raw milling operations in dry process facilities, and finish milling operations. Typically, emissions from these processes are captured by a ventilation system and collected in fabric filters. Some facilities use an air pollution control system comprising one or more mechanical collectors with a fabric filter in series. Because the dust from these units is returned to the process, they are considered to be process units as well as air pollution control devices. The industry uses shaker, reverse air, and pulse jet filters as well as some cartridge units, but most newer facilities use pulse jet filters. For process fugitive operations, the different systems are reported to achieve typical outlet PM loadings of 45 milligrams per cubic meter (mg/m^3) (0.02 grains per actual cubic foot [gr/acf]).

In the pyroprocessing units, PM emissions are controlled by fabric filters (reverse air, pulse jet, or pulse plenum) and electrostatic precipitators (ESP). Typical control measures for the kiln exhaust are reverse air fabric filters with an air-to-cloth ratio of 0.41:1 $m^3/min/m^2$ (1.5:1 $acfm/ft^2$) and ESP with a net surface collection area of 1,140 to 1,620 $m^2/1,000\ m^3$ (350 to 500 $ft^2/1,000\ ft^3$). These systems are reported to achieve outlet PM loadings of 45 mg/m^3 (0.02 gr/acf). Clinker cooler systems are controlled most frequently with pulse jet or pulse plenum fabric filters. A few gravel bed filters also have been used to control clinker cooler emissions. Typical outlet PM loadings are identical to those reported for kilns.

Cement kiln systems have highly alkaline internal environments that can absorb up to 95 percent of potential SO_2 emissions. However, in systems that have sulfide sulfur (pyrites) in the kiln feed, the sulfur absorption rate may be as low as 70 percent without unique design considerations or changes in raw materials. The cement kiln system itself has been determined to provide substantial SO_2 control. Fabric filters on cement kilns are also reported to absorb SO_2. Generally, substantial control is not achieved. An absorbing reagent (e. g., CaO) must be present in the filter cake for SO_2 capture to occur. Without the presence of water, which is undesirable in the operation of a fabric filter, $CaCO_3$ is not an absorbing reagent. It has been observed that as much as 50 percent of the SO_2 can be removed from the pyroprocessing system exhaust gases when this gas stream is used in a raw mill for heat recovery and drying. In this case, moisture and calcium carbonate are simultaneously present for sufficient time to accomplish the chemical reaction with SO_2.

Tables 11.6-1 and 11.6-2 present emission factors for PM emissions from portland cement manufacturing kilns and clinker coolers. Tables 11.6-3 and 11.6-4 present emission factors for PM emissions from raw material and product processing and handling. Particle size distributions for emissions from wet process and dry process kilns are presented in Table 11.6-5, and Table 11.6-6 presents the particle size distributions for emissions from clinker coolers. Emission factors for SO_2, NO_x, CO, CO_2, and TOC emissions from portland cement kilns are summarized in Tables 11.6-7 and 11.6-8. Table 11.6-9 summarizes emission factors for other pollutant emissions from portland cement kilns.

Because of differences in the sulfur content of the raw material and fuel and in process operations, a mass balance for sulfur may yield a more representative emission factor for a specific facility than the SO_2 emission factors presented in Tables 11.6-7 and 11.6-8. In addition, CO_2 emission factors estimated using a mass balance on carbon may be more representative for a specific facility than the CO_2 emission factors presented in Tables 11.6-7 and 11.6-8.

Table 11.6-1 (Metric Units). EMISSION FACTORS FOR PORTLAND CEMENT MANUFACTURING KILNS AND CLINKER COOLERS[a]

	Filterable[b]				Condensable[c]			
Process	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Wet process kiln (SCC 3-05-007-06)	65[d]	D	16[e]	D	ND		ND	
Wet process kiln with ESP (SCC 3-05-007-06)	0.38[f]	C	0.33[g]	D	0.076[h]	D	ND	
Wet process kiln with fabric filter (SCC 3-05-007-06)	0.23[j]	E	ND		0.10[j]	E	ND	
Wet process kiln with cooling tower, multiclone, and ESP (SCC 3-05-007-06)	0.10[k]	E	ND		0.14[k]	E	ND	
Dry process kiln with ESP (SCC 3-05-006-06)	0.50[m]	D	ND		0.19[m]	D	ND	
Dry process kiln with fabric filter (SCC 3-05-006-06)	0.10[n]	D	0.084[p]	D	0.45[n]	D	ND	
Preheater kiln (SCC 3-05-006-22)	130[q]	D	ND		ND		ND	
Preheater kiln with ESP (SCC 3-05-006-22)	0.13[r]	D	ND		ND		ND	
Preheater kiln with fabric filter (SCC 3-05-006-22)	0.13[s]	C	ND		0.017[t]	D	ND	
Preheater/precalciner kiln with ESP (SCC 3-05-006-23)	0.024[u]	D	ND		ND		ND	
Preheater/precalciner process kiln with fabric filter (SCC 3-05-006-23)	0.10[v]	D	ND		ND		ND	
Preheater/precalciner process kiln with PM controls (SCC 3-05-006-23)	ND		ND		0.078[w]	D	ND	

Table 11.6-1 (cont.).

Process	Filterable[b]				Condensable[c]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Clinker cooler with ESP (SCC 3-05-006-14)	0.048[x]	D	ND		0.0038[x]	D	ND	
Clinker cooker with fabric filter (SCC 3-05-006-14)	0.068[y]	D	ND		0.0084[z]	D	ND	
Clinker cooler with gravel bed filter (SCC 3-05-006-14)	0.11[aa]	D	0.084[bb]	D	0.0045[cc]	D	ND	

[a] Factors represent uncontrolled emissions unless, otherwise noted. Factors are kg/Mg of clinker produced, unless noted. SCC = Source Classification Code. ND = no data. ESP = electrostatic precipitator.

[b] Filterable PM is that collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that collected in the impinger portion of a PM sampling train.

[d] References 20,26.

[e] References 3,20,26.

[f] References 8-9,18,20,25-26,32,34-36,41-44,60,64.

[g] References 3,8-9,18,20,25-26,32,34-36,41-44,60,64.

[h] References 8-9,20,64.

[j] Reference 14.

[k] Reference 21.

[m] References 19,21.

[n] Reference 23.

[p] References 3,23.

[q] Reference 17.

[r] Reference 31.

[s] References 17,47-50,61.

[t] Reference 51.

[u] Reference 37.

[v] References 30,33,51,56-59,63

[w] References 30,33,37,51,59.

[x] Reference 8.

[y] References 9,12,27,30,33.

[z] References 9,12,30.

[aa] References 22,29,31

[bb] References 3,22,29,31

[cc] References 22,29

Table 11.6-2 (English Units). EMISSION FACTORS FOR PORTLAND CEMENT MANUFACTURING KILNS AND CLINKER COOLERS[a]

Process	Filterable[b]				Condensable[c]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Wet process kiln (SCC 3-05-007-06)	130[d]	D	31[e]	D	ND		ND	
Wet process kiln with ESP (SCC 3-05-007-06)	0.77[f]	C	0.65[g]	D	0.15[h]	D	ND	
Wet process kiln with fabric filter (SCC 3-05-007-06)	0.46[j]	E	ND		0.20[j]	E	ND	
Wet process kiln with cooling tower, multiclone, and ESP (SCC 3-05-007-06)	0.20[k]	E	ND		0.29[k]	E	ND	
Dry process kiln with ESP (SCC 3-05-006-06)	1.0[m]	D	ND		0.38[m]	D	ND	
Dry process kiln with fabric filter (SCC 3-05-006-06)	0.20[n]	D	0.17[p]	D	0.89[n]	D	ND	
Preheater kiln (SCC 3-05-006-22)	250[q]	D	ND		ND		ND	
Preheater kiln with ESP (SCC 3-05-006-22)	0.26[r]	D	ND		ND		ND	
Preheater kiln with fabric filter (SCC 3-05-006-22)	0.25[s]	C	ND		0.033[t]	D	ND	
Preheater/precalciner kiln with ESP (SCC 3-05-006-23)	0.048[u]	D	ND		ND		ND	
Preheater/precalciner process kiln with fabric filter (SCC 3-05-006-23)	0.21[v]	D	ND		ND		ND	
Preheater/precalciner process kiln with PM controls (SCC 3-05-006-23)	ND		ND		0.16[w]	D	ND	

Table 11.6-2 (cont.).

	Filterable[b]				Condensable[c]			
Process	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Clinker cooler with ESP (SCC 3-05-006-14)	0.096[x]	D	ND		0.0075[x]	D	ND	
Clinker cooker with fabric filter (SCC 3-05-006-14)	0.13[y]	D	ND		0.017[z]	D	ND	
Clinker cooler with gravel bed filter (SCC 3-05-006-14)	0.21[aa]	D	0.16[bb]	D	0.0090[cc]	D	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of clinker produced unless noted. SCC = Source Classification Code. ND = no data. ESP = electrostatic precipitator.

[b] Filterable PM is that collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that collected in the impinger portion of a PM sampling train.

[d] References 20,26.

[e] References 3,20,26.

[f] References 8-9,18,20,25-26,32,34-36,41-44,60,64.

[g] References 3,8-9,18,20,25-26,32,34-36,41-44,60,64.

[h] References 8-9,20,64.

[j] Reference 14.

[k] Reference 21.

[m] References 19,21.

[n] Reference 23.

[p] References 3,23.

[q] Reference 17.

[r] Reference 31.

[s] References 17,47-50,61.

[t] Reference 51.

[u] Reference 37.

[v] References 30,33,51,56-59,63

[w] References 30,33,37,51,59.

[x] Reference 8.

[y] References 9,12,27,30,33.

[z] References 9,12,30.

[aa] References 22,29,31

[bb] References 3,22,29,31

[cc] References 22,29

Table 11.6-3 (Metric Units). EMISSION FACTORS FOR PORTLAND CEMENT MANUFACTURING RAW MATERIAL AND PRODUCT PROCESSING AND HANDLING[a]

Process	Filterable[b]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Raw mill with fabric filter (SCC 3-05-006-13)	0.0062[c]	D	ND	
Raw mill feed belt with fabric filter (SCC 3-05-006-24)	0.0016[d]	E	ND	
Raw mill weigh hopper with fabric filter (SCC 3-05-006-25)	0.010[e]	E	ND	
Raw mill air separator with fabric filter (SCC 3-05-006-26)	0.016[e]	E	ND	
Finish grinding mill with fabric filter (SCC 3-05-006-17, 3-05-007-17)	0.0042[f]	D	ND	
Finish grinding mill feed belt with fabric filter (SCC 3-05-006-27, 3-05-007-27)	0.0012[d]	E	ND	
Finish grinding mill weigh hopper with fabric filter (SCC 3-05-006-28, 3-05-007-28)	0.0047[e]	E	ND	
Finish grinding mill air separator with fabric filter (SCC 3-05-006-29, 3-05-007-29)	0.014[g]	D	ND	
Primary limestone crushing with fabric filter (SCC 3-05-006-09)[h]	0.00050	E	ND	
Primary limestone screening with fabric filter (SCC 3-05-006-11)[h]	0.00011	E	ND	
Limestone transfer with fabric filter (SCC 3-05-006-12)[h]	1.5 x 10^{-5}	E	ND	
Secondary limestone screening and crushing with fabric filter (SCC 3-05-006-10 + -11, 3-05-007-10 + -11)[h]	0.00016	E	ND	

[a] Factors represent uncontrolled emissions, unless otherwise noted. Factors are kg/Mg of material process, unless noted. SCC = Source Classification Code. ND = no data.

4[b] Filterable PM is that collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] References 15,56-57.

[d] Reference 57.

[e] Reference 15.

[f] References 10,12,15,56-57.

[g] References 10,15.

[h] Reference 16. Alternatively, emission factors from Section 11.19.2, "Crushed Stone Processing", can be used for similar processes and equipment.

Table 11.6-4 (English Units). EMISSION FACTORS FOR PORTLAND CEMENT MANUFACTURING RAW MATERIAL AND PRODUCT PROCESSING AND HANDLING[a]

	Filterable[b]			
Process	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Raw mill with fabric filter (SCC 3-05-006-13)	0.012[c]	D	ND	
Raw mill feed belt with fabric filter (SCC 3-05-006-24)	0.0031[d]	E	ND	
Raw mill weigh hopper with fabric filter (SCC 3-05-006-25)	0.019[e]	E	ND	
Raw mill air separator with fabric filter (SCC 3-05-006-26)	0.032[e]	E	ND	
Finish grinding mill with fabric filter (SCC 3-05-006-17, 3-05-007-17)	0.0080[f]	E	ND	
Finish grinding mill feed belt with fabric filter (SCC 3-05-006-27, 3-05-007-27)	0.0024[d]	E	ND	
Finish grinding mill weigh hopper with fabric filter (SCC 3-05-006-28, 3-05-007-28)	0.0094[e]	E	ND	
Finish grinding mill air separator with fabric filter (SCC 3-05-006-29, 3-05-007-29)	0.028[g]	D	ND	
Primary limestone crushing with fabric filter (SCC 3-05-006-09)[h]	0.0010	E	ND	
Primary limestone screening with fabric filter (SCC 3-05-006-11)[h]	0.00022	E	ND	
Limestone transfer with fabric filter (SCC 3-05-006-12)[h]	2.9×10^{-5}	E	ND	
Secondary limestone screening and crushing with fabric filter (SCC 3-05-006-10 + -11, 3-05-007-10 + -11)[h]	0.00031	E	ND	

[a] Factors represent uncontrolled emissions, unless otherwise noted. Factors are lb/ton of material processed, unless noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] References 15,56-57.

[d] Reference 57.

[e] Reference 15.

[f] References 10,12,15,56-57.

[g] References 10,15.

[h] Reference 16. Alternatively, emission factors from the Section 11.19.2, "Crushed Stone Processing", can be used for similar processes and equipment.

Table 11.6-5. SUMMARY OF AVERAGE PARTICLE SIZE DISTRIBUTION FOR PORTLAND CEMENT KILNS[a]

Particle Size, μm	Cumulative Mass Percent Equal To Or Less Than Stated Size			
	Uncontrolled		Controlled	
	Wet process (SCC 3-05-007-06)	Dry process (SCC 3-05-006-06)	Wet process With ESP (SCC 3-05-007-06)	Dry process With FF (SCC 3-05-006-06)
2.5	7	18	64	45
5.0	20	ND	83	77
10.0	24	42	85	84
15.0	35	44	91	89
20.0	57	ND	98	100

[a] Reference 3. SCC = Source Classification Code. ND = no data.

Table 11.6-6. SUMMARY OF AVERAGE PARTICLE SIZE DISTRIBUTION FOR PORTLAND CEMENT CLINKER COOLERS[a]

Particle Size, μm	Cumulative Mass Percent Equal To Or Less Than Stated Size	
	Uncontrolled (SCC 3-05-006-14, 3-05-007-14)	With Gravel Bed Filter (SCC 3-05-006-14, 3-05-007-14)
2.5	0.54	40
5.0	1.5	64
10.0	8.6	76
15.0	21	84
20.0	34	89

[a] Reference 3. SCC = Source Classification Code.

Table 11.6-7 (Metric Units). EMISSION FACTORS FOR PORTLAND CEMENT MANUFACTURING[a]

Process	SO_2[b]	EMISSION FACTOR RATING	NO_x	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING	CO_2[c]	EMISSION FACTOR RATING	TOC	EMISSION FACTOR RATING
Wet process kiln (SCC 3-05-007-06)	4.1[d]	C	3.7[e]	D	0.060[f]	D	1,100[g]	D	0.014[f]	D
Long dry process kiln (SCC 3-05-006-06)	4.9[h]	D	3.0[j]	D	0.11[k]	E	900[m]	D	0.014[n]	E
Preheater process kiln (SCC 3-05-006-22)	0.27[p]	D	2.4[q]	D	0.49[r]	D	900[s]	C	0.090[t]	D
Preheater/precalciner kiln (SCC 3-05-006-23)	0.54[u]	D	2.1[v]	D	1.8[w]	D	900[x]	E	0.059[y]	D
Preheater/precalciner kiln with spray tower (SCC 3-05-006-23)	0.50[z]	E	ND		ND		ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are kg/Mg of clinker produced, unless noted. SCC = Source Classification Code. ND = no data.

[b] Mass balance on sulfur may yield a more representative emission factor for a specific facility than the SO_2 emission factors presented in this table.

[c] Mass balance on carbon may yield a more representative emission factor for a specific facility than the CO_2 emission factors presented in this table.

[d] References 20,25-26,32,34-36,41-44,60,64.

[e] References 26,34-36,43,64.

[f] Reference 64.

[g] References 25-26,32,34-36,44,60,64.

[h] References 11,19,39,40.

[j] References 11,38-40,65.

[k] References 39,65.

[m] References 11,21,23,65.

[n] References 40,65. TOC as measured by Method 25A or equivalent.

[p] References 47-50.

[q] References 48-50.

[r] Reference 49.

[s] References 24,31,47-50,61.

Table 11.6-7 (cont.).

[t] Reference 49; total organic compounds as measured by Method 25A or equivalent.
[u] References 28,30,33,37,53,56-59.
[v] References 28,30,33,37,45,56-59.
[w] References 28,30,37,56-58,63.
[x] References 24,31,47-50,61. Based on test data for preheater kilns; should be considered an upper limit.
[y] References 30,33,56,63; total organic compounds as measured using Method 25A or equivalent.
[z] Reference 54.

Table 11.6-8 (English Units). EMISSION FACTORS FOR PORTLAND CEMENT MANUFACTURING[a]

Process	SO_2[b]	EMISSION FACTOR RATING	NO_x	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING	CO_2[c]	EMISSION FACTOR RATING	TOC	EMISSION FACTOR RATING
Wet process kiln (SCC 3-05-007-06)	8.2[d]	C	7.4[e]	D	0.12[f]	D	2,100[g]	D	0.028[f]	D
Long dry process kiln (SCC 3-05-006-06)	10[h]	D	6.0[j]	D	0.21[k]	E	1,800[m]	D	0.028[n]	E
Preheater process kiln (SCC 3-05-006-22)	0.55[p]	D	4.8[q]	D	0.98[r]	D	1,800[s]	C	0.18[t]	D
Preheater/precalciner kiln (SCC 3-05-006-23)	1.1[u]	D	4.2[v]	D	3.7[w]	D	1,800[x]	E	0.12[y]	D
Preheater/precalciner kiln with spray tower (SCC 3-05-006-23)	1.0[z]	E	ND		ND		ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of clinker produced, unless noted. SCC = Source Classification Code. ND = no data.

[b] Mass balance on sulfur may yield a more representative emission factor for a specific facility than the SO_2 emission factors presented in this table.

[c] Mass balance on carbon may yield a more representative emission factor for a specific facility than the CO_2 emission factors presented in this table.

[d] References 20,25-26,32,34-36,41-44,60,64.

[e] References 26,34-36,43,64.

[f] Reference 64.

[g] References 25-26,32,34-36,44,60,64.

[h] References 11,19,39-40.

[j] References 11,38-40,65.

[k] References 39,65.

[m] References 11,21,23,65.

[n] References 40,65. TOC as measured by Method 25A or equivalent.

[p] References 47-50.

[q] References 48-50.

[r] Reference 49.

[s] References 24,31,47-50,61.

[t] Reference 49; total organic compounds as measured by Method 25A or equivalent.

Table 11.6-8 (cont.).

[u] References 28,30,33,37,53,56-59.
[v] References 28,30,33,37,45, and 56 to 59.
[w] References 28,30,37,56-58,63.
[x] References 24,31,47-50,61. Based on test data for preheater kilns; should be considered an upper limit.
[y] References 30,33,56,63; total organic compounds as measured using Method 25A or equivalent.
[z] Reference 54.

Table 11.6-9 (Metric And English Units). SUMMARY OF NONCRITERIA POLLUTANT EMISSION FACTORS FOR PORTLAND CEMENT KILNS[a]

(SCC 3-05-006-06, 3-05-007-06, 3-05-006-22, 3-05-006-23)

Pollutant Name	Type Of Control	Average Emission Factor		EMISSION FACTOR RATING	References
		kg/Mg	lb/ton		
Inorganic Pollutants					
Silver (Ag)	FF	3.1×10^{-7}	6.1×10^{-7}	D	63
Aluminum (Al)	ESP	0.0065	0.013	E	65
Arsenic (As)	ESP	6.5×10^{-6}	1.3×10^{-5}	E	65
Arsenic (As)	FF	6.0×10^{-6}	1.2×10^{-5}	D	63
Barium (Ba)	ESP	0.00018	0.00035	D	64
Barium (Ba)	FF	0.00023	0.00046	D	63
Beryllium (Be)	FF	3.3×10^{-7}	6.6×10^{-7}	D	63
Calcium (Ca)	ESP	0.12	0.24	E	65
Cadmium (Cd)	ESP	4.2×10^{-6}	8.3×10^{-6}	D	64
Cadmium (Cd)	FF	1.1×10^{-6}	2.2×10^{-6}	D	63
Chloride (Cl)	ESP	0.34	0.68	E	25,42-44
Chloride (Cl)	FF	0.0011	0.0021	D	63
Chromium (Cr)	ESP	3.9×10^{-6}	7.7×10^{-6}	E	64
Chromium (Cr)	FF	7.0×10^{-5}	0.00014	D	63
Copper (Cu)	FF	0.0026	0.0053	E	62
Fluoride (F)	ESP	0.00045	0.00090	E	43
Iron (Fe)	ESP	0.0085	0.017	E	65
Hydrogen chloride (HCl)	ESP	0.025	0.049	E	41,65
Hydrogen chloride (HCl)	FF	0.073	0.14	D	59,63
Mercury (Hg)	ESP	0.00011	0.00022	D	64
Mercury (Hg)	FF	1.2×10^{-5}	2.4×10^{-5}	D	11,63
Potassium (K)	ESP	0.0090	0.018	D	25,42-43
Manganese (Mn)	ESP	0.00043	0.00086	E	65
Ammonia (NH_3)	FF	0.0051	0.010	E	59
Ammonium (NH_4)	ESP	0.054	0.11	D	25,42-44
Nitrate (NO_3)	ESP	0.0023	0.0046	E	43
Sodium (Na)	ESP	0.020	0.038	D	25,42-44
Lead (Pb)	ESP	0.00036	0.00071	D	64
Lead (Pb)	FF	3.8×10^{-5}	7.5×10^{-5}	D	63
Sulfur trioxide (SO_3)	ESP	0.042	0.086	E	25
Sulfur trioxide (SO_3)	FF	0.0073	0.014	D	24,30,50
Sulfate (SO_4)	ESP	0.10	0.20	D	25,42-44
Sulfate (SO_4)	FF	0.0036	0.0072	D	30,33,52

Table 11.6-9 (cont.).

Pollutant Name		Type Of Control	Average Emission Factor		EMISSION FACTOR RATING	References
			kg/Mg	lb/ton		
	Selenium (Se)	ESP	7.5x10^{-5}	0.00015	E	65
	Selenium (Se)	FF	0.00010	0.00020	E	62
	Thallium (Th)	FF	2.7x10^{-6}	5.4x10^{-6}	D	63
	Titanium (Ti)	ESP	0.00019	0.00037	E	65
	Zinc (Zn)	ESP	0.00027	0.00054	D	64
	Zinc (Zn)	FF	0.00017	0.00034	D	63
Organic Pollutants						
CASRN^{b}	Name					
35822-46-9	1,2,3,4,6,7,8 HpCDD	FF	1.1x10^{-10}	2.2x10^{-10}	E	62
	C3 benzenes	ESP	1.3x10^{-6}	2.6x10^{-6}	E	65
	C4 benzenes	ESP	3.0x10^{-6}	6.0x10^{-6}	E	65
	C6 benzenes	ESP	4.6x10^{-7}	9.2x10^{-7}	E	65
208-96-8	acenaphthylene	FF	5.9x10^{-5}	0.00012	E	62
67-64-1	acetone	ESP	0.00019	0.00037	D	64
100-52-7	benzaldehyde	ESP	1.2x10^{-5}	2.4x10^{-5}	E	65
71-43-2	benzene	ESP	0.0016	0.0031	D	64
71-43-2	benzene	FF	0.0080	0.016	E	62
	benzo(a)anthracene	FF	2.1x10^{-8}	4.3x10^{-8}	E	62
50-32-8	benzo(a)pyrene	FF	6.5x10^{-8}	1.3x10^{-7}	E	62
205-99-2	benzo(b)fluoranthene	FF	2.8x10^{-7}	5.6x10^{-7}	E	62
191-24-2	benzo(g,h,i)perylene	FF	3.9x10^{-8}	7.8x10^{-8}	E	62
207-08-9	benzo(k)fluoranthene	FF	7.7x10^{-8}	1.5x10^{-7}	E	62
65-85-0	benzoic acid	ESP	0.0018	0.0035	D	64
95-52-4	biphenyl	ESP	3.1x10^{-6}	6.1x10^{-6}	E	65
117-81-7	bis(2-ethylhexyl)phthalate	ESP	4.8x10^{-5}	9.5x10^{-5}	D	64
74-83-9	bromomethane	ESP	2.2x10^{-5}	4.3x10^{-5}	E	64
75-15-0	carbon disulfide	ESP	5.5x10^{-5}	0.00011	D	64
108-90-7	chlorobenzene	ESP	8.0x10^{-6}	1.6x10^{-5}	D	64
74-87-3	chloromethane	ESP	0.00019	0.00038	E	64
218-01-9	chrysene	FF	8.1x10^{-8}	1.6x10^{-7}	E	62
84-74-2	di-n-butylphthalate	ESP	2.1x10^{-5}	4.1x10^{-5}	D	64
53-70-3	dibenz(a,h)anthracene	FF	3.1x10^{-7}	6.3x10^{-7}	E	62
101-41-4	ethylbenzene	ESP	9.5x10^{-6}	1.9x10^{-5}	D	64
206-44-0	fluoranthene	FF	4.4x10^{-6}	8.8x10^{-6}	E	62
86-73-7	fluorene	FF	9.4x10^{-6}	1.9x10^{-5}	E	62
50-00-0	formaldehyde	FF	0.00023	0.00046	E	62

Table 11.6-9 (cont.).

Pollutant		Type Of Control	Average Emission Factor		EMISSION FACTOR RATING	References
CASRN[b]	Name		kg/Mg	lb/ton		
	freon 113	ESP	$2.5x10^{-5}$	$5.0x10^{-5}$	E	65
193-39-5	indeno(1,2,3-cd)pyrene	FF	$4.3x10^{-8}$	$8.7x10^{-8}$	E	62
78-93-3	methyl ethyl ketone	ESP	$1.5x10^{-5}$	$3.0x10^{-5}$	E	64-65
75-09-2	methylene chloride	ESP	0.00025	0.00049	E	65
	methylnaphthalene	ESP	$2.1x10^{-6}$	$4.2x10^{-6}$	E	65
91-20-3	naphthalene	FF	0.00085	0.0017	E	62
91-20-3	naphthalene	ESP	0.00011	0.00022	D	64
85-01-8	phenanthrene	FF	0.00020	0.00039	E	62
108-95-2	phenol	ESP	$5.5x10^{-5}$	0.00011	D	64
129-00-0	pyrene	FF	$2.2x10^{-6}$	$4.4x10^{-6}$	E	62
100-42-5	styrene	ESP	$7.5x10^{-7}$	$1.5x10^{-6}$	E	65
108-88-3	toluene	ESP	0.00010	0.00019	D	64
	total HpCDD	FF	$2.0x10^{-10}$	$3.9x10^{-10}$	E	62
3268-87-9	total OCDD	FF	$1.0x10^{-9}$	$2.0x10^{-9}$	E	62
	total PCDD	FF	$1.4x10^{-9}$	$2.7x10^{-9}$	E	62
132-64-9	total PCDF	FF	$1.4x10^{-10}$	$2.9x10^{-10}$	E	62
132-64-9	total TCDF	FF	$1.4x10^{-10}$	$2.9x10^{-10}$	E	62
1330-20-7	xylenes	ESP	$6.5x10^{-5}$	0.00013	D	64

[a] Factors are kg/Mg and lb/ton of clinker produced. SCC = Source Classification Code. ESP = electrostatic precipitator. FF = fabric filter.

[b] Chemical Abstract Service Registry Number (organic compounds only).

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11.7 Ceramic Clay Manufacturing

11.7.1 Process Description[1]

The manufacture of ceramic clay involves the conditioning of the basic ores by several methods. These include the separation and concentration of the minerals by screening, floating, wet and dry grinding, and blending of the desired ore varieties. The basic raw materials in ceramic clay manufacture are kaolinite ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$) and montmorillonite [$(Mg, Ca) O \cdot Al_2O_3 \cdot 5SiO_2 \cdot nH_2O$] clays. These clays are refined by separation and bleaching, blended, kiln-dried, and formed into such items as whiteware, heavy clay products (brick, etc.), various stoneware, and other products such as diatomaceous earth, which is used as a filter aid.

11.7.2 Emissions And Controls[1]

Emissions consist primarily of particulates, but some fluorides and acid gases are also emitted in the drying process. The high temperatures of the firing kilns are also conducive to the fixation of atmospheric nitrogen and the subsequent release of NO, but no published information has been found for gaseous emissions. Particulates are also emitted from the grinding process and from storage of the ground product.

Factors affecting emissions include the amount of material processed, the type of grinding (wet or dry), the temperature of the drying kilns, the gas velocities and flow direction in the kilns, and the amount of fluorine in the ores.

Common control techniques include settling chambers, cyclones, wet scrubbers, electrostatic precipitators, and bag filters. The most effective control is provided by cyclones for the coarser material, followed by wet scrubbers, bag filters, or electrostatic precipitators for dry dust. Emission factors for ceramic clay manufacturing are presented in Table 11.7-1.

Table 11.7-1 (Metric And English Units). PARTICULATE EMISSION FACTORS FOR CERAMIC CLAY MANUFACTURING[a]

EMISSION FACTOR RATING: A

Type Of Process	Uncontrolled		Cyclone[b]		Multiple-Unit Cyclone And Scrubber[c]	
	kg/Mg	lb/ton	kg/Mg	lb/ton	lb/ton	kg/Mg
Drying[d]	35	70	9	18	7	3.5
Grinding[e]	38	76	9.5	19	ND	ND
Storage[d]	17	34	4	8	ND	ND

[a] Emission factors expressed as units per unit weight of input to process. ND = no data.
[b] Approximate collection efficiency: 75%.
[c] Approximate collection efficiency: 90%.
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11.8 Clay And Fly Ash Sintering

NOTE: Clay and fly ash sintering operations are no longer conducted in the United States. However, this section is being retained for historical purposes.

11.8.1 Process Description[1-3]

Although the process for sintering fly ash and clay are similar, there are some distinctions that justify a separate discussion of each process. Fly ash sintering plants are generally located near the source, with the fly ash delivered to a storage silo at the plant. The dry fly ash is moistened with a water solution of lignin and agglomerated into pellets or balls. This material goes to a traveling-grate sintering machine where direct contact with hot combustion gases sinters the individual particles of the pellet and completely burns off the residual carbon in the fly ash. The product is then crushed, screened, graded, and stored in yard piles.

Clay sintering involves the driving off of entrained volatile matter. It is desirable that the clay contain a sufficient amount of volatile matter so that the resultant aggregate will not be too heavy. It is thus sometimes necessary to mix the clay with finely pulverized coke (up to 10 percent coke by weight). In the sintering process, the clay is first mixed with pulverized coke, if necessary, and then pelletized. The clay is next sintered in a rotating kiln or on a traveling grate. The sintered pellets are then crushed, screened, and stored, in a procedure similar to that for fly ash pellets.

11.8.2 Emissions And Controls[1]

In fly ash sintering, improper handling of the fly ash creates a dust problem. Adequate design features, including fly ash wetting systems and particulate collection systems on all transfer points and on crushing and screening operations, would greatly reduce emissions. Normally, fabric filters are used to control emissions from the storage silo, and emissions are low. The absence of this dust collection system, however, would create a major emission problem. Moisture is added at the point of discharge from silo to the agglomerator, and very few emissions occur there. Normally, there are few emissions from the sintering machine, but if the grate is not properly maintained, a dust problem is created. The consequent crushing, screening, handling, and storage of the sintered product also create dust problems.

In clay sintering, the addition of pulverized coke presents an emission problem because the sintering of coke-impregnated dry pellets produces more particulate emissions than the sintering of natural clay. The crushing, screening, handling, and storage of the sintered clay pellets creates dust problems similar to those encountered in fly-ash sintering. Emission factors for both clay and fly-ash sintering are shown in Tables 11.8-1 and 11.8-2.

Table 11.8-1 (Metric Units). EMISSION FACTORS FOR CLAY AND FLY ASH SINTERING[a]

Source (SCC)	Filterable[b]				Condensable PM[c]			
	PM		PM-10		Inorganic		Organic	
	kg/Mg Of Material	EMISSION FACTOR RATING	kg/Mg Of Material	EMISSION FACTOR RATING	kg/Mg Of Material	EMISSION FACTOR RATING	kg/Mg Of Material	EMISSION FACTOR RATING
Fly ash crushing, screening, sintering, and storage (3-05-009-01)[d]	55	E	ND		ND		ND	
Clay/coke mixture sintering (3-05-009- 02)[e]	20	E	ND		ND		ND	
Clay/coke mixture crushing, screening, and storage (3-05-009-07)[f]	7.5	E	ND		ND		ND	
Natural clay sintering (3-05-009-03)[g]	6	E	ND		ND		ND	
Natural clay crushing, screening, and storage (3-05-009-04)[f]	6	E	ND		ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 1.

[e] References 3-5; for 90% clay, 10% pulverized coke; traveling grate, single pass, up-draft sintering machine.

[f] Based on data in Section 11.19-2.

[g] Reference 2; rotary dryer sinterer.

Table 11.8-2 (English Units). EMISSION FACTORS FOR CLAY AND FLY ASH SINTERING[a]

Source (SCC)	Filterable[b]				Condensable PM[c]			
	PM		PM-10		Inorganic		Organic	
	lb/ton Of Material	EMISSION FACTOR RATING	lb/ton Of Material	EMISSION FACTOR RATING	lb/ton Of Material	EMISSION FACTOR RATING	lb/ton Of Material	EMISSION FACTOR RATING
Fly ash crushing, screening, sintering, and storage (3-05-009-01)[d]	110	E	ND		ND		ND	
Clay/coke mixture sintering (3-05-009-02)[e]	40	E	ND		ND		ND	
Clay/coke mixture crushing, screening, and storage (3-05-009-07)[f]	15	E	ND		ND		ND	
Natural clay sintering (3-05-009-03)[g]	12	E	ND		ND		ND	
Natural clay crushing, screening, and storage (3-05-009-04)[f]	12	E	ND		ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 1.

[e] References 3-5; for 90% clay, 10% pulverized coke; traveling grate, single pass, up-draft sintering machine.

[f] Based on data in Section 11.19-2.

[g] Reference 2; rotary dryer sinterer.

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2. Communication between Resources Research, Inc., Reston, VA, and a clay sintering firm, October 2, 1969.

3. Communication between Resources Research, Inc., Reston, VA, and an anonymous air pollution control agency, October 16, 1969.

4. J. J. Henn, *et al.*, *Methods For Producing Alumina From Clay: An Evaluation Of Two Lime Sinter Processes*, U. S. Bureau Of Mines, Department Of Interior, Washington, DC, Report of Investigation No. 7299, September 1969.

5. F. A. Peters, *et al.*, *Methods For Producing Alumina From Clay: An Evaluation Of The Lime-Soda Sinter Process*, U. S. Bureau Of Mines, Department Of Interior, Washington, DC, Report of Investigation No. 6927, 1967.

11.9 Western Surface Coal Mining

11.9 General[1]

There are 12 major coal fields in the western states (excluding the Pacific Coast and Alaskan fields), as shown in Figure 11.9-1. Together, they account for more than 64 percent of the surface minable coal reserves in the United States.[2] The 12 coal fields have varying characteristics that may influence fugitive dust emission rates from mining operations including overburden and coal seam thicknesses and structure, mining equipment, operating procedures, terrain, vegetation, precipitation and surface moisture, wind speeds, and temperatures. The operations at a typical western surface mine are shown in Figure 11.9-2. All operations that involve movement of soil, coal, or equipment, or exposure of erodible surfaces, generate some amount of fugitive dust.

The initial operation is removal of topsoil and subsoil with large scrapers. The topsoil is carried by the scrapers to cover a previously mined and regraded area as part of the reclamation process or is placed in temporary stockpiles. The exposed overburden, the earth that is between the topsoil and the coal seam, is leveled, drilled, and blasted. Then the overburden material is removed down to the coal seam, usually by a dragline or a shovel and truck operation. It is placed in the adjacent mined cut, forming a spoils pile. The uncovered coal seam is then drilled and blasted. A shovel or front end loader loads the broken coal into haul trucks, and it is taken out of the pit along graded haul roads to the tipple, or truck dump. Raw coal sometimes may be dumped onto a temporary storage pile and later rehandled by a front end loader or bulldozer.

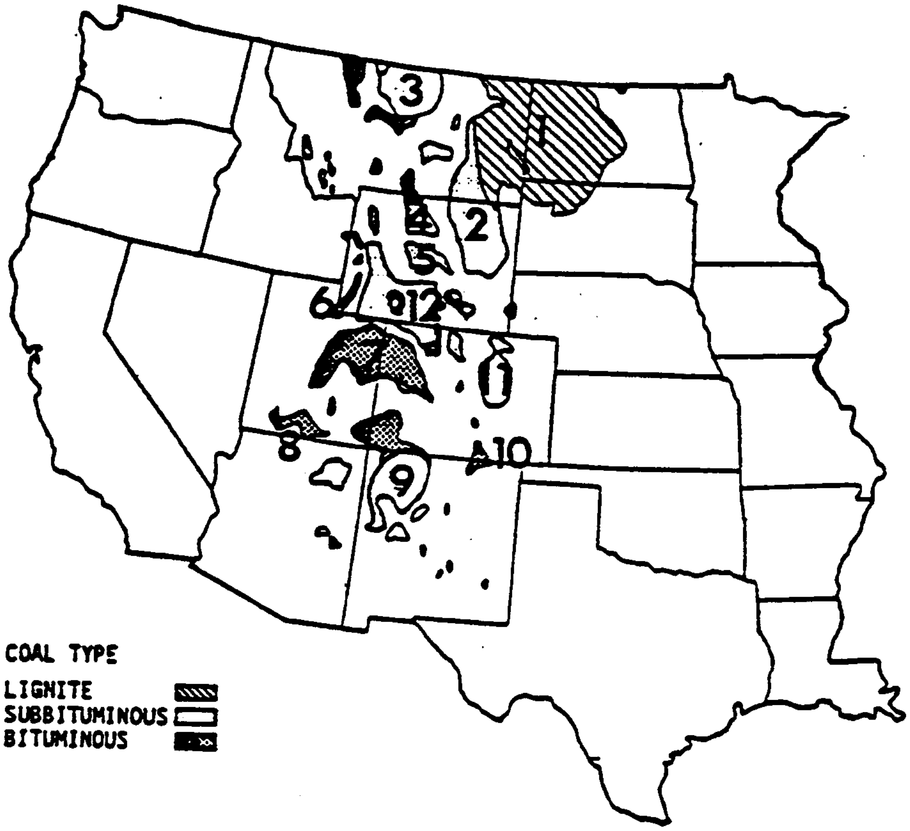
At the tipple, the coal is dumped into a hopper that feeds the primary crusher, then is conveyed through additional coal preparation equipment such as secondary crushers and screens to the storage area. If the mine has open storage piles, the crushed coal passes through a coal stacker onto the pile. The piles, usually worked by bulldozers, are subject to wind erosion. From the storage area, the coal is conveyed to a train loading facility and is put into rail cars. At a captive mine, coal will go from the storage pile to the power plant.

During mine reclamation, which proceeds continuously throughout the life of the mine, overburden spoils piles are smoothed and contoured by bulldozers. Topsoil is placed on the graded spoils, and the land is prepared for revegetation by furrowing, mulching, etc. From the time an area is disturbed until the new vegetation emerges, all disturbed areas are subject to wind erosion.

11.9 Emissions

Predictive emission factor equations for open dust sources at western surface coal mines are presented in Tables 11.9-1 and 11.9-2. Each equation is for a single dust-generating activity, such as vehicle traffic on unpaved roads. The predictive equation explains much of the observed variance in emission factors by relating emissions to 3 sets of source parameters: (1) measures of source activity or energy expended (e. g., speed and weight of a vehicle traveling on an unpaved road); (2) properties of the material being disturbed (e. g., suspendable fines in the surface material of an unpaved road); and (3) climate (in this case, mean wind speed).

The equations may be used to estimate particulate emissions generated per unit of source extent (e. g., vehicle distance traveled or mass of material transferred). The equations were



	Coal field	Strippable reserves (10^6 tons)
1	Fort Union	23,529
2	Powder River	56,727
3	North Central	All underground
4	Bighorn Basin	All underground
5	Wind River	3
6	Hams Fork	1,000
7	Uinta	308
8	Southwestern Utah	224
9	San Juan River	2,318
10	Raton Mesa	All underground
11	Denver	All underground
12	Green River	2,120

Figure 11.9-1. Coal fields of the western United States.

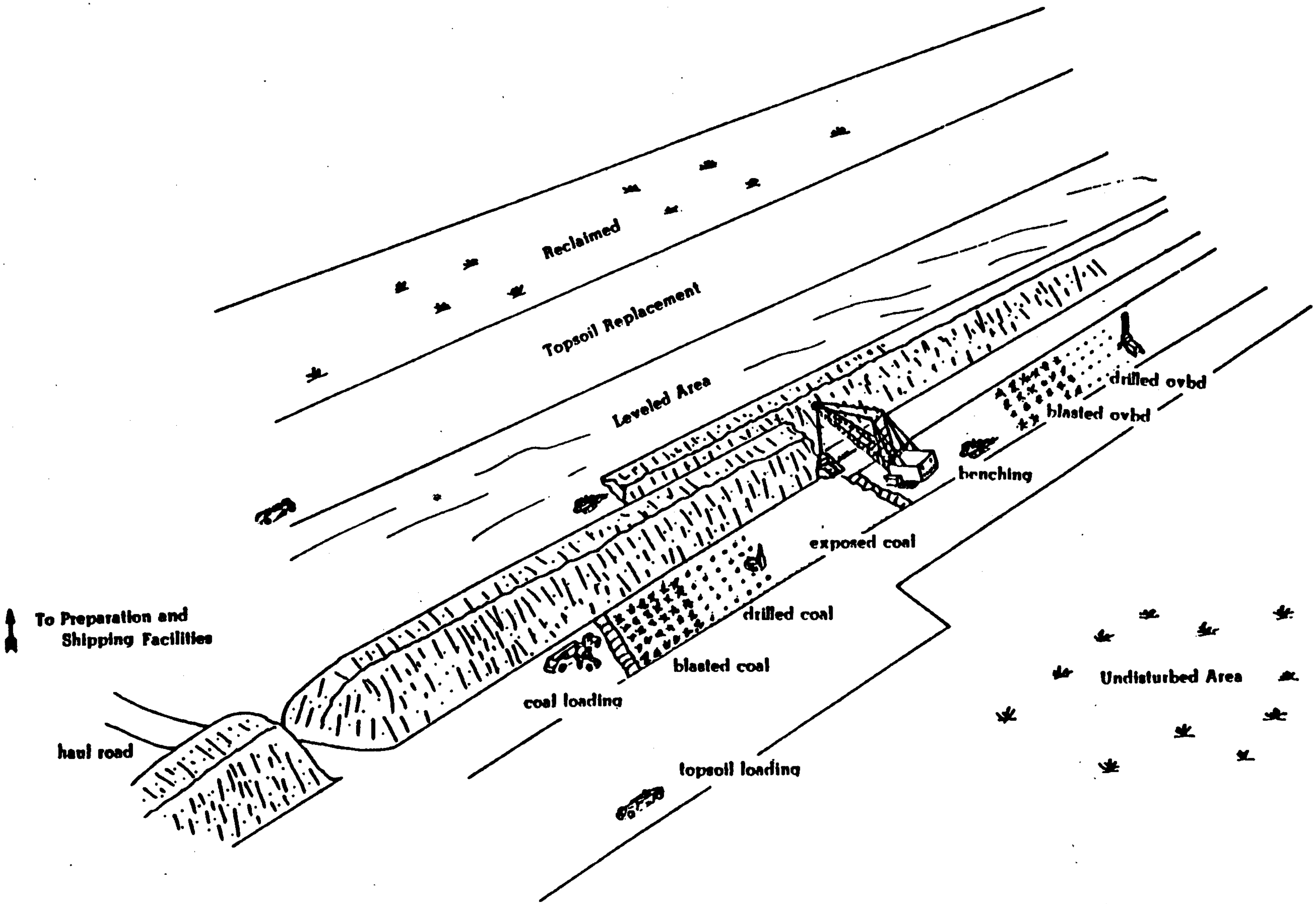


Figure 11.9-2. Operations at typical western surface coal mines.

Table 11.9-1 (Metric Units). EMISSION FACTOR EQUATIONS FOR UNCONTROLLED OPEN DUST SOURCES AT WESTERN SURFACE COAL MINES[a]

Operation	Material	Emissions By Particle Size Range (Aerodymanic Diameter)[b,c]				Units	EMISSION FACTOR RATING
		TSP ≤ 30 μm	≤15 μm	≤10 μm[d]	≤2.5 μm/TSP[e]		
Blasting	Coal or overburden	$0.00022^{1.5}$	ND	0.52[e]	ND	kg/blast	C
Truck loading	Coal	$\frac{0.580}{(M)^{1.2}}$	$\frac{0.0596}{(M)^{0.9}}$	0.75	0.019	kg/Mg	B
Bulldozing	Coal	$\frac{35.6\ (s)^{1.2}}{(M)^{1.4}}$	$\frac{8.44\ (s)^{1.5}}{(M)^{1.4}}$	0.75	0.022	kg/hr	B
	Overburden	$\frac{2.6\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{0.45\ (s)^{1.5}}{(M)^{1.4}}$	0.75	0.105	kg/hr	B
Dragline	Overburden	$\frac{0.0046\ (d)^{1.1}}{(M)^{0.3}}$	$\frac{0.0029\ (d)^{0.7}}{(M)^{0.3}}$	0.75	0.017	kg/m³	B
Scraper (travel mode)		$9.6 \times 10^{-6}\ (s)^{1.3}\ (W)^{2.4}$	$2.2 \times 10^{-6}\ (s)^{1.4}\ (W)^{2.5}$	0.60	0.026	kg/VKT	A
Grading		$0.0034\ (S)^{2.5}$	$0.0056\ (S)^{2.0}$	0.60	0.031	kg/VKT	B
Vehicle traffic (light/medium duty)		$\frac{1.63}{(M)^{4.0}}$	$\frac{1.05}{(M)^{4.3}}$	0.60	0.040	kg/VKT	B
Haul truck		$0.0019\ (w)^{3.4}\ (L)^{0.2}$	$0.0014\ (w)^{3.5}$	0.60	0.017	kg/VKT	A
Active storage pile (wind erosion and maintenance)	Coal	1.8 u	ND	ND	ND	$\frac{\text{kg}}{\text{(hectare)(hr)}}$	C[f]

[a] Reference 1, except for coal storage pile equation from Reference 4. TSP = total suspended particulate. VKT = vehicle kilometers traveled. ND = no data.

[b] TSP denotes what is measured by a standard high volume sampler (see Section 13.2).

[c] Symbols for equations:

A = horizontal area, with blasting depth ≤21 m. Not for vertical face of a bench.

M = material moisture content (%)

Table 11.9-1 (cont.).

s = material silt content (%)
u = wind speed (m/sec)
d = drop height (m)
W = mean vehicle weight (Mg)
S = mean vehicle speed (kph)
w = mean number of wheels
L = road surface silt loading (g/m^2)

[d] Multiply the ≤ 15 μm equation by this fraction to determine emissions.

[e] Multiply the TSP predictive equation by this fraction to determine emissions in the ≤ 2.5 μm size range.

[f] Rating applicable to Mine Types I, II, and IV (see Tables 11.9-5 and 11.9-6).

Table 11.9-2 (English Units). EMISSION FACTOR EQUATIONS FOR UNCONTROLLED OPEN DUST SOURCES AT WESTERN SURFACE COAL MINES[a]

Operation	Material	Emissions By Particle Size Range (Aerodymanic Diameter)[b,c]				Units	EMISSION FACTOR RATING
		TSP $\leq$ 30 μm	$\leq$15 μm	$\leq$10 μm[d]	$\leq$2.5 μm/TSP[c]		
Blasting	Coal or overburden	$0.0005A^{1.5}$	ND	0.52[e]	ND	lb/blast	C
Truck loading	Coal	$\frac{1.16}{(M)^{1.2}}$	$\frac{0.119}{(M)^{0.9}}$	0.75	0.019	lb/ton	B
Bulldozing	Coal	$\frac{78.4\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{18.6\ (s)^{1.5}}{(M)^{1.4}}$	0.75	0.022	lb/ton	B
	Overburden	$\frac{5.7\ (s)^{1.2}}{(M)^{1.3}}$	$\frac{1.0\ (c)^{1.5}}{(M)^{1.4}}$	0.75	0.105	lb/ton	B
Dragline	Overburden	$\frac{0.0021\ (d)^{1.1}}{(M)^{0.3}}$	$\frac{0.0021\ (d)^{0.7}}{(M)^{0.3}}$	0.75	0.017	lb/yd^3	B
Scraper (travel mode)		$2.7 \times 10^{-5}\ (s)^{1.3}\ (W)^{2.4}$	$6.2 \times 10^{-6}\ (s)^{1.4}\ (W)^{2.5}$	0.60	0.026	lb/VMT	A
Grading		$0.040\ (S)^{2.5}$	$0.051\ (S)^{2.0}$	0.60	0.031	lb/VMT	B
Vehicle traffic (light/medium duty)		$\frac{5.79}{(M)^{4.0}}$	$\frac{3.72}{(M)^{4.3}}$	0.60	0.040	lb/VMT	B
Haul truck		$0.0067\ (w)^{3.4}\ (L)^{0.2}$	$0.0051\ (w)^{3.5}$	0.60	0.017	lb/VMT	A
Active storage pile (wind erosion and maintenance)	Coal	1.6 u	ND	ND	ND	$\frac{lb}{(acre)(hr)}$	C[f]

[a] Reference 1, except for coal storage pile equation from Reference 4. TSP = total suspended particulate. VMT = vehicle miles traveled. ND = no data.

[b] TSP denotes what is measured by a standard high volume sampler (see Section 13.2).

[c] Symbols for equations:

A = horizontal area, with blasting depth $\leq$70 ft. Not for vertical face of a bench.

M = material moisture content (%)

Table 11.9-2 (cont.).

s = material silt content (%)
u = wind speed (m/sec)
d = drop height (ft)
W = mean vehicle weight (tons)
S = mean vehicle speed (mph)
w = mean number of wheels
L = road surface silt loading (g/m^2)

[d] Multiply the $\leq 15\ \mu m$ equation by this fraction to determine emissions.

[e] Multiply the TSP predictive equation by this fraction to determine emissions in the $\leq 2.5\ \mu m$ size range.

[f] Rating applicable to Mine Types I, II, and IV (see Tables 11.9-5 and 11.9-6).

developed through field sampling of various western surface mine types and are thus applicable to any of the surface coal mines located in the western United States.

In Tables 11.9-1 and 11.9-2, the assigned quality ratings apply within the ranges of source conditions that were tested in developing the equations given in Table 11.9-3. However, the equations should be derated 1 letter value (e. g., A to B) if applied to eastern surface coal mines.

In using the equations to estimate emissions from sources found in a specific western surface mine, it is necessary that reliable values for correction parameters be determined for the specific sources of interest if the assigned quality ranges of the equations are to be applicable. For example, actual silt content of coal or overburden measured at a facility should be used instead of estimated values. In the event that site-specific values for correction parameters cannot be obtained, the appropriate geometric mean values from Table 11.9-3 may be used, but the assigned quality rating of each emission factor equation should be reduced by 1 level (e. g., A to B).

Emission factors for open dust sources not covered in Table 11.9-3 are in Table 11.9-4. These factors were determined through source testing at various western coal mines.

Table 11.9-3 (Metric And English Units). TYPICAL VALUES FOR CORRECTION FACTORS APPLICABLE TO THE PREDICTIVE EMISSION FACTOR EQUATIONS[a]

Source	Correction Factor	Number Of Test Samples	Range	Geometric Mean	Units
Coal loading	Moisture	7	6.6 - 38	17.8	%
Bulldozers					
Coal	Moisture	3	4.0 - 22.0	10.4	%
	Silt	3	6.0 - 11.3	8.6	%
Overburden	Moisture	8	2.2 - 16.8	7.9	%
	Silt	8	3.8 - 15.1	6.9	%
Dragline	Drop distance	19	1.5 - 30	8.6	m
	Drop distance	19	5 - 100	28.1	ft
	Moisture	7	0.2 - 16.3	3.2	%
Scraper	Silt	10	7.2 - 25.2	16.4	%
	Weight	15	33 - 64	48.8	Mg
	Weight	15	36 - 70	53.8	ton
Grader	Speed	7	8.0 - 19.0	11.4	kph
	Speed		5.0 - 11.8	7.1	mph
Light/Medium duty vehicle	Moisture	7	0.9 - 1.70	1.2	%
Haul truck	Wheels	29	6.1 - 10.0	8.1	number
	Silt loading	26	3.8 - 254	40.8	g/m^2
	Silt loading	26	34 - 2270	364	lb/acre

[a] Reference 1.

Table 11.9-4 (English And Metric Units). UNCONTROLLED PARTICULATE EMISSION FACTORS FOR OPEN DUST SOURCES AT WESTERN SURFACE COAL MINES

Source	Material	Mine Location[a]	TSP Emission Factor[b]	Units	EMISSION FACTOR RATING
Drilling	Overburden	Any	1.3	lb/hole	B
			0.59	kg/hole	B
	Coal	V	0.22	lb/hole	E
			0.10	kg/hole	E
Topsoil removal by scraper	Topsoil	Any	0.058	lb/ton	E
			0.029	kg/Mg	E
		IV	0.44	lb/ton	D
			0.22	kg/Mg	D
Overburden replacement	Overburden	Any	0.012	lb/ton	C
			0.0060	kg/Mg	C
Truck loading by power shovel (batch drop)[c]	Overburden	V	0.037	lb/ton	C
			0.018	kg/Mg	C
Train loading (batch or continuous drop)[c]	Coal	Any	0.028	lb/ton	D
			0.014	kg/Mg	D
		III	0.0002	lb/ton	D
			0.0001	kg/Mg	D
Bottom dump truck unloading (batch drop)[c]	Overburden	V	0.002	lb/ton	E
			0.001	kg/ton	E
	Coal	IV	0.027	lb/ton	E
			0.014	kg/Mg	E
		III	0.005	lb/ton	E
			0.002	kg/Mg	E
		II	0.020	lb/ton	E
			0.010	kg/Mg	E

Table 11.9-4 (cont.).

Source	Material	Mine Location[a]	TSP Emission Factor[b]	Units	EMISSION FACTOR RATING
		I	0.014 0.0070	lb/T kg/Mg	D D
		Any	0.066 0.033	lb/T kg/Mg	D D
End dump truck unloading (batch drop)[c]	Coal	V	0.007 0.004	lb/T kg/Mg	E E
Scraper unloading (batch drop)[c]	Topsoil	IV	0.04 0.02	lb/T kg/Mg	C C
Wind erosion of exposed areas	Seeded land, stripped overburden, graded overburden	Any	0.38	$\frac{T}{(acre)(yr)}$	C
			0.85	$\frac{Mg}{(hectare)(yr)}$	C

[a] Roman numerals I through V refer to specific mine locations for which the corresponding emission factors were developed. Tables 11.9-4 and 11.9-5 present characteristics of each of these mines. See text for correct use of these "mine-specific" emission factors. The other factors (from Reference 5 except for overburden drilling from Reference 1) can be applied to any western surface coal mine.

[b] Total suspended particulate (TSP) denotes what is measured by a standard high volume sampler (see Section 13.2).

[c] Predictive emission factor equations, which generally provide more accurate estimates of emissions, are presented is Chapter 13.

The factors in Table 11.9-4 for mine locations I through V were developed for specific geographical areas. Tables 11.9-5 and 11.9-6 present characteristics of each of these mines (areas). A "mine-specific" emission factor should be used only if the characteristics of the mine for which an emissions estimate is needed are very similar to those of the mine for which the emission factor was developed. The other (nonspecific) emission factors were developed at a variety of mine types and thus are applicable to any western surface coal mine.

As an alternative to the single valued emission factors given in Table 11.9-4 for train or truck loading and for truck or scraper unloading, 2 empirically derived emission factor equations are presented in Section 13.2.4 of this document. Each equation was developed for a source operation (i. e., batch drop and continuous drop, respectively) comprising a single dust-generating mechanism that crosses industry lines.

Because the predictive equations allow emission factor adjustment to specific source conditions, the equations should be used in place of the factors in Table 11.9-4 for the sources identified above if emission estimates for a specific western surface coal mine are needed. However, the generally higher quality ratings assigned to the equations are applicable only if: (1) reliable values of correction parameters have been determined for the specific sources of interest, and (2) the correction parameter values lie within the ranges tested in developing the equations. Table 11.9-3 lists measured properties of aggregate materials that can be used to estimate correction parameter values for the predictive emission factor equations in Chapter 13, in the event that site-specific values are not available. Use of mean correction parameter values from Table 11.9-3 will reduce the quality ratings of the emission factor equations in Chapter 13 by 1 level.

Table 11.9-5 (Metric And English Units). GENERAL CHARACTERISTICS OF SURFACE COAL MINES REFERRED TO IN TABLE 11.9-4[a]

Mine	Location	Type Of Coal Mined	Terrain	Vegetative Cover	Surface Soil Type And Erodibility Index	Mean Wind Speed		Mean Annual Precipitation	
						m/s	mph	cm	in.
I	N.W. Colorado	Subbitum.	Moderately steep	Moderate, sagebrush	Clayey loamy (71)	2.3	5.1	38	15
II	S.W. Wyoming	Subbitum.	Semirugged	Sparse, sagebrush	Arid soil with clay and alkali or carbonate accumulation (86)	6.0	13.4	36	14
III	S.E. Montana	Subbitum.	Gently rolling to semirugged	Sparse, moderate, prairie grassland	Shallow clay loamy deposits on bedrock (47)	4.8	10.7	28 - 41	11 - 16
IV	Central North Dakota	Lignite	Gently rolling	Moderate, prairie grassland	Loamy, loamy to sandy (71)	5.0	11.2	43	17
V	N.E. Wyoming	Subbitum.	Flat to gently rolling	Sparse, sagebrush	Loamy, sandy, clayey, and clay loamy (102)	6.0	13.4	36	14

[a] Reference 4.

Table 11.9-6 (English Units). OPERATING CHARACTERISTICS OF THE COAL MINES REFERRED TO IN TABLE 11.9-4[a]

Parameter	Required Information	Units	Mine				
			I	II	III	IV	V
Production rate	Coal mined	10^6 ton/yr	1.13	5.0	9.5	3.8	12.0[b]
Coal transport	Avg. unit train frequency	per day	NA	NA	2	NA	2
Stratigraphic data	Overburden thickness	ft	21	80	90	65	35
	Overburden density	lb/yd^3	4000	3705	3000	—	—
	Coal seam thicknesses	ft	9,35	15,9	27	2,4,8	70
	Parting thicknesses	ft	50	15	NA	32,16	NA
	Spoils bulking factor	%	22	24	25	20	—
	Active pit depth	ft	52	100	114	80	105
Coal analysis data	Moisture	%	10	18	24	38	30
	Ash	%, wet	8	10	8	7	6
	Sulfur	%, wet	0.46	0.59	0.75	0.65	0.48
	Heat content	Btu/lb	11000	9632	8628	8500	8020
Surface disposition	Total disturbed land	acre	168	1030	2112	1975	217
	Active pit	acre	34	202	87	—	71
	Spoils	acre	57	326	144	—	100
	Reclaimed	acre	100	221	950	—	100
	Barren land	acre	—	30	455	—	—
	Associated disturbances	acre	12	186	476	—	46
Storage	Capacity	ton	NA	NA	—	NA	48000
Blasting	Frequency, total	per week	4	4	3	7	7[b]
	Frequency, overburden	per week	3	0.5	3	NA	7[b]
	Area blasted, coal	ft^2	16000	40000	—	30000	—
	Area blasted, overburden	ft^2	20000	—	—	NA	—

[a] Reference 4. NA = not applicable. Dash = no data.
[b] Estimate.

References For Section 11.9

1. K. Axetell and C. Cowherd, *Improved Emission Factors For Fugitive Dust From Western Surface Coal Mining Sources*, 2 Volumes, EPA Contract No. 68-03-2924, U. S. Environmental Protection Agency, Cincinnati, OH, July 1981.

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11.10 Coal Cleaning

11.10.1 Process Description[1,2]

Coal cleaning is a process by which impurities such as sulfur, ash and rock are removed from coal to upgrade its value. Coal cleaning processes are categorized as either physical cleaning or chemical cleaning. Physical coal cleaning processes, the mechanical separation of coal from its contaminants using differences in density, are by far the major processes in use today. Chemical coal cleaning processes are not commercially practical and are therefore not included in this discussion.

The scheme used in physical coal cleaning processes varies among coal cleaning plants but can generally be divided into 4 basic phases: initial preparation, fine coal processing, coarse coal processing, and final preparation. A sample process flow diagram for a physical coal cleaning plant is presented in Figure 11.10-1.

In the initial preparation phase of coal cleaning, the raw coal is unloaded, stored, conveyed, crushed, and classified by screening into coarse and fine coal fractions. The size fractions are then conveyed to their respective cleaning processes.

Fine coal processing and coarse coal processing use very similar operations and equipment to separate the contaminants. The primary differences are the severity of operating parameters. The majority of coal cleaning processes use upward currents or pulses of a fluid such as water to fluidize a bed of crushed coal and impurities. The lighter coal particles rise and are removed from the top of the bed. The heavier impurities are removed from the bottom. Coal cleaned in the wet processes then must be dried in the final preparation processes.

Final preparation processes are used to remove moisture from coal, thereby reducing freezing problems and weight, and raising the heating value. The first processing step is dewatering, in which a major portion of the water is removed by the use of screens, thickeners, and cyclones. The second step is normally thermal drying, achieved by any 1 of 3 dryer types: fluidized bed, flash, and multilouvered. In the fluidized bed dryer, the coal is suspended and dried above a perforated plate by rising hot gases. In the flash dryer, coal is fed into a stream of hot gases for instantaneous drying. The dried coal and wet gases are drawn up a drying column and into a cyclone for separation. In the multilouvered dryer, hot gases are passed through a falling curtain of coal. The coal is raised by flights of a specially designed conveyor.

11.10.2 Emissions And Controls[1,2]

Emissions from the initial coal preparation phase of either wet or dry processes consist primarily of fugitive particulates, as coal dust, from roadways, stock piles, refuse areas, loaded railroad cars, conveyor belt pouroffs, crushers, and classifiers. The major control technique used to reduce these emissions is water wetting. Another technique applicable to unloading, conveying, crushing, and screening operations involves enclosing the process area and circulating air from the area through fabric filters.

The major emission source in the fine or coarse coal processing phases is the air exhaust from the air separation processes. For the dry cleaning process, this is where the coal is stratified by

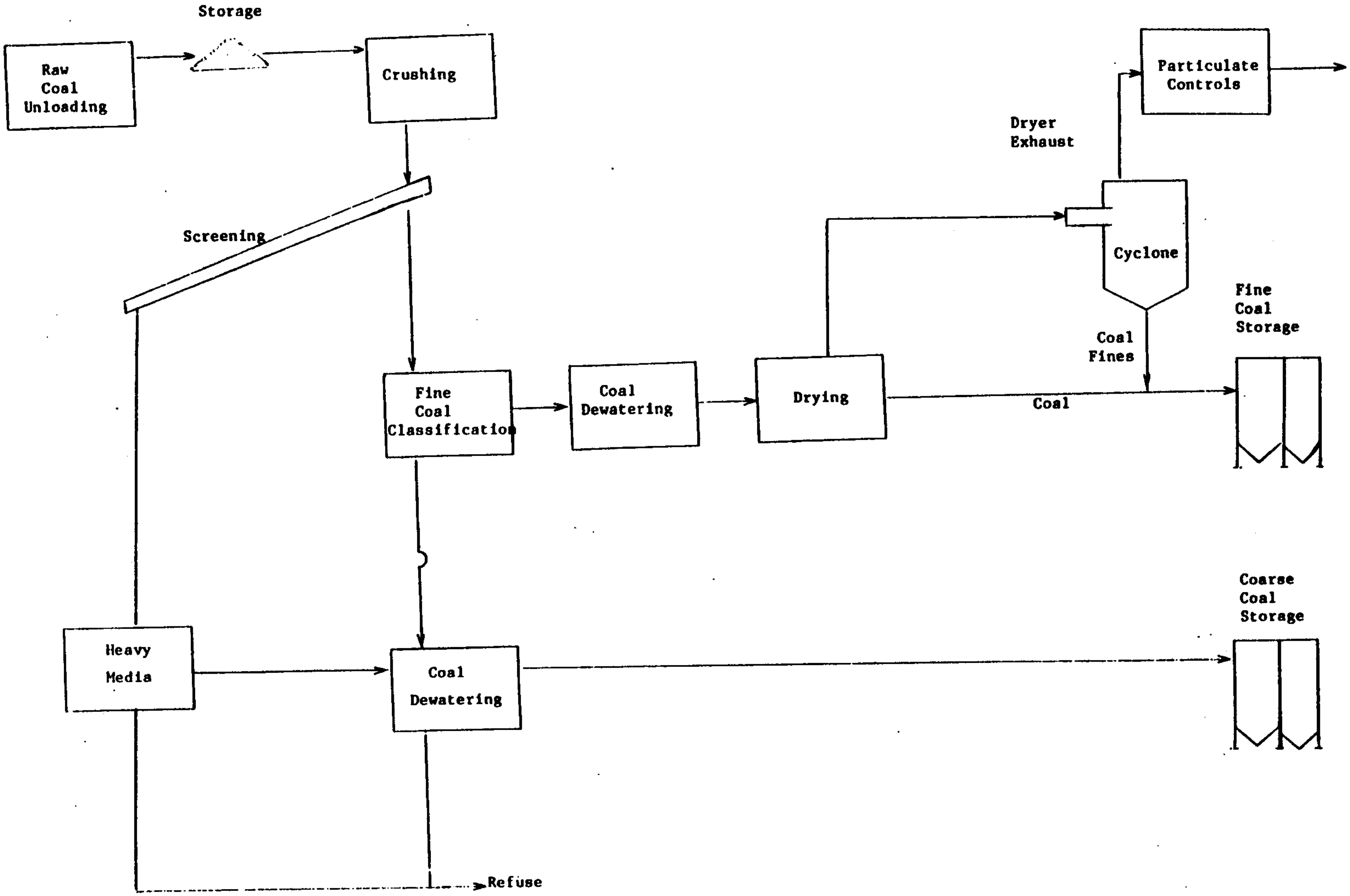

Figure 11.10-1. Typical coal cleaning process flow diagram.

pulses of air. Particulate emissions from this source are normally controlled with cyclones followed by fabric filters. Potential emissions from wet cleaning processes are very low.

The major source of emissions from the final preparation phase is the thermal dryer exhaust. This emission stream contains coal particles entrained in the drying gases in addition to the standard products of coal combustion resulting from burning coal to generate the hot gases. Factors for these emissions are presented in Table 11.10-1. The most common technologies used to control this source are venturi scrubbers and mist eliminators downstream from the product recovery cyclones. The particulate control efficiency of these technologies ranges from 98 to 99.9 percent. The venturi scrubbers also have an NO_x removal efficiency of 10 to 25 percent, and an SO_2 removal efficiency ranging from 70 to 80 percent for low-sulfur coals to 40 to 50 percent for high-sulfur coals.

Table 11.10-1 (Metric And English Units). EMISSION FACTORS FOR COAL CLEANING[a]

EMISSION FACTOR RATING: B

Operation/Pollutant	Fluidized Bed		Flash		Multilouvered	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Particulates						
Before cyclone	10[b]	20[b]	8[b]	16[b]	13[c]	25[c]
After cyclone[d]	6[e]	12[e]	5[f]	10[f]	4[c]	8[c]
After cyclone	0.05[e]	0.09[e]	0.2[f]	0.4[f]	0.05[c]	0.1[f]
SO_2[g]						
After cyclone	0.22[h]	0.43[h]	—	—	—	—
After scrubber	0.13	0.25	—	—	—	—
NO_x[j]						
After scrubber	0.07	0.14	—	—	—	—
VOC[k]						
After scrubber	0.05	0.10	—	—	—	—

[a] Emission factors expressed as units per weight of coal dried. Dash = no data.

[b] References 3-4.

[c] Reference 5.

[d] Cyclones are standard pieces of process equipment for product collection.

[e] References 6-10.

[f] Reference 1.

[g] References 7-8. The control efficiency of venturi scrubbers on SO_2 emissions depends on the inlet SO_2 loading, ranging from 70 to 80% removal for low-sulfur coals (0.7% S) down to 40 to 50% removal for high-sulfur coals (3% S).

[h] References 7-9.

[j] Reference 8. The control efficiency of venturi scrubbers on NO_x emissions is approximately 10 to 25%.

[k] Volatile organic compounds as pounds of carbon per ton of coal dried.

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11.11 Coal Conversion

In addition to its direct use for combustion, coal can be converted to organic gases and liquids, thus allowing the continued use of conventional oil- and gas-fired processes when oil and gas supplies are not available. Currently, there is little commercial coal conversion in the United States. Consequently, it is very difficult to determine which of the many conversion processes will be commercialized in the future. The following sections provide general process descriptions and general emission discussions for high-, medium- and low-Btu gasification (gasifaction) processes and for catalytic and solvent extraction liquefaction processes.

11.11.1 Process Description[1-2]

11.11.1.1 Gasification -

One means of converting coal to an alternate form of energy is gasification. In this process, coal is combined with oxygen and steam to produce a combustible gas, waste gases, char, and ash. The more than 70 coal gasification systems available or being developed in 1979 can be classified by the heating value of the gas produced and by the type of gasification reactor used. High-Btu gasification systems produce a gas with a heating value greater than 900 Btu/scf (33,000 J/m^3). Medium-Btu gasifiers produce a gas having a heating value between 250 - 500 Btu/scf (9,000 - 19,000 J/m^3). Low-Btu gasifiers produce a gas having a heating value of less than 250 Btu/scf (9,000 J/m^3).

The majority of the gasification systems consist of 4 operations: coal pretreatment, coal gasification, raw gas cleaning, and gas beneficiation. Each of these operations consists of several steps. Figure 11.11-1 is a flow diagram for an example coal gasification facility.

Generally, any coal can be gasified if properly pretreated. High-moisture coals may require drying. Some caking coals may require partial oxidation to simplify gasifier operation. Other pretreatment operations include crushing, sizing, and briqueting of fines for feed to fixed bed gasifiers. The coal feed is pulverized for fluid or entrained bed gasifiers.

After pretreatment, the coal enters the gasification reactor where it reacts with oxygen and steam to produce a combustible gas. Air is used as the oxygen source for making low-Btu gas, and pure oxygen is used for making medium- and high-Btu gas (inert nitrogen in the air dilutes the heating value of the product). Gasification reactors are classified by type of reaction bed (fixed, entrained, or fluidized), the operating pressure (pressurized or atmospheric), the method of ash removal (as molten slag or dry ash), and the number of stages in the gasifier (1 or 2). Within each class, gasifiers have similar emissions.

The raw gas from the gasifier contains varying concentrations of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen, methane, other organics, hydrogen sulfide (H_2S), miscellaneous acid gases, nitrogen (if air was used as the oxygen source), particulates, and water. Four gas purification processes may be required to prepare the gas for combustion or further beneficiation: particulate removal, tar and oil removal, gas quenching and cooling, and acid gas removal. The primary function of the particulate removal process is the removal of coal dust, ash, and tar aerosols in the raw product gas. During tar and oil removal and gas quenching and cooling, tars and oils are condensed, and other impurities such as ammonia are scrubbed from raw product gas using either aqueous or organic scrubbing liquors. Acid gases such as H_2S, COS, CS_2, mercaptans, and CO_2 can

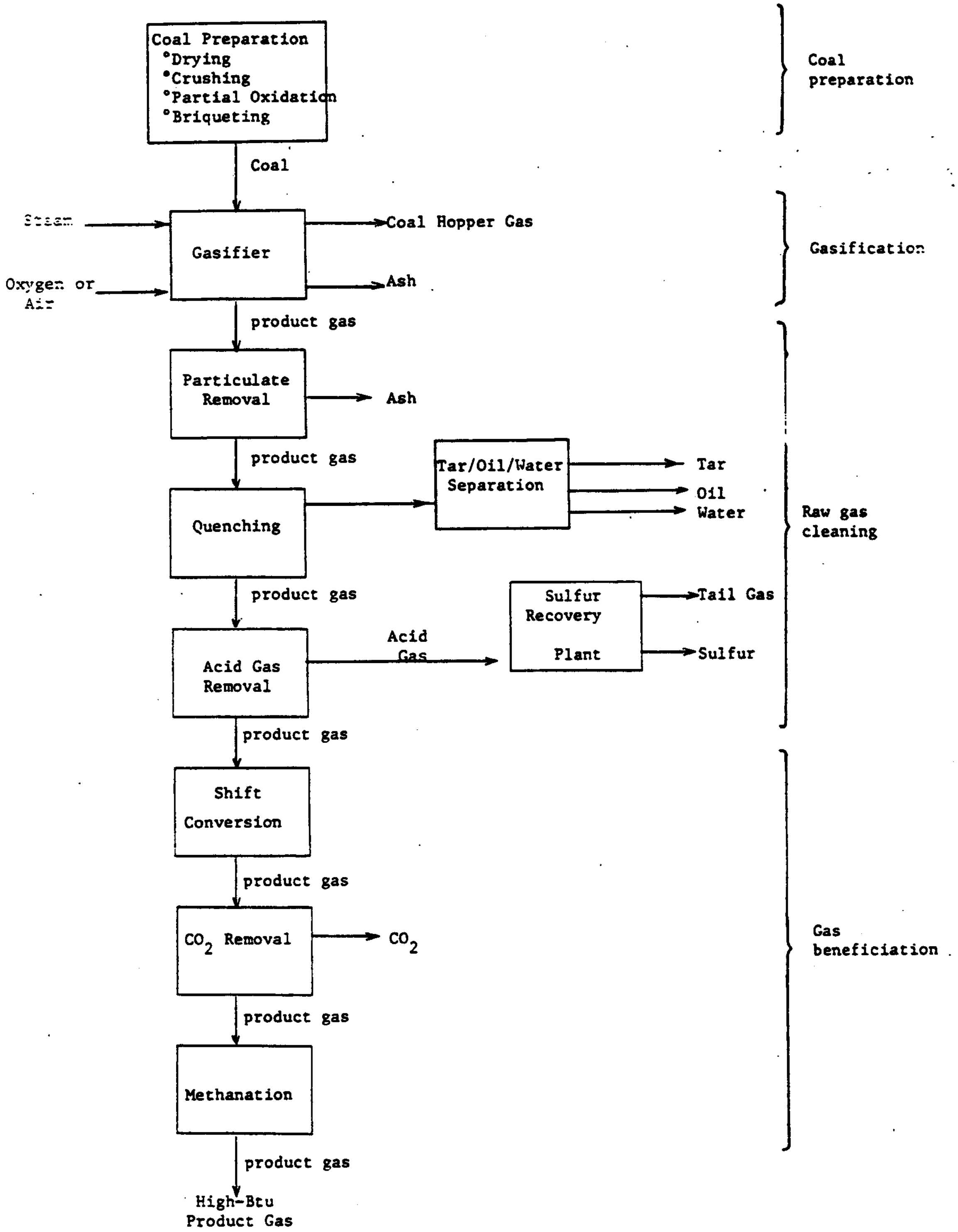

Figure 11.11-1. Flow diagram of typical coal gasification plant.

be removed from gas by an acid gas removal process. Acid gas removal processes generally absorb the acid gases in a solvent, from which they are subsequently stripped, forming a nearly pure acid gas waste stream with some hydrocarbon carryover. At this point, the raw gas is classified as either a low-Btu or medium-Btu gas.

To produce high-Btu gas, the heating value of the medium-Btu gas is raised by shift conversion and methanation. In the shift conversion process, H_2O and a portion of the CO are catalytically reacted to form CO_2 and H_2. After passing through an absorber for CO_2 removal, the remaining CO and H_2 in the product gas are reacted in a methanation reactor to yield CH_4 and H_2O.

There are also many auxiliary processes accompanying a coal gasification facility, which provide various support functions. Among the typical auxiliary processes are oxygen plant, power and steam plant, sulfur recovery unit, water treatment plant, and cooling towers.

11.11.1.2 Liquefaction -

Liquefaction is a conversion process designed to produce synthetic organic liquids from coal. This conversion is achieved by reducing the level of impurities and increasing the hydrogen-to-carbon ratio of coal to the point that it becomes fluid. There were over 20 coal liquefaction processes in various stages of development by both industry and Federal agencies in 1979. These processes can be grouped into 4 basic liquefaction techniques:

- Indirect liquefaction
- Pyrolysis
- Solvent extraction
- Catalytic liquefaction

Indirect liquefaction involves the gasification of coal followed by the catalytic conversion of the product gas to a liquid. Pyrolysis liquefaction involves heating coal to very high temperatures, thereby cracking the coal into liquid and gaseous products. Solvent extraction uses a solvent generated within the process to dissolve the coal and to transfer externally produced hydrogen to the coal molecules. Catalytic liquefaction resembles solvent extraction, except that hydrogen is added to the coal with the aid of a catalyst.

Figure 11.11-2 presents the flow diagram of a typical solvent extraction or catalytic liquefaction plant. These coal liquefaction processes consist of 4 basic operations: coal pretreatment, dissolution and liquefaction, product separation and purification, and residue gasification.

Coal pretreatment generally consists of coal pulverizing and drying. The dissolution of coal is best effected if the coal is dry and finely ground. The heater used to dry coal is typically coal fired, but it may also combust low-BTU-value product streams or may use waste heat from other sources.

The dissolution and liquefaction operations are conducted in a series of pressure vessels. In these processes, the coal is mixed with hydrogen and recycled solvent, heated to high temperatures, dissolved, and hydrogenated. The order in which these operations occur varies among the liquefaction processes and, in the case of catalytic liquefaction, involves contact with a catalyst. Pressures in these processes range up to 2000 psig (14,000 Pa), and temperatures range up to 900°F (480°C). During the dissolution and liquefaction process, the coal is hydrogenated to liquids and some gases, and the oxygen and sulfur in the coal are hydrogenated to H_2O and H_2S.

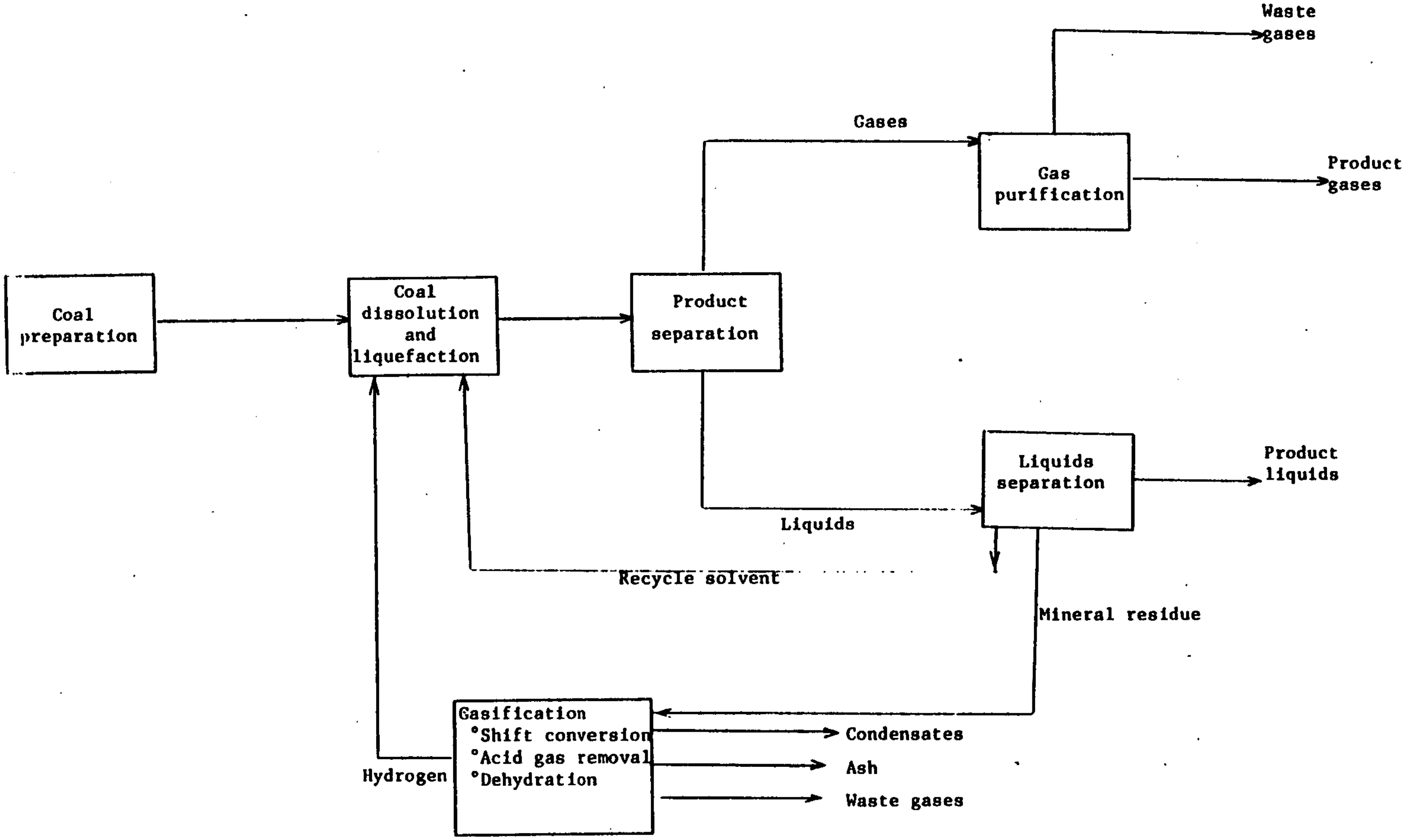

Figure 11.11-2. Flow diagram for an example coal liquefaction facility.

After hydrogenation, the liquefaction products are separated through a series of flash separators, condensers, and distillation units into a gaseous stream, various product liquids, recycle solvent, and mineral residue. The gases from the separation process are separated further by absorption into a product gas stream and a waste acid gas stream. The recycle solvent is returned to the dissolution/liquefaction process, and the mineral residue of char, undissolved coal, and ash is used in a conventional gasification plant to produce hydrogen.

The residue gasification plant closely resembles a conventional high-Btu coal gasifaction plant. The residue is gasified in the presence of oxygen and steam to produce CO, H_2, H_2O, other waste gases, and particulates. After treatment for removal of the waste gases and particulates, the CO and H_2O go into a shift reactor to produce CO_2 and additional H_2. The H_2-enriched product gas from the residue gasifier is used subsequently in the hydrogenation of the coal.

There are also many auxiliary processes accompanying a coal liquefaction facility that provide various support functions. Among the typical auxiliary processes are oxygen plant, power and steam plant, sulfur recovery unit, water treatment plant, cooling towers, and sour water strippers.

11.11.2 Emissions And Controls[1-3]

Although characterization data are available for some of the many developing coal conversion processes, describing these data in detail would require a more extensive discussion than possible here. So, this section will cover emissions and controls for coal conversion processes on a qualitative level only.

11.11.2.1 Gasification -

All of the major operations associated with low-, medium- and high-Btu gasification technology (coal pretreatment, gasification, raw gas cleaning, and gas beneficiation) can produce potentially hazardous air emissions. Auxiliary operations, such as sulfur recovery and combustion of fuel for electricity and steam generation, could account for a major portion of the emissions from a gasification plant. Discharges to the air from both major and auxiliary operations are summarized and discussed in Table 11.11-1.

Dust emissions from coal storage, handling, and crushing/sizing can be controlled with available techniques. Controlling air emissions from coal drying, briqueting, and partial oxidation processes is more difficult because of the volatile organics and possible trace metals liberated as the coal is heated.

The coal gasification process itself appears to be the most serious potential source of air emissions. The feeding of coal and the withdrawal of ash release emissions of coal or ash dust and organic and inorganic gases that are potentially toxic and carcinogenic. Because of their reduced production of tars and condensable organics, slagging gasifiers pose less severe emission problems at the coal inlet and ash outlet.

Gasifiers and associated equipment also will be sources of potentially hazardous fugitive leaks. These leaks may be more severe from pressurized gasifiers and/or gasifiers operating at high temperatures.

Raw gas cleaning and gas beneficiation operations appear to be smaller sources of potential air emissions. Fugitive emissions have not been characterized but are potentially large. Emissions from the acid gas removal process depend on the kind of removal process employed at a plant. Processes used for acid gas removal may remove both sulfur compounds and CO_2 or may be operated

Table 11.11-1. SUMMARY OF EMISSIONS FROM COAL GASIFICATION PLANTS[1-3]

Operation/Emission Source/Stream	Characterization Of Emission	Summary Of Emission Control Choices
Coal Pretreatment		
Storage, handling, and crushing/sizing - Dust emissions	Emissions from coal storage, handling, and crushing/sizing mainly consist of coal dust. These emissions vary from site to site depending on wind velocities, coal and pile size, and water content.	Water sprays and polymer coatings are used to control dust emissions from coal storage piles. Water sprays and enclosed equipment are vented to a baghouse to reduce or capture particulates from coal handling. Emissions from crushing/sizing are also usually vented to a baghouse or other particulate control device.
Drying, partial oxidation, and briquetting - Vent gases	These emissions comprise coal dust and combustion gases along with a variety of organic compounds devolatilized from the coal. Organic species have not been determined.	In addition to particulate control devices, afterburners may be needed to destroy organic species.
Coal gasification		
Feeding - Vent gases	These gases contain all the hazardous species found in the raw product gas exiting the gasifier including H_2S, COS, CS_2, SO_2, CO, NH_3, CH_4, HCN, tars and oils, particulates, and trace organics and inorganics. The size and composition of this stream depend on the type of gasifier, e. g., fluidized bed gasifiers emit substantially fewer tars and oils than fixed bed gasifiers.	This stream could represent a significant environmental problem. Control could include scrubbing or incineration (to capture or destroy the most hazardous species), or venting to the raw product gas or gasifier inlet air. The desired control depends on the type and size of gasification facility. Screw fed conveyors can be used instead of lock hoppers.
Ash removal - Vent gases	Emissions from ash removal and disposal depend on the type of gasifier. Ash dust will be released from all gasifiers that are not slagging or agglomerating ash units. If contaminated water is used for ash quenching, volatile organic and inorganic species may be released from the quench liquor.	These emissions have not been sufficiently characterized to recommend necessary controls. Particluate or organic emission controls could be needed. Clean water may be used for quenching to avoid the potential emission of hazardous volatile organic and inorganic species.
Startup - Vent gases	This vent gas inititally resembles a coal combustion gas in composition. As the operating temperature of the gas increases, the startup gas begins to resemble the raw product gas.	A flare can incinerate the combustible constitutents in the startup gas, but heavy tars and coal particulates will affect the performance of the flare. Potential problems with tars and particulates can be avoided by using charcoal or coke as the startup fuel.

Table 11.11-1 (cont.).

Operation/Emission Source/Stream	Characterization Of Emission	Summary Of Emission Control Choices
Fugitives	These emissions have not been characterized, but they comprise hazardous species found in the raw product gas such as H_2S, COS, CS_2, CO, HCN, CH_4, and others.	Control methods mainly involve good maintenance and operating practices.
Raw Gas Cleaning/Benefication		
Fugitives	These emissions have not been characterized, but they comprise hazardous species found in the various gas streams. Other emissions result from leaks from pump seals, valves, flanges, and byproduct storage tanks.	Control methods mainly involve good maintenance and operating practices.
Acid Gas Removal - Tail gases	The composition of this stream highly depends on the kind of acid gas removal employed. Processes featuring the direct removal and conversion of sulfur species in a single step (e. g., the Stretford process) produce tail gases containing small amounts of HN_3 and other species. Processes absorbing and consequently desorbing a concentrated acid gas stream require a sulfur recovery process to avoid the emission of highly toxic gases having quantities of H_2S.	Some tail gas streams (from the Stretford process, for example) are probably not very hazardous. These streams have not been characterized, nor have control technology needs been demonstrated. Tail gases from other processes always require the removal of sulfur species. Trace constituents such as organics, trace elements and cyanides affect the performance of the auxiliary sulfur removal processes.
Auxiliary Operations		
Sulfur recovery	See Section 8.13	
Power and steam generation	See Section 1.1	
Waste Water Treatment - Expansion gases	These streams comprise volatile organic and inorganic species that desorb from quenching/cooling liquor. The streams potentially include all the hazardous species found in the product gas.	Three streams could pose significant environmental problems. Potential controls are generally similar to those needed to treat coal feeding vent gases.
Cooling Towers - Exhaust gas	Emissions from cooling towers are usually minor. However, if contaminated water is used as cooling water makeup, volatile organic and inorganic species from the contaminated water could be released.	The potential emission of hazardous volatile organic and inorganic species may be avoided by using clean water for cooling.

selectively to remove only the sulfur compounds. Typically, the acid gases are stripped from the solvent and processed in a sulfur plant. Some processes, however, directly convert the absorbed hydrogen sulfide to elemental sulfur. Emissions from these direct conversion processes (e. g., the Stretford process) have not been characterized but are probably minor, consisting of CO_2, air, moisture, and small amounts of NH_3.

Emission controls for 2 auxiliary processes (power and steam generation and sulfur recovery) are discussed elsewhere in this document (Sections 1.1 and 8.13, respectively). Gases stripped or desorbed from process waste waters are potentially hazardous, since they contain many of the components found in the product gas. These include sulfur and nitrogen species, organics, and other species that are toxic and potentially carcinogenic. Possible controls for these gases include incineration, byproduct recovery, or venting to the raw product gas or inlet air. Cooling towers are usually minor emission sources, unless the cooling water is contaminated.

11.11.2.2 Liquefaction -

The potential exists for generation of significant levels of atmospheric pollutants from every major operation in a coal liquefaction facility. These pollutants include coal dust, combustion products, fugitive organics, and fugitive gases. The fugitive organics and gases could include carcinogenic polynuclear organics, and toxic gases such as metal carbonyls, hydrogen sulfides, ammonia, sulfurous gases, and cyanides. Many studies are currently underway to characterize these emissions and to establish effective control methods. Table 11.11-2 presents information now available on liquefaction emissions.

Emissions from coal preparation include coal dust from the many handling operations and combustion products from the drying operation. The most significant pollutant from these operations is the coal dust from crushing, screening, and drying activities. Wetting down the surface of the coal, enclosing the operations, and venting effluents to a scrubber or fabric filter are effective means of particulate control.

A major source of emissions from the coal dissolution and liquefaction operation is the atmospheric vent on the slurry mix tank. The slurry mix tank is used for mixing feed coal and recycle solvent. Gases dissolved in the recycle solvent stream under pressure will flash from the solvent as it enters the unpressurized slurry mix tank. These gases can contain hazardous volatile organics and acid gases. Control techniques proposed for this source include scrubbing, incineration, or venting to the combustion air supply for either a power plant or a process heater.

Emissions from process heaters fired with waste process gas or waste liquids will consist of standard combustion products. Industrial combustion emission sources and available controls are discussed in Section 1.1.

The major emission source in the product separation and purification operations is the sulfur recovery plant tail gas. This can contain significant levels of acid or sulfurous gases. Emission factors and control techniques for sulfur recovery tail gases are discussed in Section 8.13.

Emissions from the residue gasifier used to supply hydrogen to the system are very similar to those for coal gasifiers previously discussed in this section.

Emissions from auxiliary processes include combustion products from onsite steam/electric power plant and volatile emissions from the waste water system, cooling towers, and fugitive emission sources. Volatile emissions from cooling towers, waste water systems, and fugitive

Table 11.11-2. SUMMARY OF EMISSIONS FROM A COAL GASIFICATION PLANTS[1]

Operation/Emission Source/Stream	Characterization Of Emission	Summary Of Emission Control Choices
Coal Preparation		
Storage, handling and crushing/sizing	Emissions primarily consist of fugitive coal dust generated at transfer points and points exposed to wind erosion. A potentially significant source.	Water sprays and polymer coatings are used to control dust from storage sites. Water sprays and enclosures vented to baghouses are effective on crushing and sizing operations.
Drying	Emissions include coal dust, combustion products from heater, and organics volatilized from the coal. A potentially significant particulate source.	Scrubbers, electrostatic precipitators, and baghouses are effective coal dust controls. Low drying temperatures reduce organics formation.
Coal Dissolution and Liquefaction		
Process heater (fired with low-grade fuel gas)	Emissions consist of combustion products (particulates, CO, SO_2, NO_x, and HC).	Fuel desulfurization for SO_2 control and combustion modifications for reduced CO, HC, and NO_x
Slurry mix tank	Evolution of dissolved gases from recycle solvent (HC, acid gases, organics) due to low pressure (atmospheric) of tank. Some pollutants are toxic even in small quantities.	Controls might include scrubbing, incineration, or venting to heater combustion air supply.
Product Separation and Liquefaction -		
Sulfur recovery plant	Tail gases containing acids (H_2S, SO_2, COS, CS_2, NH_3, and particulate sulfur).	Venting to tail gas treatment plant, or operating sulfur recovery plant at higher efficiency.
Residue Gasification	See 11.11.2.1 in text	
Auxiliary Processes		
Power and steam generation	See Section 1.1	
Waste water system	Volatile organics, acid gases, ammonia, and cyanides, that evolve from various waste water collection and treating systems.	Enclosure of the waste water system and venting gases from system to scrubbers or incinerators.
Cooling towers	Any chemical in the facility can leak to cooling water systems from leaking heat exchangers and can be stripped to the atmosphere in the cooling tower.	Good heat exchanger maintenance and surveillance of cooling water quality.
Fugitives	All organic and gaseous compounds in plant can leak from valves, flanges, seals, and sample ports. This may be the largest source of hazardous organics.	Good housekeeping, frequent maintenance, and selection of durable components are major control techniques.

emission sources possibly can include every chemical compound present in the plant. These sources will be the most significant and most difficult to control in a coal liquefaction facility. Compounds that can be present include hazardous organics, metal carbonyls, trace elements such as mercury, and toxic gases such as CO_2, H_2S, HCN, NH_3, COS, and CS_2.

Emission controls for waste water systems involve minimizing the contamination of water with hazardous compounds, enclosing the waste water systems, and venting the waste water systems to a scrubbing or incinerating system. Cooling tower controls focus on good heat exchanger maintenance, to prevent chemical leaks into the system, and on surveillance of cooling water quality. Fugitive emissions from various valves, seals, flanges, and sampling ports are individually small but collectively very significant. Diligent housekeeping and frequent maintenance, combined with a monitoring program, are the best controls for fugitive sources. The selection of durable low leakage components, such as double mechanical seals, is also effective.

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11.12 Concrete Batching

11.12 Process Description[1-4]

Concrete is composed essentially of water, cement, sand (fine aggregate), and coarse aggregate. Coarse aggregate may consist of gravel, crushed stone, or iron blast furnace slag. Some specialty aggregate products could be either heavyweight aggregate (of barite, magnetite, limonite, ilmenite, iron, or steel) or lightweight aggregate (with sintered clay, shale, slate, diatomaceous shale, perlite, vermiculite, slag, pumice, cinders, or sintered fly ash). Concrete batching plants store, convey, measure, and discharge these constituents into trucks for transport to a job site. In some cases, concrete is prepared at a building construction site or for the manufacture of concrete products such as pipes and prefabricated construction parts. Figure 11.12-1 is a generalized process diagram for concrete batching.

The raw materials can be delivered to a plant by rail, truck, or barge. The cement is transferred to elevated storage silos pneumatically or by bucket elevator. The sand and coarse aggregate are transferred to elevated bins by front end loader, clam shell crane, belt conveyor, or bucket elevator. From these elevated bins, the constituents are fed by gravity or screw conveyor to weigh hoppers, which combine the proper amounts of each material.

Truck mixed (transit mixed) concrete involves approximately 75 percent of U. S. concrete batching plants. At these plants, sand, aggregate, cement, and water are all gravity fed from the weigh hopper into the mixer trucks. The concrete is mixed on the way to the site where the concrete is to be poured. Central mix facilities (including shrink mixed) constitute the other one-fourth of the industry. With these, concrete is mixed and then transferred to either an open bed dump truck or an agitator truck for transport to the job site. Shrink mixed concrete is concrete that is partially mixed at the central mix plant and then completely mixed in a truck mixer on the way to the job site. Dry batching, with concrete mixed and hauled to the construction site in dry form, is seldom, if ever, used.

11.12-2 Emissions And Controls[5-7]

Emission factors for concrete batching are given in Tables 11.12-1 and 11.12-2, with potential air pollutant emission points shown. Particulate matter, consisting primarily of cement dust but including some aggregate and sand dust emissions, is the only pollutant of concern. All but one of the emission points are fugitive in nature. The only point source is the transfer of cement to the silo, and this is usually vented to a fabric filter or "sock". Fugitive sources include the transfer of sand and aggregate, truck loading, mixer loading, vehicle traffic, and wind erosion from sand and aggregate storage piles. The amount of fugitive emissions generated during the transfer of sand and aggregate depends primarily on the surface moisture content of these materials. The extent of fugitive emission control varies widely from plant to plant.

Types of controls used may include water sprays, enclosures, hoods, curtains, shrouds, movable and telescoping chutes, and the like. A major source of potential emissions, the movement of heavy trucks over unpaved or dusty surfaces in and around the plant, can be controlled by good maintenance and wetting of the road surface.

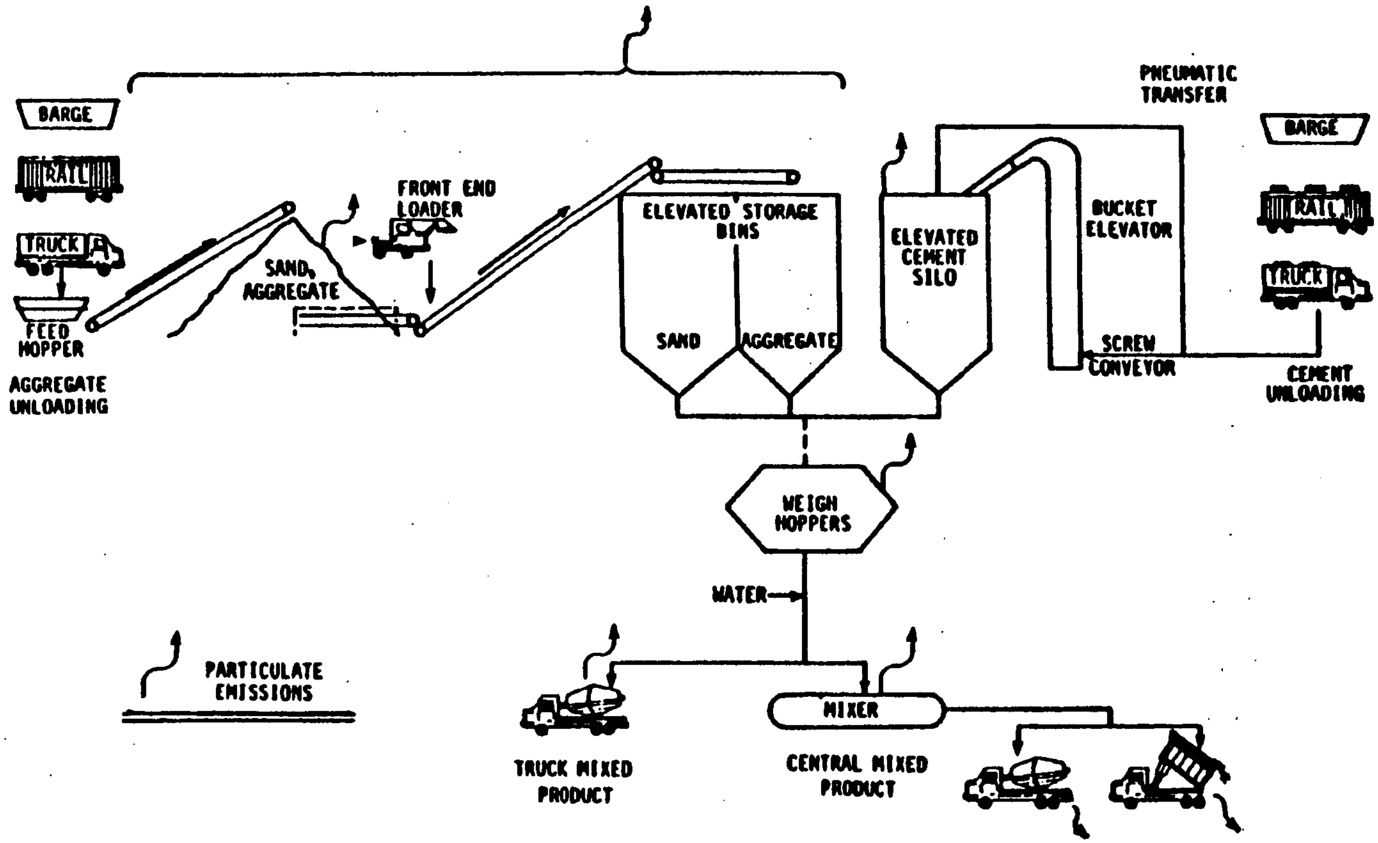

Figure 11.12-1. Typical concrete batching process.

Table 11.12-1 (Metric Units). EMISSION FACTORS FOR CONCRETE BATCHING[a]

	Filterable[b]			Condensable PM[c]	
Source (SCC)	PM	RATING	PM-10	Inorganic	Organic
Sand and aggregate transfer to elevated bin (3-05-011-06)[d]	0.014	E	ND	ND	ND
Cement unloading to elevated storage silo					
Pneumatic[e]	0.13	D	ND	ND	ND
Bucket elevator (3-05-011-07)[f]	0.12	E	ND	ND	ND
Weigh hopper loading (3-05-011-8)[g]	0.01	E	ND	ND	ND
Mixer loading (central mix) (3-05-011-09)[g]	0.02	E	ND	ND	ND
Truck loading (truck mix) (3-05-011-10)[g]	0.01	E	ND	ND	ND
Vehicle traffic (unpaved roads) (3-05-011-__)[h]	4.5	C	ND	ND	ND
Wind erosion from sand and aggregate storage piles (3-05-011__)[i]	3.9	D	ND	ND	ND
Total process emissions (truck mix)(3-05-011-__)[j]	0.05	E	ND	ND	ND

[a] Factors represent uncontrolled emissions unless otherwise noted. All emission factors are in kg/Mg of material mixed unless noted. Based on a typical yd^3 weighing 1.818 kg (4,000 lb) and containing 227 kg (500 lb) cement, 564 kg (1,240 lb) sand, 864 kg (1,900 lb) coarse aggregate, and 164 kg (360 lb) water. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 6.

[e] For uncontrolled emissions measured before filter. Based on 2 tests on pneumatic conveying controlled by a fabric filter.

[f] Reference 7. From test of mechanical unloading to hopper and subsequent transport of cement by enclosed bucket elevator to elevated bins with fabric socks over bin vent.

[g] Reference 5. Engineering judgment, based on observations and emissions tests of similar controlled sources.

[h] From Section 13.2-1, with $k = 0.8$, $s = 12$, $S = 20$, $W = 20$, $w = 14$, and $p = 100$; units of kg/vehicle kilometers traveled; based on facility producing 23,100 m^3/yr (30,000 yd^3/yr) of concrete, with average truck load of 6.2 m^3 (8 yd^3) and plant road length of 161 meters (0.1 mile).

[i] From Section 11.19-1, for emissions <30 micrometers from inactive storage piles; units of kg/hectare/day.

[j] Based on pneumatic conveying of cement at a truck mix facility. Does not include vehicle traffic or wind erosion from storage piles.

Table 11.12-2 (English Units). EMISSION FACTORS FOR CONCRETE BATCHING[a,b]

Source (SCC)	Filterable[c]			Condensable PM[d]	
	PM	RATING	PM-10	Inorganic	Organic
Sand and aggregate transfer to elevated bin (3-05-011-06)[e]	0.029 (0.05)	E	ND	ND	ND
Cement unloading to elevated storage silo					
Pneumatic[f]	0.27 (0.07)	D	ND	ND	ND
Bucket elevator (3-05-011-07)[g]	0.24 (0.06)	E	ND	ND	ND
Weigh hopper loading (3-05-011-08)[h]	0.02 (0.04)	E	ND	ND	ND
Mixer loading (central mix) (3-05-011-09)[h]	0.04 (0.07)	E	ND	ND	ND
Truck loading (truck mix) (3-05-011-10)[h]	0.02 (0.04)	E	ND	ND	ND
Vehicle traffic (unpaved roads) (3-05-011-__)[i]	16 (0.02)	C	ND	ND	ND
Wind erosion from sand and aggregate storage piles (3-05-011-__)[j]	3.5[k] (0.1)[l]	D	ND	ND	ND
Total process emissions (truck mix) (3-05-011-__)[m]	0.1 (0.2)	E	ND	ND	ND

[a] Factors represent uncontrolled emissions unless otherwise noted. All emission factors are in lb/ton (lb/yd^3) of material mixed unless noted. SCC = Source Classification Code. ND = no data.

[b] Based on a typical yd^3 weighing 1.818 kg (4,000 lb) and containing 227 kg (500 lb) cement, 564 kg (1,240 lb) sand, 864 kg (1,900 lb) coarse aggregate, and 164 kg (360 lb) water.

[c] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[d] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[e] Reference 6.

[f] For uncontrolled emissions measured before filter. Based on 2 tests on pneumatic conveying controlled by a fabric filter.

[g] Reference 7. From test of mechanical unloading to hopper and subsequent transport of cement by enclosed bucket elevator to elevated bins with fabric socks over bin vent.

[h] Reference 5. Engineering judgment, based on observations and emission tests of similar controlled sources.

[i] From Section 13.2.1, with $k = 0.8$, $s = 12$, $S = 20$, $W = 20$, $w = 14$, and $p = 100$; units of lb/vehicle miles traveled; based on facility producing 23,100 m^3/yr (30,000 yd^3/yr) of concrete, with average truck load of 6.2 m^3 (8 yd^3) and plant road length of 161 meters (0.1 mile).

[j] From Section 11.19.1, for emissions <30 micrometers from inactive storage piles.

[k] Units of lb/acre/day.

[l] Assumes 1,011 m^2 (1/4 acre) of sand and aggregate storage at plant with production of 23,000 m^3/yr (30,000 yd^3/yr).

[m] Based on pneumatic conveying of cement at a truck mix facility; does not include vehicle traffic or wind erosion from storage piles.

Predictive equations that allow for emission factor adjustment based on plant-specific conditions are given in Chapter 13. Whenever plant specific data are available, they should be used in lieu of the fugitive emission factors presented in Table 11.12-1.

References For Section 11.12

1. *Air Pollutant Emission Factors*, APTD-0923, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1970.

2. *Air Pollution Engineering Manual*, 2nd Edition, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1974. Out of Print.

3. Telephone and written communication between Edwin A. Pfetzing, PEDCo Environmental, Inc., Cincinnati, OH, and Richard Morris and Richard Meininger, National Ready Mix Concrete Association, Silver Spring, MD, May 1984.

4. *Development Document For Effluent Limitations Guidelines And Standards Of Performance, The Concrete Products Industries, Draft*, U. S. Environmental Protection Agency, Washington, DC, August 1975.

5. *Technical Guidance For Control Of Industrial Process Fugitive Particulate Emissions*, EPA-450/3-77-010, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1977.

6. *Fugitive Dust Assessment At Rock And Sand Facilities In The South Coast Air Basin*, Southern California Rock Products Association and Southern California Ready Mix Concrete Association, Santa Monica, CA, November 1979.

7. Telephone communication between T. R. Blackwood, Monsanto Research Corp., Dayton, OH, and John Zoller, PEDCo Environmental, Inc., Cincinnati, OH, October 18, 1976.

11.13 Glass Fiber Manufacturing

11.13.1 General[1-4]

Glass fiber manufacturing is the high-temperature conversion of various raw materials (predominantly borosilicates) into a homogeneous melt, followed by the fabrication of this melt into glass fibers. The 2 basic types of glass fiber products, textile and wool, are manufactured by similar processes. A typical diagram of these processes is shown in Figure 11.13-1. Glass fiber production can be segmented into 3 phases: raw materials handling, glass melting and refining, and wool glass fiber forming and finishing, this last phase being slightly different for textile and wool glass fiber production.

Raw Materials Handling -

The primary component of glass fiber is sand, but it also includes varying quantities of feldspar, sodium sulfate, anhydrous borax, boric acid, and many other materials. The bulk supplies are received by rail car and truck, and the lesser-volume supplies are received in drums and packages. These raw materials are unloaded by a variety of methods, including drag shovels, vacuum systems, and vibrator/gravity systems. Conveying to and from storage piles and silos is accomplished by belts, screws, and bucket elevators. From storage, the materials are weighed according to the desired product recipe and then blended well before their introduction into the melting unit. The weighing, mixing, and charging operations may be conducted in either batch or continuous mode.

Glass Melting And Refining -

In the glass melting furnace, the raw materials are heated to temperatures ranging from 1500 to 1700°C (2700 to 3100°F) and are transformed through a sequence of chemical reactions to molten glass. Although there are many furnace designs, furnaces are generally large, shallow, and well-insulated vessels that are heated from above. In operation, raw materials are introduced continuously on top of a bed of molten glass, where they slowly mix and dissolve. Mixing is effected by natural convection, gases rising from chemical reactions, and, in some operations, by air injection into the bottom of the bed.

Glass melting furnaces can be categorized by their fuel source and method of heat application into 4 types: recuperative, regenerative, unit, and electric melter. The recuperative, regenerative, and unit melter furnaces can be fueled by either gas or oil. The current trend is from gas-fired to oil-fired. Recuperative furnaces use a steel heat exchanger, recovering heat from the exhaust gases by exchange with the combustion air. Regenerative furnaces use a lattice of brickwork to recover waste heat from exhaust gases. In the initial mode of operation, hot exhaust gases are routed through a chamber containing a brickwork lattice, while combustion air is heated by passage through another corresponding brickwork lattice. About every 20 minutes, the airflow is reversed, so that the combustion air is always being passed through hot brickwork previously heated by exhaust gases. Electric furnaces melt glass by passing an electric current through the melt. Electric furnaces are either hot-top or cold-top. The former use gas for auxiliary heating, and the latter use only the electric current. Electric furnaces are currently used only for wool glass fiber production because of the electrical properties of the glass formulation. Unit melters are used only for the "indirect" marble melting process, getting raw materials from a continuous screw at the back of the furnace adjacent to the exhaust air discharge. There are no provisions for heat recovery with unit melters.

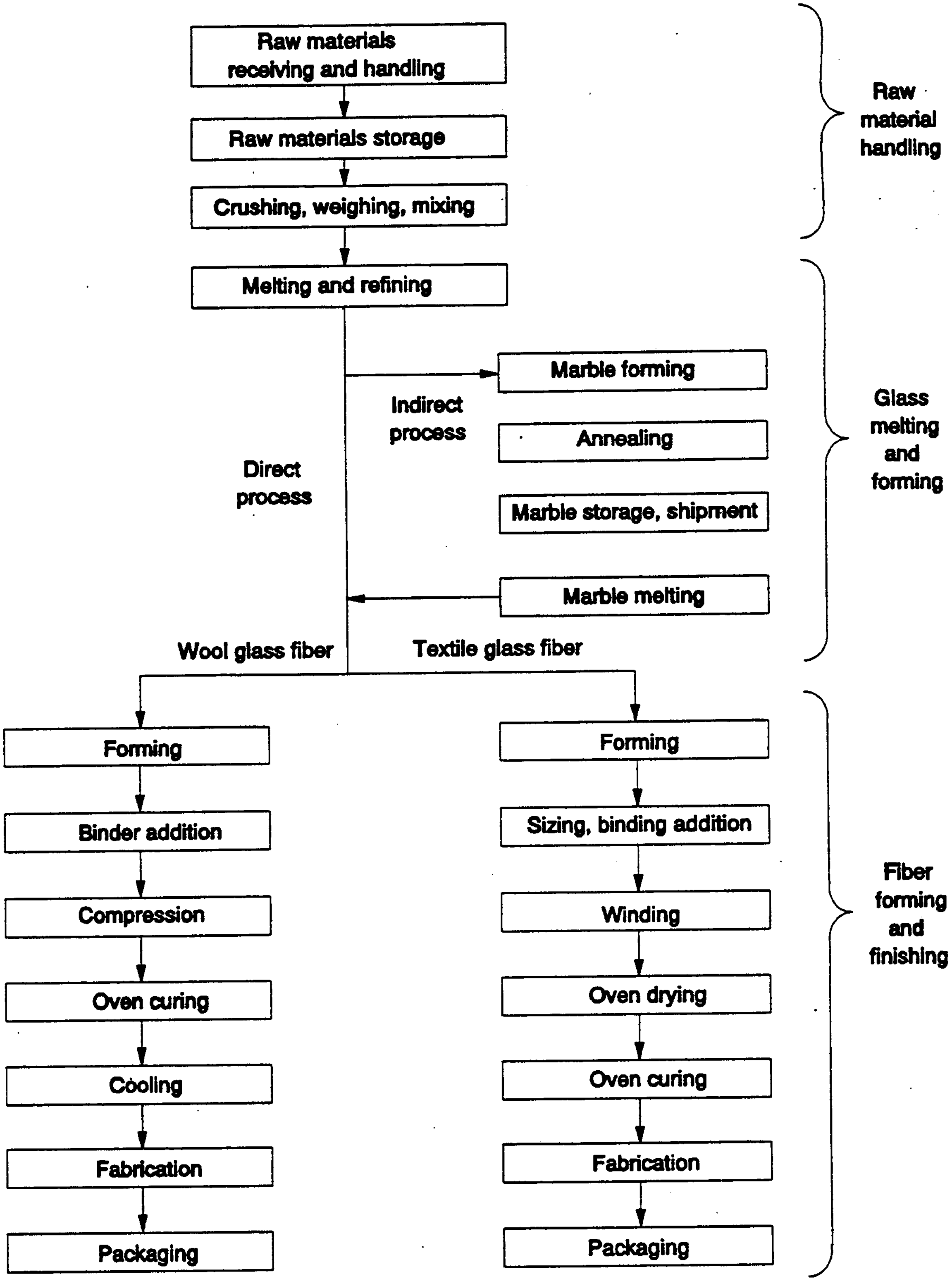

Figure 11.13-1. Typical flow diagram of the glass fiber production process.

In the "indirect" melting process, molten glass passes to a forehearth, where it is drawn off, sheared into globs, and formed into marbles by roll-forming. The marbles are then stress-relieved in annealing ovens, cooled, and conveyed to storage or to other plants for later use. In the "direct" glass fiber process, molten glass passes from the furnace into a refining unit, where bubbles and particles are removed by settling, and the melt is allowed to cool to the proper viscosity for the fiber forming operation.

Wool Glass Fiber Forming And Finishing -

Wool fiberglass is produced for insulation and is formed into mats that are cut into batts. (Loose wool is primarily a waste product formed from mat trimming, although some is a primary product, and is only a small part of the total wool fiberglass produced. No specific emission data for loose wool production are available.) The insulation is used primarily in the construction industry and is produced to comply with ASTM C167-64, the "Standard Test Method for Thickness and Density of Blanket- or Batt-Type Thermal Insulating Material".

Wool fiberglass insulation production lines usually consist of the following processes: (1) preparation of molten glass, (2) formation of fibers into a wool fiberglass mat, (3) curing the binder-coated fiberglass mat, (4) cooling the mat, and (5) backing, cutting, and packaging the insulation. Fiberglass plants contain various sizes, types, and numbers of production lines, although a typical plant has 3 lines. Backing (gluing a flat flexible material, usually paper, to the mat), cutting, and packaging operations are not significant sources of emissions to the atmosphere.

The trimmed edge waste from the mat and the fibrous dust generated during the cutting and packaging operations are collected by a cyclone and either are transported to a hammer mill to be chopped into blown wool (loose insulation) and bulk packaged or are recycled to the forming section and blended with newly formed product.

During the formation of fibers into a wool fiberglass mat (the process known as "forming" in the industry), glass fibers are made from molten glass, and a chemical binder is simultaneously sprayed on the fibers as they are created. The binder is a thermosetting resin that holds the glass fibers together. Although the binder composition varies with product type, typically the binder consists of a solution of phenol-formaldehyde resin, water, urea, lignin, silane, and ammonia. Coloring agents may also be added to the binder. Two methods of creating fibers are used by the industry. In the rotary spin process, depicted in Figure 11.13-2, centrifugal force causes molten glass to flow through small holes in the wall of a rapidly rotating cylinder to create fibers that are broken into pieces by an air stream. This is the newer of the 2 processes and dominates the industry today. In the flame attenuation process, molten glass flows by gravity from a furnace through numerous small orifices to create threads that are then attenuated (stretched to the point of breaking) by high velocity, hot air, and/or a flame. After the glass fibers are created (by either process) and sprayed with the binder solution, they are collected by gravity on a conveyor belt in the form of a mat.

The conveyor carries the newly formed mat through a large oven to cure the thermosetting binder and then through a cooling section where ambient air is drawn down through the mat. Figure 11.13-3 presents a schematic drawing of the curing and cooling sections. The cooled mat remains on the conveyor for trimming of the uneven edges. Then, if product specifications require it, a backing is applied with an adhesive to form a vapor barrier. The mat is then cut into batts of the desired dimensions and packaged.

Textile Glass Fiber Forming And Finishing -

Molten glass from either the direct melting furnace or the indirect marble melting furnace is temperature-regulated to a precise viscosity and delivered to forming stations. At the forming

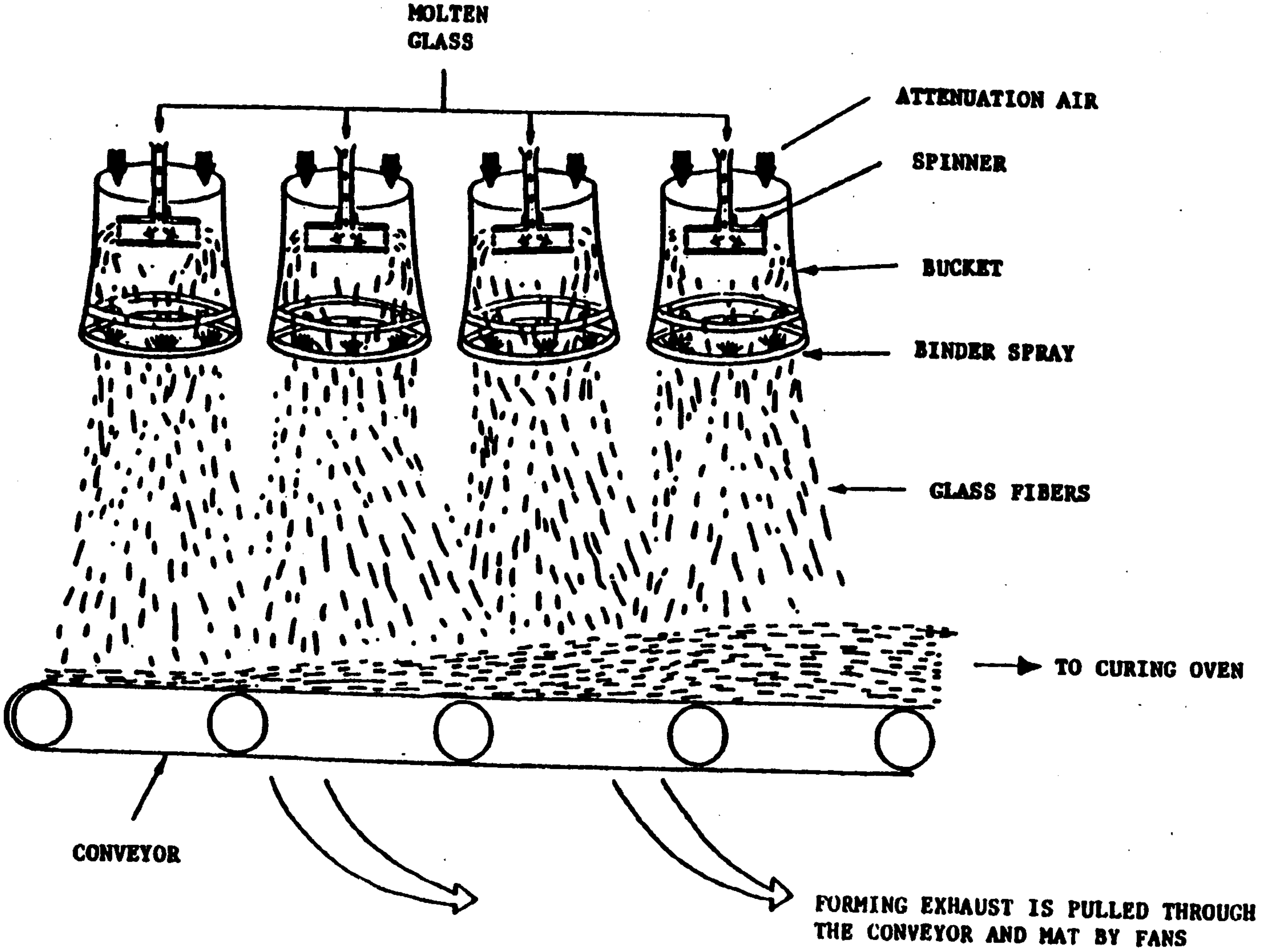

Figure 11.13-2. A typical spin process.

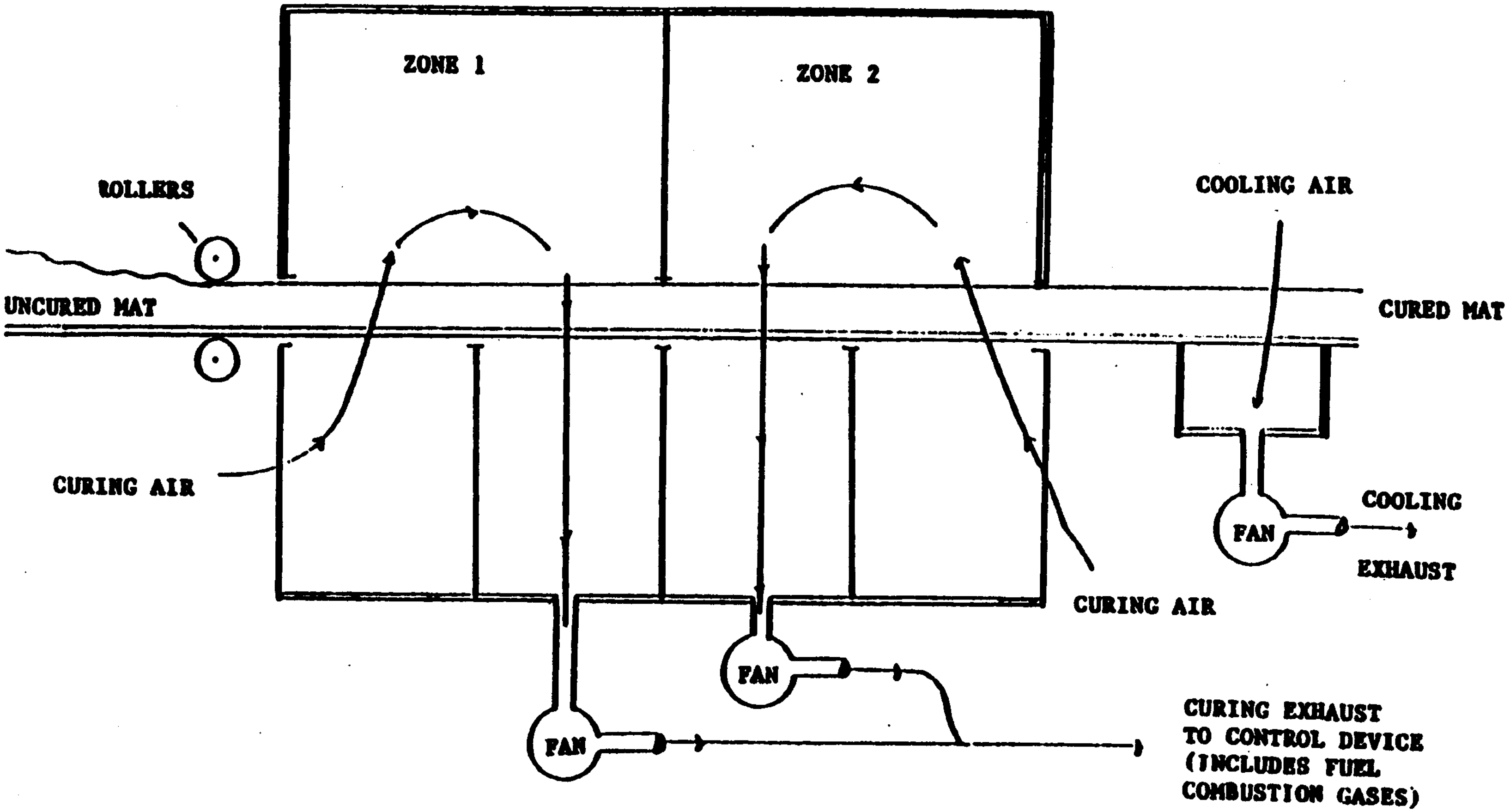

Figure 11.13-3. Side view of curing oven (indirect heating) and cooling section.

stations, the molten glass is forced through heated platinum bushings containing numerous very small openings. The continuous fibers emerging from the openings are drawn over a roller applicator, which applies a coating of a water-soluble sizing and/or coupling agent. The coated fibers are gathered and wound into a spindle. The spindles of glass fibers are next conveyed to a drying oven, where moisture is removed from the sizing and coupling agents. The spindles are then sent to an oven to cure the coatings. The final fabrication includes twisting, chopping, weaving, and packaging the fiber.

11.13.2 Emissions And Controls[1,3,4]

Emissions and controls for glass fiber manufacturing can be categorized by the 3 production phases with which they are associated. Emission factors for the glass fiber manufacturing industry are given in Tables 11.13-1, 11.13-2, and 11.13-3.

Raw Materials Handling -

The major emissions from the raw materials handling phase are fugitive dust and raw material particles generated at each of the material transfer points. Such a point would be where sand pours from a conveyor belt into a storage silo. The 2 major control techniques are wet or moist handling and fabric filters. When fabric filters are used, the transfer points are enclosed, and air from the transfer area is continuously circulated through the fabric filters.

Glass Melting And Refining -

The emissions from glass melting and refining include volatile organic compounds from the melt, raw material particles entrained in the furnace flue gas, and, if furnaces are heated with fossil fuels, combustion products. The variation in emission rates among furnaces is attributable to varying operating temperatures, raw material compositions, fuels, and flue gas flow rates. Of the various types of furnaces used, electric furnaces generally have the lowest emission rates, because of the lack of combustion products and of the lower temperature of the melt surface caused by bottom heating. Emission control for furnaces is primarily fabric filtration. Fabric filters are effective on particulate matter (PM) and sulfur oxides (SO_x) and, to a lesser extent, on carbon monoxide (CO), nitrogen oxides (NO_x), and fluorides. The efficiency of these compounds is attributable to both condensation on filterable PM and chemical reaction with PM trapped on the filters. Reported fabric filter efficiencies on regenerative and recuperative wool furnaces are for PM, 95+ percent; SO_x, 99+ percent; CO, 30 percent; and fluoride, 91 to 99 percent. Efficiencies on other furnaces are lower because of lower emission loading and pollutant characteristics.

Wool Fiber Forming And Finishing -

Emissions generated during the manufacture of wool fiberglass insulation include solid particles of glass and binder resin, droplets of binder, and components of the binder that have vaporized. Glass particles may be entrained in the exhaust gas stream during forming, curing, or cooling operations. Test data show that approximately 99 percent of the total emissions from the production line are emitted from the forming and curing sections. Even though cooling emissions are negligible at some plants, cooling emissions at others may include fugitives from the curing section. This commingling of emissions occurs because fugitive emissions from the open terminal end of the curing oven may be induced into the cooling exhaust ductwork and be discharged into the atmosphere. Solid particles of resin may be entrained in the gas stream in either the curing or cooling sections. Droplets of organic binder may be entrained in the gas stream in the forming section or may be a result of condensation of gaseous pollutants as the gas stream is cooled. Some of the liquid binder used in the forming section is vaporized by the elevated temperatures in the forming and curing processes. Much of the vaporized material will condense when the gas stream cools in the ductwork or in the emission control device.

Table 11.13-1 (Metric Units). EMISSION FACTORS FOR GLASS FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: B

Source	Filterable[b]		Condensable PM[c]	
	PM	PM-10	Inorganic	Organic
	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg of Material Processed
Unloading and conveying (SCC 3-05-012-21)[d]	1.5	ND	ND	ND
Storage bins (SCC 3-05-012-22)[d]	0.1	ND	ND	ND
Mixing and weighing (SCC 3-05-012-23)[d]	0.3	ND	ND	ND
Crushing and batch charging (SCC 3-05-012-24)[d]	Neg	ND	ND	ND
Glass furnace - wool[e]				
Electric (SCC 3-05-012-03)	0.25	ND	ND	ND
Gas - regenerative (SCC 3-05-012-02)	11	ND	ND	ND
Gas - recuperative (SCC 3-05-012-01)	13 - 15	ND	ND	ND
Gas - unit melter (SCC 3-05-012-07)	4.5	ND	ND	ND
Glass furnace - textile[e]				
Gas - recuperative (SCC 3-05-012-12)	1	ND	ND	ND
Gas - regenerative (SCC 3-05-012-11)	8	ND	ND	ND
Gas - unit melter (SCC 3-05-012-13)	3	ND	ND	ND
Forming - wool				
Flame attenuation (SCC 3-05-012-08)[e]	1	ND	ND	ND
Forming - textile (SCC 3-05-012-14)[e]	0.5	ND	ND	ND
Oven curing - wool				
Flame attenuation (SCC 3-05-012-09)[e]	3	ND	ND	ND
Oven curing and cooling - textile (SCC 3-05-012-15)[e]	0.6	ND	ND	ND

Table 11.13-1 (cont.).

Source	Filterable[b]		Condensable PM[c]	
	PM	PM-10	Inorganic	Organic
	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed
Rotary spin wool glass manufacturing (3-05-012-04)[f]				
R-19	17.81	ND	ND	4.25
R-11	19.61	ND	ND	3.19
Ductboard	27.72	ND	ND	8.55
Heavy density	4.91	ND	ND	1.16

[a] Factors are uncontrolled, unless otherwise noted. SCC = Source Classification Code. ND = no data. Neg = negligible.

[b] Filterable PM is that PM collected on or before to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 1.

[e] Reference 5.

[f] Reference 4. Units are expressed kg/Mg of finished product.

Table 11.13-2 (English Units). EMISSION FACTORS FOR GLASS FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: B

Source	Filterable[b]		Condensable PM[c]	
	PM	PM-10	Inorganic	Organic
	lb/ton Of Material Processed	lb/ton Of Material Processed	lb/ton Of Material Processed	lb/ton Of Material Processed
Unloading and conveying (SCC 3-05-012-21)[d]	3.0	ND	ND	ND
Storage bins (SCC 3-05-012-22)[d]	0.2	ND	ND	ND
Mixing and weighing (SCC 3-05-012-23)[d]	0.6	ND	ND	ND
Crushing and batch charging (SCC 3-05-012-24)[d]	Neg	ND	ND	ND
Glass furnace - wool[e]				
Electric (SCC 3-05-012-03)	0.5	ND	ND	ND
Gas - recuperative (SCC 3-05-012-02)	22	ND	ND	ND
Gas - regenerative (SCC 3-05-012-01)	25 - 30	ND	ND	ND
Gas - unit melter (SCC 3-05-012-07)	9	ND	ND	ND
Glass furnace - textile[e]				
Gas - recuperative (SCC 3-05-012-12)	2	ND	ND	ND
Gas - regenerative (SCC 3-05-012-11)	16	ND	ND	ND
Gas - unit melter (SCC 3-05-012-13)	6	ND	ND	ND
Forming - wool				
Flame attenuation (SCC 3-05-012-08)[e]	2	ND	ND	ND
Forming - textile (SCC 3-05-012-14)[e]	1	ND	ND	ND
Oven curing - wool				
Flame attenuation (SCC 3-05-012-09)[e]	6	ND	ND	ND
Oven curing and cooling - textile (SCC 3-05-012-15)[e]	1.2	ND	ND	ND

Table 11.13-2 (cont.).

Source	Filterable[b]		Condensable PM[c]	
	PM	PM-10	Inorganic	Organic
	lb/ton Of Material Processed	lb/ton Of Material Processed	lb/ton Of Material Processed	lb/ton Of Material Processed
Rotary spin wool glass manufacturing (SCC 3-05-012-04)[f]				
R-19	36.21	ND	ND	8.52
R-11	39.21	ND	ND	6.37
Ductboard	55.42	ND	ND	17.08
Heavy density	9.81	ND	ND	2.33

[a] Factors are uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data. Neg = negligible.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 1.

[e] Reference 5.

[f] Reference 4. Units are lb/ton of finished product.

Table 11.13-3 (Metric Units). EMISSION FACTORS FOR GLASS FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: B

Source	SO_x	NO_x	CO
	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed
Glass furnace - wool[b]			
Electric (SCC 3-05-012-03)	0.02	0.14	0.025
Gas - regenerative (SCC 3-05-012-01)	5	2.5	0.13
Gas - recuperative (SCC 3-05-012-02)	5	0.85	0.13
Gas - unit melter (SCC 3-05-012-07)	0.3	0.15	0.13
Glass furnace - textile[b]			
Gas - recuperative (SCC 3-05-012-12)	1.5	10	0.25
Gas - regenerative (SCC 3-05-012-11)	15	10	0.5
Gas - unit melter (SCC 3-05-012-13)	ND	10	0.45
Forming - wool[b]			
Flame attenuation (SCC 3-05-012-08)	NA	NA	NA
Forming - textile[b] (SCC 3-05-012-14)	NA	NA	NA
Oven curing - wool[b]			
Flame attenuation (SCC 3-05-012-09)	ND	1	1.8
Oven curing and cooling - textile[b] (SCC 3-05-012-15)	NA	1.3	0.75

[a] Factors are uncontrolled unless otherwise noted. SCC = Source Classification Code. ND = no data. NA = not applicable.
[b] Reference 5.

Table 11.13-4 (English Units). EMISSION FACTORS FOR GLASS FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: B

Source	SO_x	NO_x	CO
	lb/ton Of Material Processed	lb/ton Of Material Processed	lb/ton Of Material Processed
Glass furnace - wool			
Electric (SCC 3-05-012-03)[b]	0.04	0.27	0.05
Gas - regenerative (SCC 3-05-012-01)	10	5	0.25
Gas - recuperative (SCC 3-05-012-02)	10	1.7	0.25
Gas - unit melter (SCC 3-05-012-07)	0.6	0.3	0.25
Glass furnace - textile			
Gas - recuperative (SCC 3-05-012-12)[b]	3	20	0.5
Gas - regenerative (SCC 3-05-012-11)	30	20	1
Gas - unit melter (SCC 3-05-012-13)	ND	20	0.9
Forming - wool			
Flame attenuation (SCC 3-05-012-08)[b]	NA	NA	NA
Forming - textile (SCC 3-05-012-14)[b]	NA	NA	NA
Oven curing - wool			
Flame attenuation (SCC 3-05-012-09)[b]	ND	2	3.5
Oven curing and cooling - textile (SCC 3-05-012-15)[b]	NA	2.6	1.5

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 5.

Table 11.13-5 (Metric Units). EMISSION FACTORS FOR GLASS FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: B

Source	VOC	Phenolics	Phenol	Formaldehyde	Fluorides
	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed	kg/Mg Of Material Processed
Glass furnace - wool					
Electric (SCC 3-05-012-03)[b]	ND	ND	ND	ND	0.001
Gas - regenerative (SCC 3-05-012-01)	ND	ND	ND	ND	0.06
Gas - recuperative (SCC 3-05-012-02)	ND	ND	ND	ND	0.06
Gas - unit melter (SCC 3-05-012-07)	ND	ND	ND	ND	0.06
Glass furnace - textile[b]					
Gas - recuperative (SCC 3-05-012-12)	ND	ND	ND	ND	1
Gas - regenerative (SCC 3-05-012-11)	ND	ND	ND	ND	1
Gas - unit melter (SCC 3-05-012-13)	ND	ND	ND	ND	1
Forming - wool					
Flame attenuation (SCC 3-05-012-08)[b]	0.15	ND	ND	ND	ND
Forming - textile (SCC 3-05-012-14)[b]	Neg	ND	ND	ND	NA
Oven curing - wool					
Flame attenuation (SCC 3-05-012-09)[b]	3.5	ND	ND	ND	ND
Oven curing and cooling - textile (SCC 3-05-012-15)[b]	Neg	ND	ND	ND	ND
Rotary spin wool glass fiber manufacturing (SCC 3-05-012-04)[c]					
R-19	ND	3.21	0.96	0.75	ND
R-11	ND	6.21	0.92	1.23	ND
Ductboard	ND	10.66	3.84	1.80	ND
Heavy density	ND	0.88	0.53	0.43	ND

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data. NA = not applicable. Neg = negligible.

[b] Reference 5.

[c] Reference 4.

Table 11.13-6 (English Units). EMISSION FACTORS FOR GLASS FIBER MANUFACTURING[a]

EMISSION FACTOR RATING: B

Source	VOC lb/ton Of Material Processed	Phenolics lb/ton Of Material Processed	Phenol lb/ton Of Material Processed	Formaldehyde lb/ton Of Material Processed	Fluorides lb/ton Of Material Processed
Glass furnace - wool					
Electric (SCC 3-05-012-03)[b]	ND	ND	ND	ND	0.002
Gas - regenerative (SC 3-05-012-01)	ND	ND	ND	ND	0.12
Gas - recuperative (SCC 3-05-012-02)	ND	ND	ND	ND	0.11
Gas - unit melter (SCC 3-05-012-07)	ND	ND	ND	ND	0.12
Glass furnace - textile[b]					
Gas - recuperative (SCC 3-05-021-12)	ND	ND	ND	ND	2
Gas - regenerative (SCC 3-05-021-11)	ND	ND	ND	ND	2
Gas - unit melter (SCC 3-05-021-13)	ND	ND	ND	ND	2
Forming - wool					
Flame attenuation (SCC 3-05-021-08)[b]	0.3	ND	ND	ND	ND
Forming - textile (SCC 3-05-021-14)[b]	Neg	ND	ND	ND	NA
Oven curing - wool					
Flame attenuation (SCC 3-05-021-09)[b]	7	ND	ND	ND	ND
Oven curing and cooling - textile (SCC 3-05-021-15)[b]	Neg	ND	ND	ND	ND
Rotary spin wool glass fiber manufacturing (SCC 3-05-021-04)[f]					
R-19	ND	6.92	1.92	1.50	ND
R-11	ND	12.41	1.84	2.46	ND
Ductboard	ND	21.31	7.68	3.61	ND
Heavy duty	ND	1.74	1.04	0.85	ND

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data. NA = not applicable. Neg = negligible.

[b] Reference 5.

[c] Reference 4.

Particulate matter is the principal pollutant that has been identified and measured at wool fiberglass insulation manufacturing facilities. It was known that some fraction of the PM emissions results from condensation of organic compounds used in the binder. Therefore, in evaluating emissions and control device performance for this source, a sampling method, EPA Reference Method 5E, was used that permitted collection and measurement of both solid particles and condensed PM.

Tests were performed during the production of R-11 building insulation, R-19 building insulation, ductboard, and heavy-density insulation. These products, which account for 91 percent of industry production, had densities ranging from 9.1 to 12.3 kilograms per cubic meter (kg/m^3) (0.57 to 0.77 pounds per cubic foot [lb/ft^3]) for R-11, 8.2 to 9.3 kg/m^3 (0.51 to 0.58 lb/ft^3) for R-19, and 54.5 to 65.7 kg/m^3 (3.4 to 4.1 lb/ft^3) for ductboard. The heavy-density insulation had a density of 118.5 kg/m^3 (7.4 lb/ft^3). (The remaining 9 percent of industry wool fiberglass production is a variety of specialty products for which qualitative and quantitative information is not available.) The loss on ignition (LOI) of the product is a measure of the amount of binder present. The LOI values ranged from 3.9 to 6.5 percent, 4.5 to 4.6 percent, and 14.7 to 17.3 percent for R-11, R-19, and ductboard, respectively. The LOI for heavy-density insulation is 10.6 percent. A production line may be used to manufacture more than one of these product types because the processes involved do not differ. Although the data base did not show sufficient differences in mass emission levels to establish separate emission standards for each product, the uncontrolled emission factors are sufficiently different to warrant their segregation for AP-42.

The level of emissions control found in the wool fiberglass insulation manufacturing industry ranges from uncontrolled to control of forming, curing, and cooling emissions from a line. The exhausts from these process operations may be controlled separately or in combination. Control technologies currently used by the industry include wet ESPs, low- and high-pressure-drop wet scrubbers, low- and high-temperature thermal incinerators, high-velocity air filters, and process modifications. These added control technologies are available to all firms in the industry, but the process modifications used in this industry are considered confidential. Wet ESPs are considered to be best demonstrated technology for the control of emissions from wool fiberglass insulation manufacturing lines. Therefore, it is expected that most new facilities will be controlled in this manner.

Textile Fiber Forming And Finishing -

Emissions from the forming and finishing processes include glass fiber particles, resin particles, hydrocarbons (primarily phenols and aldehydes), and combustion products from dryers and ovens. Emissions are usually lower in the textile fiber glass process than in the wool fiberglass process because of lower turbulence in the forming step, roller application of coatings, and use of much less coating per ton of fiber produced.

References For Section 11.13

1. J. R. Schorr *et al.*, *Source Assessment: Pressed And Blown Glass Manufacturing Plants*, EPA-600/2-77-005, U. S. Environmental Protection Agency, Cincinnati, OH, January 1977.

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3. *Standard Of Performance For Wool Fiberglass Insulation Manufacturing Plants*, 50 FR 7700, February 25, 1985.

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11.14 Frit Manufacturing

[Work In Progress]

11.15 Glass Manufacturing

11.15.1 General[1-5]

Commercially produced glass can be classified as soda-lime, lead, fused silica, borosilicate, or 96 percent silica. Soda-lime glass, since it constitutes 77 percent of total glass production, is discussed here. Soda-lime glass consists of sand, limestone, soda ash, and cullet (broken glass). The manufacture of such glass is in four phases: (1) preparation of raw material, (2) melting in a furnace, (3) forming and (4) finishing. Figure 11.15-1 is a diagram for typical glass manufacturing.

The products of this industry are flat glass, container glass, and pressed and blown glass. The procedures for manufacturing glass are the same for all products except forming and finishing. Container glass and pressed and blown glass, 51 and 25 percent respectively of total soda-lime glass production, use pressing, blowing or pressing and blowing to form the desired product. Flat glass, which is the remainder, is formed by float, drawing, or rolling processes.

As the sand, limestone, and soda ash raw materials are received, they are crushed and stored in separate elevated bins. These materials are then transferred through a gravity feed system to a weigher and mixer, where the material is mixed with cullet to ensure homogeneous melting. The mixture is conveyed to a batch storage bin where it is held until dropped into the feeder to the melting furnace. All equipment used in handling and preparing the raw material is housed separately from the furnace and is usually referred to as the batch plant. Figure 11.15-2 is a flow diagram of a typical batch plant.

The furnace most commonly used is a continuous regenerative furnace capable of producing between 45 and 272 megagrams (Mg) (50 and 300 tons) of glass per day. A furnace may have either side or end ports that connect brick checkers to the inside of the melter. The purpose of brick checkers (Figure 11.15-3 and Figure 11.15-4) is to conserve fuel by collecting furnace exhaust gas heat that, when the air flow is reversed, is used to preheat the furnace combustion air. As material enters the melting furnace through the feeder, it floats on the top of the molten glass already in the furnace. As it melts, it passes to the front of the melter and eventually flows through a throat leading to the refiner. In the refiner, the molten glass is heat conditioned for delivery to the forming process. Figures 11.15-3 and 11.15-4 show side port and end port regenerative furnaces.

After refining, the molten glass leaves the furnace through forehearths (except in the float process, with molten glass moving directly to the tin bath) and goes to be shaped by pressing, blowing, pressing and blowing, drawing, rolling, or floating to produce the desired product. Pressing and blowing are performed mechanically, using blank molds and glass cut into sections (gobs) by a set of shears. In the drawing process, molten glass is drawn upward in a sheet through rollers, with thickness of the sheet determined by the speed of the draw and the configuration of the draw bar. The rolling process is similar to the drawing process except that the glass is drawn horizontally on plain or patterned rollers and, for plate glass, requires grinding and polishing. The float process is different, having a molten tin bath over which the glass is drawn and formed into a finely finished surface requiring no grinding or polishing. The end product undergoes finishing (decorating or coating) and annealing (removing unwanted stress areas in the glass) as required, and is then inspected and prepared for shipment to market. Any damaged or undesirable glass is transferred back to the batch plant to be used as cullet.

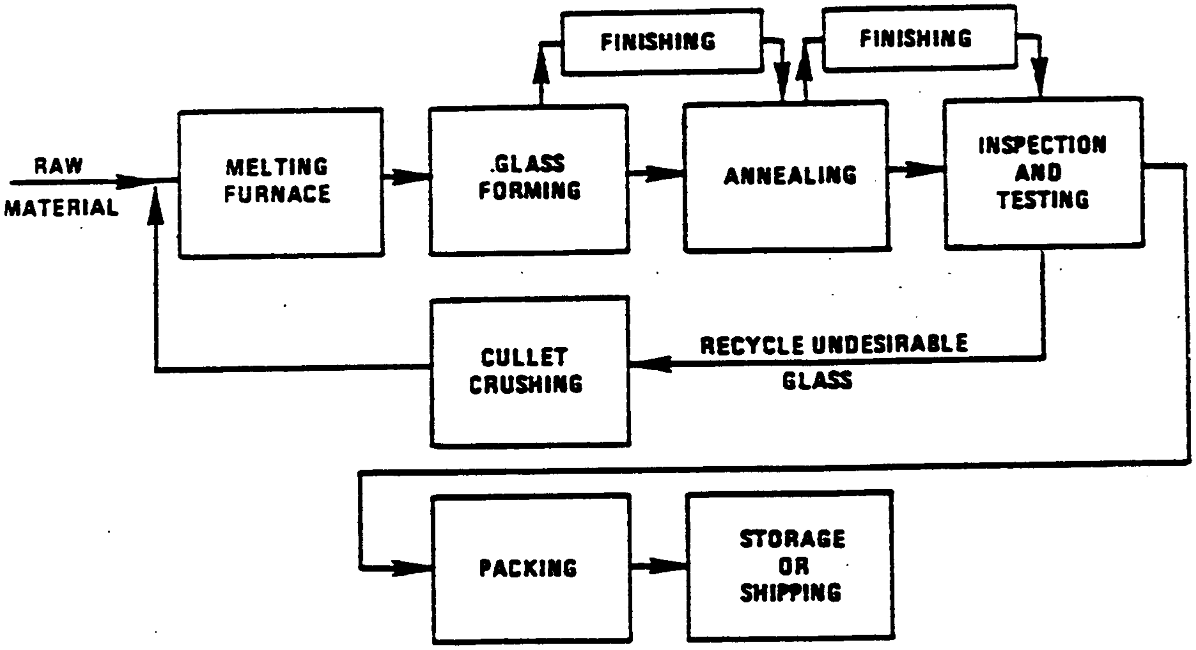

Figure 11.15-1. Typical glass manufacturing process.

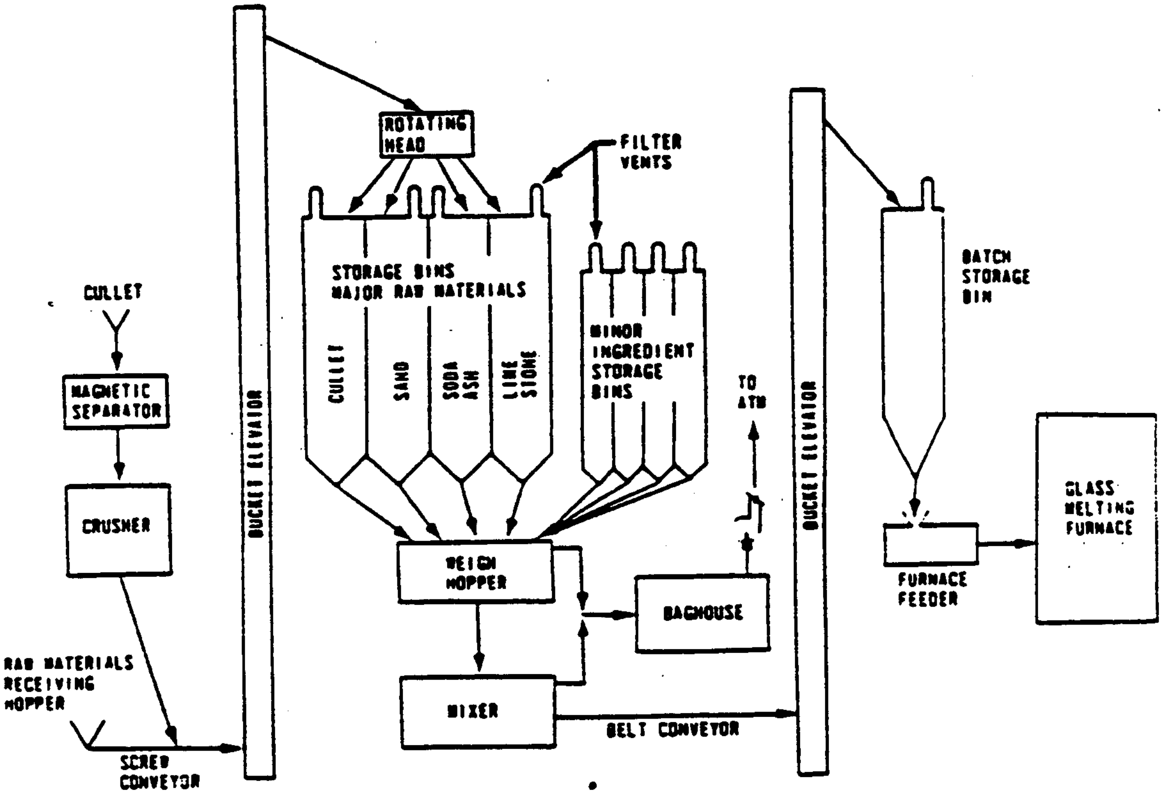

Figure 11.15-2. General diagram of a batch plant.

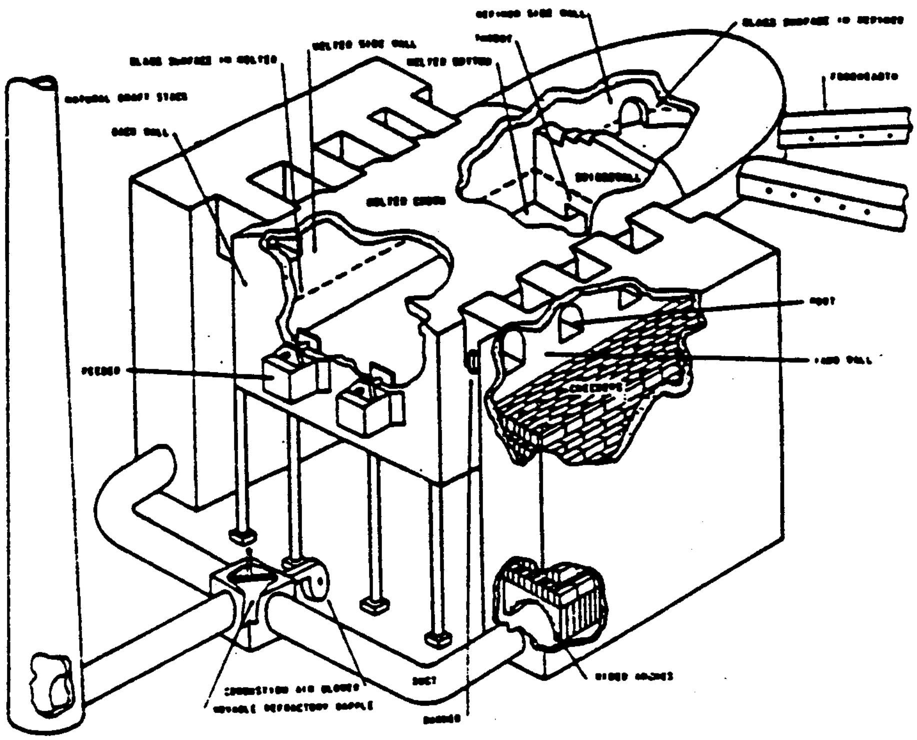

Figure 11.15-3. Side port continuous regenerative furnace.

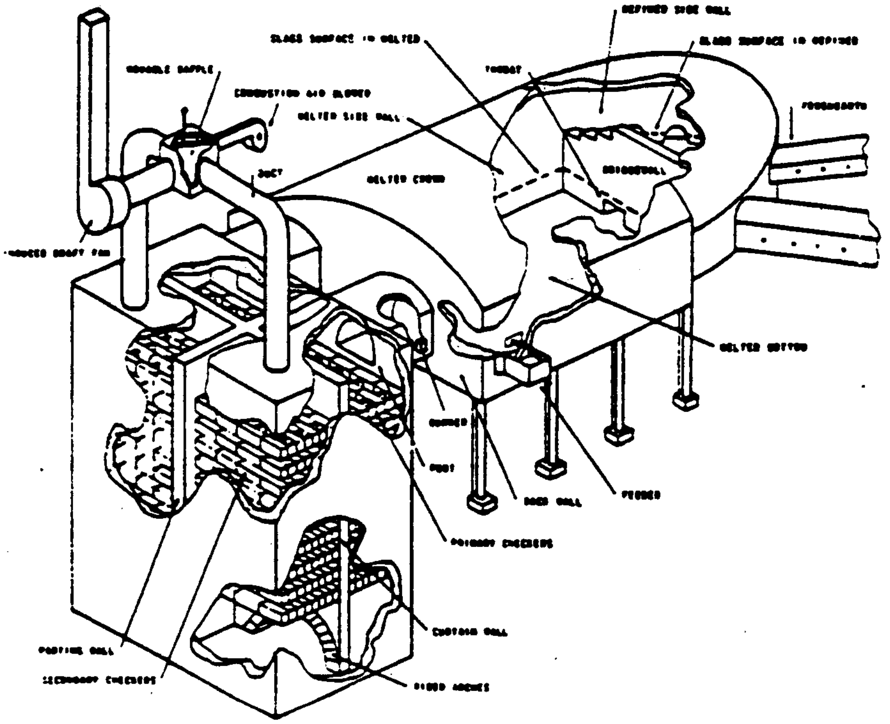

Figure 11.15-4. End port continuous regenerative furnace.

11.15.2 Emissions And Controls[1-5]

The main pollutant emitted by the batch plant is particulates in the form of dust. This can be controlled with 99 to 100 percent efficiency by enclosing all possible dust sources and using baghouses or cloth filters. Another way to control dust emissions, also with an efficiency approaching 100 percent, is to treat the batch to reduce the amount of fine particles present, by presintering, briquetting, pelletizing, or liquid alkali treatment.

The melting furnace contributes over 99 percent of the total emissions from a glass plant, both particulates and gaseous pollutants. Particulates result from volatilization of materials in the melt that combine with gases and form condensates. These either are collected in the checker work and gas passages or are emitted to the atmosphere. Serious problems arise when the checkers are not properly cleaned in that slag can form, clog the passages, and eventually deteriorate the condition and efficiency of the furnace. Nitrogen oxides form when nitrogen and oxygen react in the high temperatures of the furnace. Sulfur oxides result from the decomposition of the sulfates in the batch and sulfur in the fuel. Proper maintenance and firing of the furnace can control emissions and also add to the efficiency of the furnace and reduce operational costs. Low-pressure wet centrifugal scrubbers have been used to control particulate and sulfur oxides, but their inefficiency (approximately 50 percent) indicates their inability to collect particulates of submicrometer size. High-energy venturi scrubbers are approximately 95 percent effective in reducing particulate and sulfur oxide emissions. Their effect on nitrogen oxide emissions is unknown. Baghouses, with up to 99 percent particulate collection efficiency, have been used on small regenerative furnaces, but fabric corrosion requires careful temperature control. Electrostatic precipitators have an efficiency of up to 99 percent in the collection of particulates. Tables 11.15-1 and 11.15-2 list controlled and uncontrolled emission factors for glass manufacturing. Table 11.15-3 presents particle size distributions and corresponding emission factors for uncontrolled and controlled glass melting furnaces, and these are depicted in Figure 11.15-5.

Emissions from the forming and finishing phases depend upon the type of glass being manufactured. For container, press, and blow machines, the majority of emissions results from the gob coming into contact with the machine lubricant. Emissions, in the form of a dense white cloud that can exceed 40 percent opacity, are generated by flash vaporization of hydrocarbon greases and oils. Grease and oil lubricants are being replaced by silicone emulsions and water soluble oils, which may virtually eliminate this smoke. For flat glass, the only contributor to air pollutant emissions is gas combustion in the annealing lehr (oven), which is totally enclosed except for product entry and exit openings. Since emissions are small and operational procedures are efficient, no controls are used on flat glass processes.

Table 11.15-1 (Metric And English Units). PARTICULATE, SULFUR OXIDES, AND NITROGEN OXIDES EMISSION FACTORS FOR GLASS MANUFACTURING[a]

EMISSION FACTOR RATING: B

Process	Particulate		Sulfur Oxides		Nitrogen Oxides	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Raw materials handling[b] (all types of glass)	Neg	Neg	0	0	0	0
Melting furnace[c]						
Container						
Uncontrolled	0.7	1.4	1.7	3.4	3.1	6.2
	(0.4 - 0.9)	(0.9 - 1.9)	(1.0 - 2.4)	(2.0 - 4.8)	(1.6 - 4.5)	(3.3 - 9.1)
w/low-energy scrubber[d]	0.4	0.7	0.9	1.7	3.1	6.2
w/venturi scrubber[e]	<0.1	0.1	0.1	0.2	3.1	6.2
w/baghouse[f]	Neg	Neg	1.7	3.4	3.1	6.2
w/electrostatic precipitator[g]	Neg	Neg	1.7	3.4	3.1	6.2
Flat						
Uncontrolled	1.0	2.0	1.5	3.0	4.0	8.0
	(0.4 - 1.0)	(0.8 - 3.2)	(1.1 - 1.9)	(2.2 - 3.8)	(2.8 - 5.2)	(5.6 - 10.4)
w/low-energy scrubber[d]	0.5	1.0	0.8	1.5	4.0	8.0
w/venturi scrubber[e]	Neg	Neg	0.1	0.2	4.0	8.0
w/baghouse[f]	Neg	Neg	1.5	3.0	4.0	8.0
w/electrostatic precipitator[g]	Neg	Neg	1.5	3.0	4.0	8.0
Pressed and blown						
Uncontrolled	8.4	17.4	2.8	5.6	4.3	8.5
	(0.5 - 12.6)	(1.0 - 25.1)	(0.5 - 5.4)	(1.1 - 10.9)	(0.4 - 10.0)	(0.8 - 20.0)

Table 11.15-1 (cont.).

Process	Particulate		Sulfur Oxides		Nitrogen Oxides	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
w/low-energy scrubber[d]	4.2	8.4	1.3	2.7	4.3	8.5
w/venturi scrubber[e]	0.5	0.9	0.1	0.3	4.3	8.5
w/baghouse[f]	0.1	0.2	2.8	5.6	4.3	8.5
w/electrostatic precipitator[g]	0.1	0.2	2.8	5.6	4.3	8.5
Forming and finishing						
Container[h,j]	Neg	Neg	Neg	Neg	Neg	Neg
Flat	Neg	Neg	Neg	Neg	Neg	Neg
Pressed and blown[h,j]	Neg	Neg	Neg	Neg	Neg	Neg
Lead glass manufacturing, all processes[k]	ND	ND	ND	ND	ND	ND

[a] Reference 2-3,5. ND = no data. Neg = negligible. Ranges in parentheses, where available. Expressed as kg/Mg (lb/ton) of glass produced.

[b] Not separated into types of glass produced, since batch preparation is the same for all types. Particulate emissions are negligible because almost all plants utilize some form of control (i. e., baghouses, scrubbers, centrifugal collectors).

[c] Control efficiencies for the various devices are applied only to the average emission factor.

[d] Approximately 52% efficiency in reducing particulate and sulfur oxides emissions. Effect on nitrogen oxides is unknown.

[e] Approximately 95% efficiency in reducing particulate and sulfur oxide emissions. Effect on nitrogen oxides is unknown.

[f] Approximately 99% efficiency in reducing particulate emissions.

[g] Calculated using data for furnaces melting soda lime and lead glasses. No data available for borosilicate or opal glasses.

[h] Organic emissions are from decorating process. Can be controlled by incineration, absorption, or condensation, but efficiencies are not known.

[j] For container and pressed and blown glass, tin chloride, hydrated tin chloride and hydrogen chloride are also emitted during surface treatment process at a rate of <0.1 kg/Mg (0.2 lb/ton) each.

[k] References 6-7. Particulate containing 23% lead.

Table 11.15-2 (Metric And English Units). VOC, CARBON MONOXIDE, AND LEAD EMISSION FACTORS FOR GLASS MANUFACTURING[a]

EMISSION FACTOR RATING: B

Process	VOC		Carbon Monoxide		Lead	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
Raw materials handling[b] (all types of glass)	0	0	0	0	ND	ND
Melting furnace[c]						
Container						
Uncontrolled	0.1 (0 - 0.2)	0.2 (0 - 0.4)	0.1 (0 - 0.2)	0.2 (0 - 0.5)	ND	ND
w/low-energy scrubber[d]	0.1	0.2	0.1	0.2	ND	ND
w/venturi scrubber[e]	0.1	0.2	0.1	0.2	ND	ND
w/baghouse[f]	0.1	0.2	0.1	0.2	ND	ND
w/electrostatic precipitator[g]	0.1	0.2	0.1	0.2	ND	ND
Flat						
Uncontrolled	<0.1	<0.1	<0.1	<0.1	ND	ND
w/low-energy scrubber[d]	<0.1	<0.1	<0.1	<0.1	ND	ND
w/venturi scrubber[e]	<0.1	<0.1	<0.1	<0.1	ND	ND
w/baghouse[f]	<0.1	<0.1	<0.1	<0.1	ND	ND
w/electrostatic precipitator[g]	<0.1	<0.1	<0.1	<0.1	ND	ND
Pressed and blown						
Uncontrolled	0.2 (0.1 - 0.3)	0.3 (0.1 - 1.0)	0.1 (0.1 - 0.2)	0.2 (0.1 - 0.3)	ND	ND

Table 11.15-2 (cont.).

Process	VOC		Carbon Monoxide		Lead	
	kg/Mg	lb/ton	kg/Mg	lb/ton	kg/Mg	lb/ton
w/low-energy scrubber[d]	0.2	0.3	0.1	0.2	ND	ND
w/venturi scrubber[e]	0.2	0.3	0.1	0.2	ND	ND
w/baghouse[f]	0.2	0.3	0.1	0.2	ND	ND
w/electrostatic precipitator[g]	0.2	0.3	0.1	0.2	ND	ND
Forming and finishing						
Container[h,j]	4.4	8.7	Neg	Neg	ND	ND
Flat	Neg	Neg	Neg	Neg	ND	ND
Pressed and blown[h,j]	4.5	9.0	Neg	Neg	ND	ND
Lead glass manufacturing, all processes[k]	ND	ND	ND	ND	2.5	5

[a] Reference 2-3,5. ND = no data. Neg = negligible. Ranges in parentheses, where available. Expressed as kg/Mg (lb/ton) of glass produced.

[b] Not separated into types of glass produced, since batch preparation is the same for all types. Particulate emissions are negligible because almost all plants utilize some form of control (i. e., baghouses, scrubbers, centrifugal collectors).

[c] Control efficiencies for the various devices are applied only to the average emission factor.

[d] Approximately 52% efficiency in reducing particulate and sulfur oxides emissions. Effect on nitrogen oxides is unknown.

[e] Approximately 95% efficiency in reducing particulate and sulfur oxide emissions. Effect on nitrogen oxides is unknown.

[f] Approximately 99% efficiency in reducing particulate emissions.

[g] Calculated using data for furnaces melting soda lime and lead glasses. No data are available for borosilicate or opal glasses.

[h] Organic emissions are from decorating process. Can be controlled by incineration, absorption or condensation, but efficiencies are not known.

[j] For container and pressed and blown glass, tin chloride, hydrated tin chloride and hydrogen chloride are also emitted during surface treatment process at a rate of <0.1 kg/Mg (0.2 lb/ton) each.

[k] References 6-7. Particulate containing 23% lead.

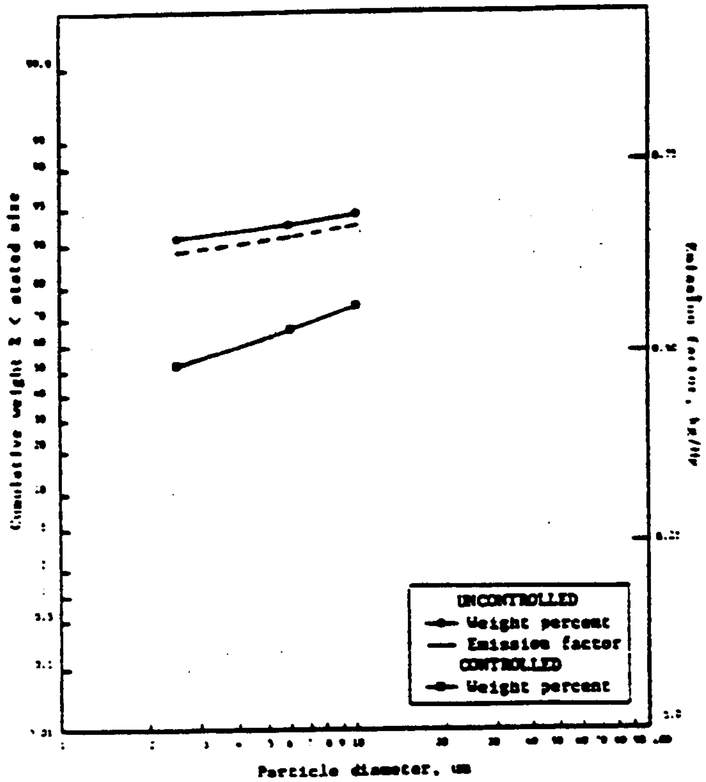

Figure 11.15-5. Particle size distributions and emission factors for glass melting furnace exhaust.

Table 11.15-3 (Metric Units). PARTICLE SIZE DISTRIBUTIONS AND EMISSION FACTORS FOR UNCONTROLLED AND CONTROLLED MELTING FURNACES IN GLASS MANUFACTURING[a]

EMISSION FACTOR RATING: E

Aerodynamic Particle Diameter, μm	Particle Size Distribution[b]		Size-Specific Emission Factor, kg/Mg[c]
	Uncontrolled	ESP Controlled[d]	Uncontrolled
2.5	91	53	0.64
6.0	93	66	0.65
10	95	75	0.66

[a] References 8-11.

[b] Cumulative weight % of particles < corresponding particle size.

[c] Based on mass particulate emission factor of 0.7 kg/Mg glass produced, from Table 11.15-1. Size-specific emission factor = mass particulate emission factor x particle size distribution, %/100. After ESP control, size-specific emission factors are negligible.

[d] References 8-9. Based on a single test.

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10. Environmental Assessment Data Systems, *op. cit.*, Series No. 223.

11. Environmental Assessment Data Systems, *op. cit.*, Series No. 225.

11.16 Gypsum Manufacturing

11.16.1 Process Description[1-2]

Gypsum is calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), a white or gray naturally occurring mineral. Raw gypsum ore is processed into a variety of products such as a portland cement additive, soil conditioner, industrial and building plasters, and gypsum wallboard. To produce plasters or wallboard, gypsum must be partially dehydrated or calcined to produce calcium sulfate hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$), commonly called stucco.

A flow diagram for a typical gypsum process producing both crude and finished gypsum products is shown in Figure 11.16-1. In this process gypsum is crushed, dried, ground, and calcined. Not all of the operations shown in Figure 11.16-1 are performed at all gypsum plants. Some plants produce only wallboard, and many plants do not produce soil conditioner.

Gypsum ore, from quarries and underground mines, is crushed and stockpiled near a plant. As needed, the stockpiled ore is further crushed and screened to about 50 millimeters (2 inches) in diameter. If the moisture content of the mined ore is greater than about 0.5 weight percent, the ore must be dried in a rotary dryer or a heated roller mill. Ore dried in a rotary dryer is conveyed to a roller mill, where it is ground to the extent that 90 percent of it is less 149 micrometers (μm) (100 mesh). The ground gypsum exits the mill in a gas stream and is collected in a product cyclone. Ore is sometimes dried in the roller mill by heating the gas stream, so that drying and grinding are accomplished simultaneously and no rotary dryer is needed. The finely ground gypsum ore is known as landplaster, which may be used as a soil conditioner.

In most plants, landplaster is fed to kettle calciners or flash calciners, where it is heated to remove three-quarters of the chemically bound water to form stucco. Calcination occurs at approximately 120 to 150°C (250 to 300°F), and 0.908 megagrams (Mg) (1 ton) of gypsum calcines to about 0.77 Mg (0.85 ton) of stucco.

In kettle calciners, the gypsum is indirectly heated by hot combustion gas passed through flues in the kettle, and the stucco product is discharged into a "hot pit" located below the kettle. Kettle calciners may be operated in either batch or continuous mode. In flash calciners, the gypsum is directly contacted with hot gases, and the stucco product is collected at the bottom of the calciner.

At some gypsum plants, drying, grinding, and calcining are performed in heated impact mills. In these mills hot gas contacts gypsum as it is ground. The gas dries and calcines the ore and then conveys the stucco to a product cyclone for collection. The use of heated impact mills eliminates the need for rotary dryers, calciners, and roller mills.

Gypsum and stucco are usually transferred from one process to another by means of screw conveyors or bucket elevators. Storage bins or silos are normally located downstream of roller mills and calciners but may also be used elsewhere.

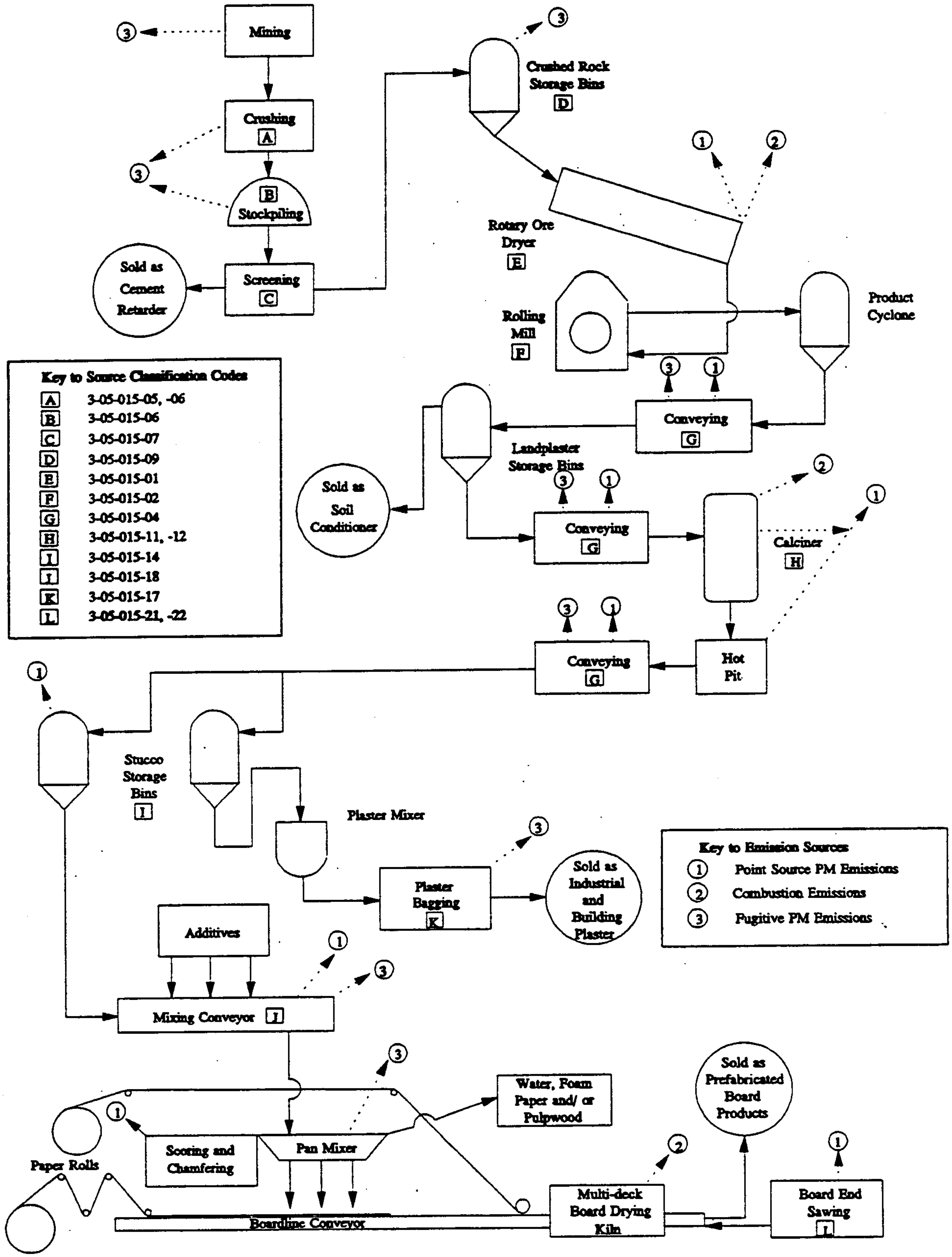

Figure 11.16-1. Overall process flow diagram for gypsum processing.[2]

In the manufacture of plasters, stucco is ground further in a tube or ball mill and then batch-mixed with retarders and stabilizers to produce plasters with specific setting rates. The thoroughly mixed plaster is fed continuously from intermediate storage bins to a bagging operation.

In the manufacture of wallboard, stucco from storage is first mixed with dry additives such as perlite, starch, fiberglass, or vermiculite. This dry mix is combined with water, soap foam, accelerators and shredded paper, or pulpwood in a pin mixer at the head of a board forming line. The slurry is then spread between 2 paper sheets that serve as a mold. The edges of the paper are scored, and sometimes chamfered, to allow precise folding of the paper to form the edges of the board. As the wet board travels the length of a conveying line, the calcium sulfate hemihydrate combines with the water in the slurry to form solid calcium sulfate dihydrate, or gypsum, resulting in rigid board. The board is rough-cut to length, and it enters a multideck kiln dryer, where it is dried by direct contact with hot combustion gases or by indirect steam heating. The dried board is conveyed to the board end sawing area and is trimmed and bundled for shipment.

11.16.2 Emissions And Controls[2,7]

Potential emission sources in gypsum processing plants are shown in Figure 11.16-1. While particulate matter (PM) is the dominant pollutant in gypsum processing plants, several sources may emit gaseous pollutants also. The major sources of PM emissions include rotary ore dryers, grinding mills, calciners, and board end sawing operations. Particulate matter emission factors for these operations are shown in Table 11.16-1 and 11.16-2. In addition, emission factors for PM less than or equal to 10 μm in aerodynamic diameter (PM-10) emissions from selected processes are presented in Tables 11.16-1 and 11.16-2. All of these factors are based on output production rates. Particle size data for ore dryers, calciners, and board end sawing operations are shown in Tables 11.16-2 and 11.16-3.

The uncontrolled emission factors presented in Table 11.16-1 and 11.16-2 represent the process dust entering the emission control device. It is important to note that emission control devices are frequently needed to collect the product from some gypsum processes and, thus, are commonly thought of by the industry as process equipment and not as added control devices.

Emissions sources in gypsum plants are most often controlled with fabric filters. These sources include:

- rotary ore dryers (SCC 3-05-015-01)
- roller mills (SCC 3-05-015-02)
- impact mills (SCC 3-05-015-13)
- kettle calciners (SCC 3-05-015-11)
- flash calciners (SCC 3-05-015-12)
- board end sawing (SCC 3-05-015-21,-22)
- scoring and chamfering (SCC 3-05-015-__)
- plaster mixing and bagging (SCC 3-05-015-16,-17)
- conveying systems (SCC 3-05-015-04)
- storage bins (SCC 3-05-015-09,-10,-14)

Uncontrolled emissions from scoring and chamfering, plaster mixing and bagging, conveying systems, and storage bins are not well quantified.

Emissions from some gypsum sources are also controlled with electrostatic precipitators (ESP). These sources include rotary ore dryers, roller mills, kettle calciners, and conveying systems. Although rotary ore dryers may be controlled separately, emissions from roller mills and conveying systems are usually controlled jointly with kettle calciner emissions. Moisture in the kettle calciner exit gas improves the ESP performance by lowering the resistivity of the dust.

Table 11.16-1 (Metric Units). EMISSION FACTORS FOR GYPSUM PROCESSING[a]

EMISSION FACTOR RATING: D

Process	Filterable PM[b]	PM-10	CO_2[c]
Crushers, screens, stockpiles, and roads (SCC 3-05-015-05,-06,-07,-08)	—[d]	—[d]	NA
Rotary ore dryers (SCC 3-05-015-01)	$0.0042(FFF)^{1.7}$[e]	$0.00034(FFF)^{1.7}$	12[f]
Rotary ore dryers w/fabric filters (SCC 3-05-015-01)	0.020[g]	0.0052	NA
Roller mills w/cyclones (SCC 3-05-015-02)	1.3[h]	ND	NA
Roller mills w/fabric filters (SCC 3-05-015-02)	0.060[h]	ND	NA
Roller mill and kettle calciner w/electrostatic precipitators (SCC 3-05-015-02,-11)	0.050[h,j]	ND	ND
Continuous kettle calciners and hot pit (SCC 3-05-015-11)	21[k]	13	ND
Continuous kettle calciners and hot pit w/fabric filters (SCC 3-05-015-11)	0.0030[k]	ND	NA
Continuous kettle calciners w/cyclones and electrostatic precipitators (SCC 3-05-015-11)	0.050[k]	ND	NA
Flash calciners (SCC 3-05-015-12)	19[m]	7.2[m]	55[n]
Flash calciners w/fabric filters (SCC 3-05-015-12)	0.020[m]	0.017[m]	ND
Impact mills w/cyclones (SCC 3-05-015-13)	50[p]	ND	NA
Impact mills w/fabric filters (SCC 3-05-015-13)	0.010[p]	ND	NA
Board end sawing--2.4-m boards (SCC 3-05-015-21)	0.040[q]	ND	NA
Board end sawing--3.7-m boards (SCC 3-05-015-22)	0.030[q]	ND	NA
Board end sawing w/fabric filters--2.4-and 3.7-m boards (SCC 3-05-015-21,-22)	36[r]	27[r]	NA

[a] Factors represent uncontrolled emissions unless otherwise specified. All emission factors are kg/Mg of output rate. SCC = Source Classification Code. NA = not applicable. ND = no data.

[b] Filterable PM is that PM collected on or prior to an EPA Method 5 (or equivalent) sampling train.

Table 11.16-1 (cont.).

[c] Typical pollution control devices generally have a negligible effect on CO_2 emissions.

[d] Factors for these operations are in Sections 11.19 and 13.2.

[e] References 3-4,8,11-12. Equation is for the emission rate upstream of any process cyclones and applies only to concurrent rotary ore dryers with flow rates of 7.5 cubic meters per second (m^3/s) or less. FFF in the uncontrolled emission factor equation is "flow feed factor," the ratio of gas mass rate per unit dryer cross section area to the dry mass feed rate, in the following units: ($kg/hr\text{-}m^2$ of gas flow)/(Mg/hr dry feed). Measured uncontrolled emission factors for 4.2 and 5.7 m^3/s range from 5 to 60 kg/Mg.

[f] References 3-4.

[g] References 3-4,8,11-12. Applies to rotary dryers with and without cyclones upstream of fabric filter.

[h] References 11-14. Applies to both heated and unheated roller mills.

[j] References 11-14. Factor is for combined emissions from roller mills and kettle calciners, based on the sum of the roller mill and kettle calciner output rates.

[k] References 4-5,11,13-14. Emission factors based on the kettle and the hot pit do not apply to batch kettle calciners.

[m] References 3,6,10.

[n] References 3,6,9.

[p] References 9,15. As used here, an impact mill is a process unit used to dry, grind, and calcine gypsum simultaneously.

[q] References 4-5,16. Emission factor units = kg/m^2. Based on 13-mm board thickness and 1.2 m board width. For other thicknesses, multiply the appropriate emission factor by 0.079 times board thickness in mm.

[r] References 4-5,16. Emission factor units = $kg/10^6\ m^2$.

Table 11.16-2 (English Units). EMISSION FACTORS FOR GYPSUM PROCESSING[a]

EMISSION FACTOR RATING: D

Process	Filterable PM[b]	PM-10	CO_2[c]
Crushers, screens, stockpiles, and roads (SCC 3-05-015-05,-06,-07,-08)	—[d]	—[d]	NA
Rotary ore dryers (SCC 3-05-015-01)	$0.16(FFF)^{1.77}$[e]	$0.013(FFF)^{1.7}$	23[f]
Rotary ore dryers w/fabric filters (SCC 3-05-015-01)	0.040[g]	0.010	NA
Roller mills w/cyclones (SCC 3-05-015-02)	2.6[h]	ND	NA
Roller mills w/fabric filters (SCC 3-05-015-02)	0.12[h]	ND	NA
Roller mill and kettle calciner w/electrostatic precipitators (SCC 3-05-015-02,-11)	0.090[h,j]	ND	ND
Continuous kettle calciners and hot pit (SCC 3-05-015-11)	41[k]	26	ND
Continuous kettle calciners and hot pit w/fabric filters (SCC 3-05-015-11)	0.0060[k]	ND	NA
Continuous kettle calciners w/cyclones and electrostatic precipitators (SCC 3-05-015-11)	0.090[k]	ND	NA
Flash calciners (SCC 3-05-015-12)	37[m]	14[m]	110[n]
Flash calciners w/fabric filters (SCC 3-05-015-12)	0.040[m]	0.034[m]	ND
Impact mills w/cyclones (SCC 3-05-015-13)	100[p]	ND	NA
Impact mills w/fabric filters (SCC 3-05-015-13)	0.020[p]	ND	NA
Board end sawing–8-ft boards (SCC 3-05-015-21)	0.80[q]	ND	NA
Board end sawing–12-ft boards (SCC 3-05-015-22)	0.50[q]	ND	NA
Board end sawing w/fabric filters–8- and 12-ft boards (SCC 3-05-015-21,-22)	7.5[r]	5.7[r]	NA

[a] Factors represent uncontrolled emissions unless otherwise specified. All emission factors are lb/ton of output rate. SCC = Source Classification Codes. NA = not applicable. ND = no data.

Table 11.16-2 (cont.).

[b] Filterable PM is that particulate collected on or prior to an EPA Method 5 (or equivalent) sampling train.

[c] Typical pollution control devices generally have a negligible effect on CO_2 emissions.

[d] Factors for these operations are in Sections 8.19 and 13.2.

[e] References 3-4,8,11-12. Equation is for the emission rate upstream of any process cyclones and applies only to concurrent rotary ore dryers with flow rates of 16,000 actual cubic feet per minute (acfm) or less. FFF in the uncontrolled emission factor equation is "flow feed factor," the ratio of gas mass rate per unit dryer cross section area to the dry mass feed rate, in the following units: (lb/hr-ft^2 of gas flow)/(ton/hr dry feed). Measured uncontrolled emission factors for 9,000 and 12,000 acfm range from 10 to 120 lb/ton.

[f] References 3-4.

[g] References 3-4,8,11-12. Applies to rotary dryers with and without cyclones upstream of fabric filter.

[h] References 11-14. Applies to both heated and unheated roller mills.

[j] References 11-14. Factor is for combined emissions from roller mills and kettle calciners, based on the sum of the roller mill and kettle calciner output rates.

[k] References 4-5,11,13-14. Emission factors based on the kettle and the hot pit do not apply to batch kettle calciners.

[m] References 3,6,10.

[n] References 3,6,9.

[p] References 9,15. As used here, an impact mill is a process unit used to dry, grind, and calcine gypsum simultaneously.

[q] References 4-5,16. Emission factor units = lb/100 ft^2. Based on 1/2-in. board thickness and 4-ft board width. For other thicknesses, multiply the appropriate emission factor by 2 times board thickness in inches.

[r] References 4-5,16. Emission factor units = lb/10^6 ft^2.

Table 11.16-3. SUMMARY OF PARTICLE SIZE DISTRIBUTION DATA FOR UNCONTROLLED PM EMISSIONS FROM GYPSUM PROCESSING[a]

EMISSION FACTOR RATING: D

Diameter (μm)	Cumulative % Less Than Diameter			
	Rotary Ore Dryer[b]	Rotary Ore Dryer With Cyclone[c]	Continuous Kettle Calciner[d]	Flash Calciner[e]
2.0	1	12	17	10
10.0	8	45	63	38

[a] Weight % given as filterable PM. Diameter is given as aerodynamic diameter, except for continuous kettle calciner, which is given as equivalent diameter, as determined by Bahco and Sedigraph analyses.

[b] Reference 3.

[c] Reference 4.

[d] References 4-5..

[e] References 3,6.

Table 11.16-4. SUMMARY OF PARTICLE SIZE DISTRIBUTION DATA FOR FABRIC FILTER-CONTROLLED PM EMISSIONS FROM GYPSUM MANUFACTURING[a]

EMISSION FACTOR RATING: D

Diameter (μm)	Cumulative % Less Than Diameter		
	Rotary Ore Dryer[b]	Flash Calciner[c]	Board End Sawing[c]
2.0	9	52	49
10.0	26	84	76

[a] Aerodynamic diameters, Andersen analysis.
[b] Reference 3.
[c] Reference 3,6.

Other sources of PM emissions in gypsum plants are primary and secondary crushers, screens, stockpiles, and roads. If quarrying is part of the mining operation, PM emissions may also result from drilling and blasting. Emission factors for some of these sources are presented in Sections 11.19 and 13.2. Gaseous emissions from gypsum processes result from fuel combustion and may include nitrogen oxides, sulfur oxides, carbon monoxide, and carbon dioxide (CO_2). Processes using fuel include rotary ore dryers, heated roller mills, impact mills, calciners, and board drying kilns. Although some plants use residual fuel oil, the majority of the industry uses clean fuels such as natural gas or distillate fuel oil. Emissions from fuel combustion may be estimated using emission factors presented in Sections 1.3 and 1.4 and fuel consumption data in addition to those emission factors presented in Table 11.16-1.

References For Section 11.16

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11.17 Lime Manufacturing

11.17.1 Process Description[1-5]

Lime is the high-temperature product of the calcination of limestone. Although limestone deposits are found in every state, only a small portion is pure enough for industrial lime manufacturing. To be classified as limestone, the rock must contain at least 50 percent calcium carbonate. When the rock contains 30 to 45 percent magnesium carbonate, it is referred to as dolomite, or dolomitic limestone. Lime can also be produced from aragonite, chalk, coral, marble, and sea shells. The Standard Industry Classification (SIC) code for lime manufacturing is 3274. The six-digit Source Classification Code (SCC) for lime manufacturing is 3-05-016.

Lime is manufactured in various kinds of kilns by 1 of the following reactions:

$$CaCO_3 + \text{heat} \rightarrow CO_2 + CaO \text{ (high calcium lime)}$$
$$CaCO_3 \cdot MgCO_3 + \text{heat} \rightarrow 2CO_2 + CaO \cdot MgO \text{ (dolomitic lime)}$$

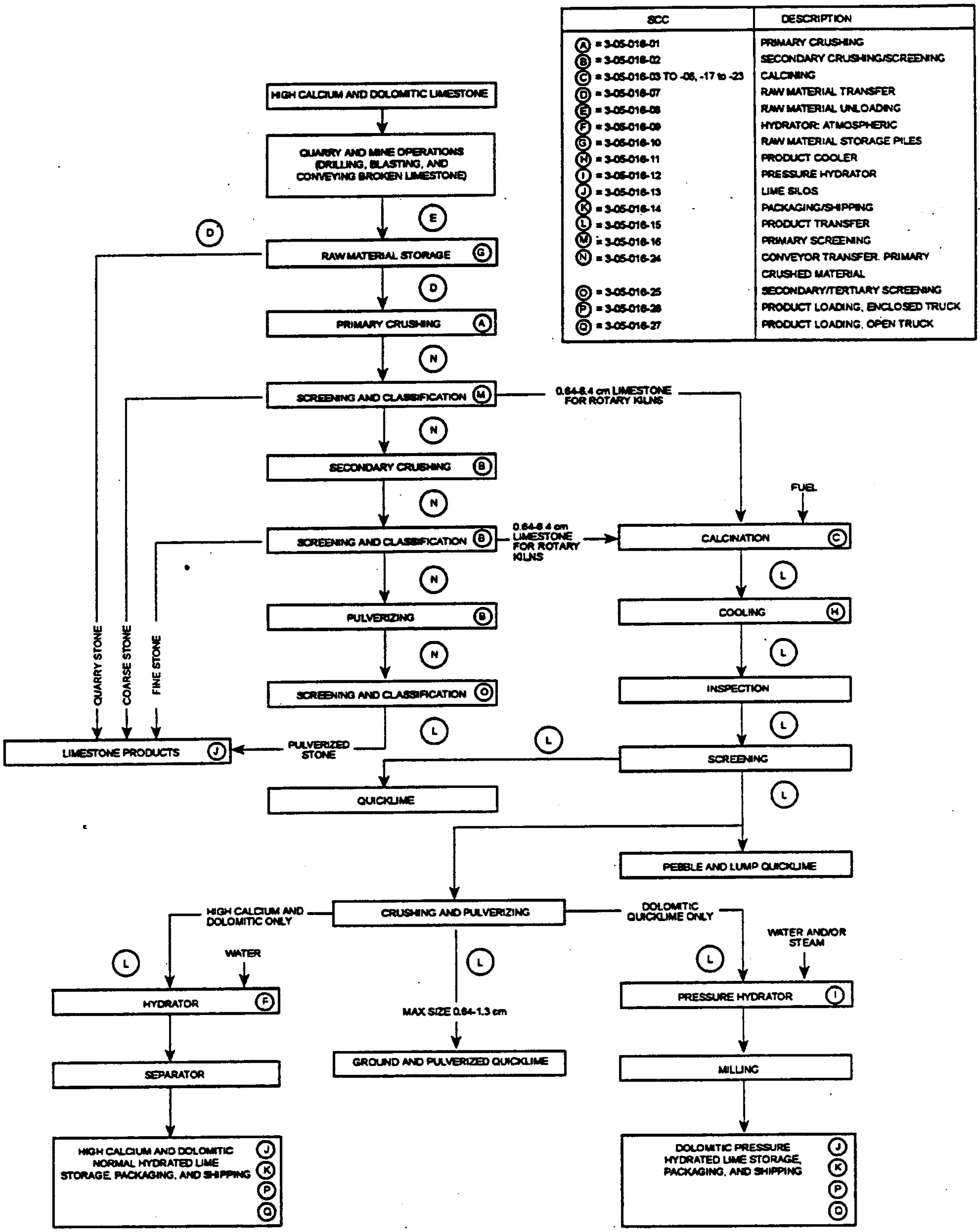
In some lime plants, the resulting lime is reacted (slaked) with water to form hydrated lime. The basic processes in the production of lime are: (1) quarrying raw limestone; (2) preparing limestone for the kilns by crushing and sizing; (3) calcining limestone; (4) processing the lime further by hydrating; and (5) miscellaneous transfer, storage, and handling operations. A generalized material flow diagram for a lime manufacturing plant is given in Figure 11.17-1. Note that some operations shown may not be performed in all plants.

The heart of a lime plant is the kiln. The prevalent type of kiln is the rotary kiln, accounting for about 90 percent of all lime production in the United States. This kiln is a long, cylindrical, slightly inclined, refractory-lined furnace, through which the limestone and hot combustion gases pass countercurrently. Coal, oil, and natural gas may all be fired in rotary kilns. Product coolers and kiln feed preheaters of various types are commonly used to recover heat from the hot lime product and hot exhaust gases, respectively.

The next most common type of kiln in the United States is the vertical, or shaft, kiln. This kiln can be described as an upright heavy steel cylinder lined with refractory material. The limestone is charged at the top and is calcined as it descends slowly to discharge at the bottom of the kiln. A primary advantage of vertical kilns over rotary kilns is higher average fuel efficiency. The primary disadvantages of vertical kilns are their relatively low production rates and the fact that coal cannot be used without degrading the quality of the lime produced. There have been few recent vertical kiln installations in the United States because of high product quality requirements.

Other, much less common, kiln types include rotary hearth and fluidized bed kilns. Both kiln types can achieve high production rates, but neither can operate with coal. The "calcimatic" kiln, or rotary hearth kiln, is a circular kiln with a slowly revolving doughnut-shaped hearth. In fluidized bed kilns, finely divided limestone is brought into contact with hot combustion air in a turbulent zone, usually above a perforated grate. Because of the amount of lime carryover into the exhaust gases, dust collection equipment must be installed on fluidized bed kilns for process economy.

Another alternative process that is beginning to emerge in the United States is the parallel flow regenerative (PR) lime kiln. This process combines 2 advantages. First, optimum



SCC	DESCRIPTION
Ⓐ = 3-05-016-01	PRIMARY CRUSHING
Ⓑ = 3-05-016-02	SECONDARY CRUSHING/SCREENING
Ⓒ = 3-05-016-03 TO -06, -17 to -23	CALCINING
Ⓓ = 3-05-016-07	RAW MATERIAL TRANSFER
Ⓔ = 3-05-016-08	RAW MATERIAL UNLOADING
Ⓕ = 3-05-016-09	HYDRATOR: ATMOSPHERIC
Ⓖ = 3-05-016-10	RAW MATERIAL STORAGE PILES
Ⓗ = 3-05-016-11	PRODUCT COOLER
Ⓘ = 3-05-016-12	PRESSURE HYDRATOR
Ⓙ = 3-05-016-13	LIME SILOS
Ⓚ = 3-05-016-14	PACKAGING/SHIPPING
Ⓛ = 3-05-016-15	PRODUCT TRANSFER
Ⓜ = 3-05-016-16	PRIMARY SCREENING
Ⓝ = 3-05-016-24	CONVEYOR TRANSFER. PRIMARY CRUSHED MATERIAL
Ⓞ = 3-05-016-25	SECONDARY/TERTIARY SCREENING
Ⓟ = 3-05-016-26	PRODUCT LOADING, ENCLOSED TRUCK
Ⓠ = 3-05-016-27	PRODUCT LOADING, OPEN TRUCK

Figure 11.17-1. Process flow diagram for lime manufacturing.[4]
(SCC = Source Classification Code.)

heating conditions for lime calcining are achieved by concurrent flow of the charge material and combustion gases. Second, the multiple-chamber regenerative process uses the charge material as the heat transfer medium to preheat the combustion air. The basic PR system has 2 shafts, but 3 shaft systems are used with small size grains to address the increased flow resistance associated with smaller feed sizes.

In the 2-shaft system, the shafts alternate functions, with 1 shaft serving as the heating shaft and the other as the flue gas shaft. Limestone is charged alternatively to the 2 shafts and flows downward by gravity flow. Each shaft includes a heating zone, a combustion/burning zone, and a cooling zone. The 2 shafts are connected in the middle to allow gas flow between them. In the heating shaft, combustion air flows downward through the heated charge material. After being preheated by the charge material, the combustion air combines with the fuel (natural gas or oil), and the air/fuel mixture is fired downward into the combustion zone. The hot combustion gases pass from the combustion zone in the heating shaft to the combustion zone in the flue gas shaft. The heated exhaust gases flow upward through the flue gas shaft combustion zone and into the preheating zone where they heat the charge material. The function of the 2 shafts reverses on a 12-minute cycle. The bottom of both shafts is a cooling zone. Cooling air flows upward through the shaft countercurrently to the flow of the calcined product. This air mixes with the combustion gases in the crossover area providing additional combustion air. The product flows by gravity from the bottom of both shafts.

About 15 percent of all lime produced is converted to hydrated (slaked) lime. There are 2 kinds of hydrators: atmospheric and pressure. Atmospheric hydrators, the more prevalent type, are used in continuous mode to produce high-calcium and dolomitic hydrates. Pressure hydrators, on the other hand, produce only a completely hydrated dolomitic lime and operate only in batch mode. Generally, water sprays or wet scrubbers perform the hydrating process and prevent product loss. Following hydration, the product may be milled and then conveyed to air separators for further drying and removal of coarse fractions.

The major uses of lime are metallurgical (aluminum, steel, copper, silver, and gold industries), environmental (flue gas desulfurization, water softening, pH control, sewage-sludge destabilization, and hazardous waste treatment), and construction (soil stabilization, asphalt additive, and masonry lime).

11.17.2 Emissions And Controls[1-4,33]

Potential air pollutant emission points in lime manufacturing plants are indicated by SCC in Figure 11.17-1. Except for gaseous pollutants emitted from kilns, particulate matter (PM) is the only dominant pollutant. Emissions of filterable PM from rotary lime kilns constructed or modified after May 3, 1977 are regulated to 0.30 kilograms per megagram (kg/Mg) (0.60 pounds per ton [lb/ton]) of stone feed under 40 CFR Part 60, subpart HH.

The largest ducted source of particulate is the kiln. The properties of the limestone feed and the ash content of the coal (in coal-fired kilns) can significantly affect PM emission rates. Of the various kiln types, fluidized beds have the highest levels of uncontrolled PM emissions because of the very small feed rate combined with the high air flow through these kilns. Fluidized bed kilns are well controlled for maximum product recovery. The rotary kiln is second worst in uncontrolled PM emissions because of the small feed rate and relatively high air velocities and because of dust entrainment caused by the rotating chamber. The calcimatic (rotary hearth) kiln ranks third in dust production primarily because of the larger feed rate and the fact that, during calcination, the limestone remains stationary relative to the hearth. The vertical kiln has the lowest uncontrolled dust emissions due to the large lump feed, the relatively low air velocities, and the slow movement of material through the kiln. In coal-fired kilns, the properties of the limestone feed and the ash content of the coal can significantly affect PM emissions.

Some sort of particulate control is generally applied to most kilns. Rudimentary fallout chambers and cyclone separators are commonly used to control the larger particles. Fabric and gravel bed filters, wet (commonly venturi) scrubbers, and electrostatic precipitators are used for secondary control.

Carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NO_x) are all produced in kilns. Sulfur dioxide emissions are influenced by several factors, including the sulfur content of the fuel, the sulfur content and mineralogical form (pyrite or gypsum) of the stone feed, the quality of lime being produced, and the type of kiln. Due to variations in these factors, plant-specific SO_2 emission factors are likely to vary significantly from the average emission factors presented here. The dominant source of sulfur emissions is the kiln's fuel, and the vast majority of the fuel sulfur is not emitted because of reactions with calcium oxides in the kiln. Sulfur dioxide emissions may be further reduced if the pollution equipment uses a wet process or if it brings CaO and SO_2 into intimate contact.

Product coolers are emission sources only when some of their exhaust gases are not recycled through the kiln for use as combustion air. The trend is away from the venting of product cooler exhaust, however, to maximize fuel use efficiencies. Cyclones, baghouses, and wet scrubbers have been used on coolers for particulate control.

Hydrator emissions are low because water sprays or wet scrubbers are usually installed to prevent product loss in the exhaust gases. Emissions from pressure hydrators may be higher than from the more common atmospheric hydrators because the exhaust gases are released intermittently, making control more difficult.

Other particulate sources in lime plants include primary and secondary crushers, mills, screens, mechanical and pneumatic transfer operations, storage piles, and roads. If quarrying is a part of the lime plant operation, particulate emissions may also result from drilling and blasting. Emission factors for some of these operations are presented in Sections 11.19 and 13.2 of this document.

Tables 11.17-1 (metric units) and 11.17-2 (English units) present emission factors for PM emissions from lime manufacturing calcining, cooling, and hydrating. Tables 11.17-3 (metric units) and 11.17-4 (English units) include emission factors for the mechanical processing (crushing, screening, and grinding) of limestone and for some materials handling operations. Section 11.19, Construction Aggregate Processing, also includes stone processing emission factors that are based on more recent testing, and, therefore, may be more representative of emissions from stone crushing, grinding, and screening. In addition, Section 13.2, Fugitive Dust Sources, includes emission factors for materials handling that may be more representative of materials handling emissions than the emission factors in Tables 11.17-3 and 11.17-4.

Emission factors for emissions of SO_2, NO_x, CO, and CO_2 from lime manufacturing are presented in Tables 11.17-5 and 11.17-6. Particle size distribution for rotary lime kilns is provided in Table 11.17-7.

Table 11.17-1 (Metric Units). EMISSION FACTORS FOR LIME MANUFACTURING CALCINING, COOLING, AND HYDRATING[a]

Source	Filterable[b]				Condensable PM[c]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Coal-fired rotary kiln (SCC 3-05-016-18)	180[d]	D	22[e]	D	0.67[f]	D	0.51[g]	E
Coal-fired rotary kiln with large diameter cyclone (SCC 3-05-016-18)	60[h]	D	ND		ND		ND	
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	0.14[j]	D	0.077[k]	D	0.19[m]	E	ND	
Coal-fired rotary kiln with ESP (SCC 3-05-016-18)	4.3[h]	D	2.2[n]	D	ND		ND	
Coal-fired rotary kiln with venturi scrubber (SCC 3-05-016-18)	0.72[p]	D	ND		0.14[q]	D	ND	
Gas-fired rotary kiln with ESP (SCC 3-05-016-19)	0.086[r]	E	ND		0.11[r]	E	ND	
Gas-fired rotary kiln with gravel bed filter (SCC 3-05-016-19)	0.51[s]	E	ND		0.24[s]	E	ND	
Coal- and gas fired rotary kiln (SCC 3-05-016-20)	40[t]	E	ND		ND		ND	
Coal- and gas-fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	0.44[t]	D	ND		0.041[t]	D	ND	
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	0.83[u]	D	ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone (SCC 3-05-016-22)	42[v]	E	ND		0.040[v]	E	ND	
Coal-fired rotary preheater kiln with gravel bed filter (SCC 3-05-016-22)	0.59[w]	E	ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	0.56[x]	E	ND		0.57[x]	E	0.076[x]	E

Table 11.17-1 (cont.).

Source	Filterable[b]				Condensable PM[c]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Gas-fired calcimatic kiln (SCC 3-05-016-05)	48[y]	E	ND		0.14[y]	E	ND	
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.051[z]	D	ND		ND		ND	
Atmospheric hydrator with wet scrubber (SCC 3-05-016-09)	0.033[aa]	D	ND		0.0067[aa]	D	ND	
Product cooler (SCC 3-05-016-11)	3.4[y]	E	ND		0.011[y]	E	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. All emission factors in kg/Mg of lime produced unless noted. ND = no data. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] References 9-10.

[e] References 4,9-10.

[f] References 9,11.

[g] Reference 9.

[h] Reference 10.

[j] References 10,18,29,31.

[k] References 4,10,18,29,31.

[m] References 7,18-21,31.

[n] References 4,10.

[p] References 8,26-27.

[q] References 8,13-14.

[r] Reference 12.

[s] References 15,30.

[t] Reference 17.

[u] Reference 28.

[v] Reference 11.

[w] Reference 16.

[x] Reference 32.

[y] Reference 23.

[z] Reference 34.

[aa] Reference 22; units are kg/Mg of hydrated lime produced.

Table 11.17-2 (English Units). EMISSION FACTORS FOR LIME MANUFACTURING CALCINING, COOLING, AND HYDRATING[a]

	Filterable[b]				Condensable PM[c]			
Source	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Coal-fired rotary kiln (SCC 3-05-016-18)	350[d]	D	42[e]	D	1.3[f]	D	1.0[g]	E
Coal-fired rotary kiln with large diameter cyclone (SCC 3-05-016-18)	120[h]	D	ND		ND		ND	
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	0.28[j]	D	0.15[k]	D	0.38[m]	E	ND	
Coal-fired rotary kiln with ESP (SCC 3-05-016-18)	8.5[h]	D	4.3[n]	D	ND		ND	
Coal-fired rotary kiln with venturi scrubber (SCC 3-05-016-18)	1.4[p]	D	ND		0.28[q]	D	ND	
Gas-fired rotary kiln with ESP (SCC 3-05-016-19)	0.17[r]	E	ND		0.22[r]	E	ND	
Gas-fired rotary kiln with gravel bed filter (SCC 3-05-016-19)	0.99[s]	E	ND		0.48[s]	E	ND	
Coal- and gas fired rotary kiln (SCC 3-05-016-20)	80[t]	E	ND		ND		ND	
Coal- and gas-fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	0.87[t]	D	ND		0.082[t]	D	ND	
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	1.7[u]	D	ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone (SCC 3-05-016-22)	84[v]	E	ND		0.081[v]	E	ND	
Coal-fired rotary preheater kiln with gravel bed filter (SCC 3-05-016-22)	1.2[w]	E	ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	1.1[x]	E	ND		1.1[x]	E	0.15[x]	E
Gas-fired calcimatic kiln (SCC 3-05-016-05)	97[y]	E	ND		0.27[y]	E	ND	

Table 11.17-2 (cont.).

	Filterable[b]				Condensable PM[c]			
Source	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING	Inorganic	EMISSION FACTOR RATING	Organic	EMISSION FACTOR RATING
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.026[z]	D	ND		ND		ND	
Atmospheric hydrator with wet scrubber (SCC 3-05-016-09)	0.067[aa]	D	ND		0.013[aa]	D	ND	
Product cooler (SCC 3-05-016-11)	6.8[y]	E	ND		0.023[y]	E	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of lime produced unless noted. ND = no data. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] References 9-10.

[e] References 4,9-10.

[f] References 9,11.

[g] Reference 9.

[h] Reference 10.

[j] References 10,18,29,31.

[k] References 4,10,18,29,31.

[m] References 7,18-21,31.

[n] References 4,10.

[p] References 8,26-27.

[q] References 8,13-14.

[r] Reference 12.

[s] References 15,30.

[t] Reference 17.

[u] Reference 28.

[v] Reference 11.

[w] Reference 16.

[x] Reference 32.

[y] Reference 23.

[z] Reference 34.

[aa] Reference 22; units are lb/ton of hydrated lime produced.

Table 11.17-3 (Metric Units). EMISSION FACTORS FOR LIME MANUFACTURING RAW MATERIAL AND PRODUCT PROCESSING AND HANDLING[a]

Source	Filterable[b]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Primary crusher[c] (SCC 3-05-016-01)	0.0083	E	ND	
Scalping screen and hammermill (secondary crusher)[c] (SCC 3-05-016-02)	0.31	E	ND	
Primary crusher with fabric filter[d] (SCC 3-05-016-01)	0.00021	D	ND	
Primary screen with fabric filter[e] (SCC 3-05-016-16)	0.0030	D	ND	
Crushed material conveyor transfer with fabric filter[f] (SCC 3-05-016-24)	4.4×10^{-5}	D	ND	
Secondary and tertiary screen with fabric filter[g] (SCC 3-05-016-25)	6.5×10^{-5}	D	ND	
Product transfer and conveying (SCC 3-05-016-15)[h]	1.1	E	ND	
Product loading, enclosed truck (SCC 3-05-016-26)[h]	0.31	D	ND	
Product loading, open truck (SCC 3-05-016-27)[h]	0.75	D	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are kg/Mg of material processed unless noted. ND = no data. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Reference 6; units of kg/Mg of stone processed.

[d] Reference 34. Emission factors in units of kg/Mg of material processed. Includes scalping screen, scalping screen discharges, primary crusher, primary crusher discharges, and ore discharge.

[e] Reference 34. Emission factors in units of kg/Mg of material processed. Includes primary screening, including the screen feed, screen discharge, and surge bin discharge.

[f] Reference 34. Emission factors in units of kg/Mg of material processed. Based on average of three runs each of emissions from two conveyor transfer points on the conveyor from the primary crusher to the primary stockpile.

[g] Reference 34. Emission factors in units of kg/Mg of material processed. Based on sum of emissions from two emission points that include conveyor transfer point for the primary stockpile underflow to the secondary screen, secondary screen, tertiary screen, and tertiary screen discharge.

[h] Reference 10; units of kg/Mg of product loaded.

Table 11.17-4 (English Units). EMISSION FACTORS FOR LIME MANUFACTURING RAW MATERIAL AND PRODUCT PROCESSING AND HANDLING[a]

Source	Filterable[b]			
	PM	EMISSION FACTOR RATING	PM-10	EMISSION FACTOR RATING
Primary crusher[c] (SCC 3-05-016-01)	0.017	E	ND	
Scalping screen and hammermill (secondary crusher) (SCC 3-05-016-02)[c]	0.62	E	ND	
Primary crusher with fabric filter[d] (SCC 3-05-016-01)	0.00043	D	ND	
Primary screen with fabric filter[e] (SCC 3-05-016-16)	0.00061	D	ND	
Crushed material conveyor transfer with fabric filter[f] (SCC 3-05-016-24)	8.8×10^{-5}	D	ND	
Secondary and tertiary screen with fabric filter[g] (SCC 3-05-016-25)	0.00013	D	ND	
Product transfer and conveying (SCC 3-05-016-15)[h]	2.2	E	ND	
Product loading, enclosed truck (SCC 3-05-016-26)[h]	0.61	D	ND	
Product loading, open truck (SCC 3-05-016-27)[h]	1.5	D	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of material processed unless noted. ND = no data. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Reference 6; factors are lb/ton.

[d] Reference 34. Factors are lb/ton of material processed. Includes scalping screen, scalping screen discharges, primary crusher, primary crusher discharges, and ore discharge.

[e] Reference 34. Factors are lb/ton of material processed. Includes primary screening, including the screen feed, screen discharge, and surge bin discharge.

[f] Reference 34. Factors are lb/ton of material processed. Based on average of three runs each of emissions from two conveyor transfer points on the conveyor from the primary crusher to the primary stockpile.

[g] Reference 34. Emission factors in units of kg/Mg of material processed. Based on sum of emissions from two emission points that include conveyor transfer point for the primary stockpile underflow to the secondary screen, secondary screen, tertiary screen, and tertiary screen discharge.

[h] Reference 10; units are lb/ton of product loaded.

Table 11.17-5 (Metric Units). EMISSION FACTORS FOR LIME MANUFACTURING[a]

Source	SO_2[b]	EMISSION FACTOR RATING	SO_3	EMISSION FACTOR RATING	NO_x	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING	CO_2[c]	EMISSION FACTOR RATING
Coal-fired rotary kiln (SCC 3-05-016-18)	2.7[d]	D	ND		1.6[e]	C	0.74[f]	D	1,600[g]	C
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	0.83[h]	D	ND		ND		ND		ND	
Coal-fired rotary kiln with wet scrubber (SCC 3-05-016-18)	0.15[j]	D	0.11[k]	E	ND		ND		ND	
Gas-fired rotary kiln (SCC 3-05-016-19)	ND		ND		1.7[m]	E	1.1[m]	E	ND	
Coal- and gas-fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	ND		ND		1.4[n]	D	0.41[n]	D	1,600[n]	D
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	ND		ND		ND		ND		1,500[p]	D
Coal-fired rotary preheater kiln with dry PM controls (SCC 3-05-016-22)	1.1[q]	E	ND		ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	3.2[r]	E	ND		ND		3.2[r]	E	1,200[r]	E
Gas-fired calcimatic kiln (SCC 3-05-016-05)	ND		ND		0.076[s]	D	ND		1,300[s]	E
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.0060[t]	D	ND		0.12[t]	D	0.23[t]	D	ND	
Product cooler (SCC 3-05-016-11)	ND	ND			ND		ND		3.9[s]	E

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are kg/Mg of lime produced unless noted. ND = no data. SCC = Source Classification Code.

[b] Mass balance on sulfur may yield a more representative emission factor for a specific facility.

[c] Mass balance on carbon may yield a more representative emission factor for a specific facility.

[d] References 9,18.

[e] References 9,11,18,29,31.

[f] References 18,25.

[g] References 8-9,24-27,29.

Table 11.17-5 (cont.).

[h] References 18,29,31.
[j] Reference 25.
[k] Reference 13.
[m] Reference 12.
[n] Reference 17.
[p] Reference 28.
[q] References 16,24.
[r] Reference 32.
[s] Reference 23.
[t] Reference 34.

Table 11.17-6 (English Units). EMISSION FACTORS FOR LIME MANUFACTURING[a]

Source	SO_2[b]	EMISSION FACTOR RATING	SO_3	EMISSION FACTOR RATING	NO_x	EMISSION FACTOR RATING	CO	EMISSION FACTOR RATING	CO_2[c]	EMISSION FACTOR RATING
Coal-fired rotary kiln (SCC 3-05-016-18)	5.4[d]	D	ND		3.1[e]	C	1.5[f]	D	3,200[g]	C
Coal-fired rotary kiln with fabric filter (SCC 3-05-016-18)	1.7[h]	D	ND		ND		ND		ND	
Coal-fired rotary kiln with wet scrubber (SCC 3-05-016-18)	0.30[j]	D	0.21[k]	E	ND		ND		ND	
Gas-fired rotary kiln (SCC 3-05-016-19)	ND		ND		3.5[m]	E	2.2[m]	E	ND	
Coal- and gas fired rotary kiln with venturi scrubber (SCC 3-05-016-20)	ND		ND		2.7[n]	D	0.83[n]	D	3,200[n]	D
Coal- and coke-fired rotary kiln with venturi scrubber (SCC 3-05-016-21)	ND		ND		ND		ND		3,000[p]	D
Coal-fired rotary preheater kiln with dry PM controls (SCC 3-05-016-22)	2.3[q]	E	ND		ND		ND		ND	
Coal-fired rotary preheater kiln with multiclone, water spray, and fabric filter (SCC 3-05-016-22)	6.4[r]	E	ND		ND		6.3[r]	E	2,400[r]	E
Gas-fired calcimatic kiln (SCC 3-05-016-05)	ND		ND		0.15[s]	D	ND		2,700[s]	E
Gas-fired parallel flow regenerative kiln with fabric filter (SCC 3-05-016-23)	0.0012[t]	D	ND		0.24[t]	D	0.45[t]	D	ND	
Product cooler (SCC 3-05-016-11)	ND		ND		ND		ND		7.8[s]	E

[a] Factors represent uncontrolled emissions unless otherwise noted. Factors are lb/ton of lime produced unless noted. ND = no data. SCC = Source Classification Code.

[b] Mass balance on sulfur may yield a more representative emission factor for a specific facility.

[c] Mass balance on carbon may yield a more representative emission factor for a specific facility.

[d] References 9,18.

[e] References 9,11,18,29,31.

[f] References 18,25.

[g] References 8-9,24-27,29.

Table 11.17-6 (cont.).

[h] References 18,29,31.
[j] Reference 25.
[k] Reference 13.
[m] Reference 12.
[n] Reference 17.
[p] Reference 28.
[q] References 16,24.
[r] Reference 32.
[s] Reference 23.
[t] Reference 34.

Table 11.17-7. AVERAGE PARTICLE SIZE DISTRIBUTION FOR ROTARY LIME KILNS[a]

Particle Size (μm)	Cumulative Mass Percent Less Than Stated Particle Size			
	Uncontrolled Rotary Kiln	Rotary Kiln With Multiclone	Rotary Kiln With ESP	Rotary Kiln With Fabric Filter
2.5	1.4	6.1	14	27
5.0	2.9	9.8	ND	ND
10.0	12	16	50	55
15.0	31	23	62	73
20.0	ND	31	ND	ND

[a] Reference 4, Table 4-28; based on A- and C-rated particle size data. Source Classification Codes 3-05-016-04, and -18 to -21. ND = no data.

Because of differences in the sulfur content of the raw material and fuel and in process operations, a mass balance on sulfur may yield a more representative emission factor for a specific facility than the SO_2 emission factors presented in Tables 11.17-5 and 11.17-6. In addition, CO_2 emission factors estimated using a mass balance on carbon may be more representative for a specific facility than the CO_2 emission factors presented in Tables 11.17-5 and 11.17-6. Additional information on estimating emission factors for CO_2 emissions from lime kilns can be found in the background report for this AP-42 section.

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11.18 Mineral Wool Manufacturing

11.18.1 General[1,2]

Mineral wool often is defined as any fibrous glassy substance made from minerals (typically natural rock materials such as basalt or diabase) or mineral products such as slag and glass. Because glass wool production is covered separately in AP-42 (Section 11.13), this section deals only with the production of mineral wool from natural rock and slags such as iron blast furnace slag, the primary material, and copper, lead, and phosphate slags. These materials are processed into insulation and other fibrous building materials that are used for structural strength and fire resistance. Generally, these products take 1 of 4 forms: "blowing" wool or "pouring" wool, which is put into the structural spaces of buildings; batts, which may be covered with a vapor barrier of paper or foil and are shaped to fit between the structural members of buildings; industrial and commercial products such as high-density fiber felts and blankets, which are used for insulating boilers, ovens, pipes, refrigerators, and other process equipment; and bulk fiber, which is used as a raw material in manufacturing other products, such as ceiling tile, wall board, spray-on insulation, cement, and mortar.

Mineral wool manufacturing facilities are included in Standard Industrial Classification (SIC) Code 3296, mineral wool. This SIC code also includes the production of glass wool insulation products, but those facilities engaged in manufacturing textile glass fibers are included in SIC Code 3229. The 6-digit Source Classification Code (SCC) for mineral wool manufacturing is 3-05-017.

11.18.2 Process Description[1,4,5]

Most mineral wool produced in the United States today is produced from slag or a mixture of slag and rock. Most of the slag used by the industry is generated by integrated iron and steel plants as a blast furnace byproduct from pig iron production. Other sources of slag include the copper, lead, and phosphate industries. The production process has 3 primary components--molten mineral generation in the cupola, fiber formation and collection, and final product formation. Figure 11.18-1 illustrates the mineral wool manufacturing process.

The first step in the process involves melting the mineral feed. The raw material (slag and rock) is loaded into a cupola in alternating layers with coke at weight ratios of about 5 to 6 parts mineral to 1 part coke. As the coke is ignited and burned, the mineral charge is heated to the molten state at a temperature of 1300 to 1650°C (2400 to 3000°F). Combustion air is supplied through tuyeres located near the bottom of the furnace. Process modifications at some plants include air enrichment and the use of natural gas auxiliary burners to reduce coke consumption. One facility also reported using an aluminum flux byproduct to reduce coke consumption.

The molten mineral charge exits the bottom of the cupola in a water-cooled trough and falls onto a fiberization device. Most of the mineral wool produced in the United States is made by variations of 2 fiberization methods. The Powell process uses groups of rotors revolving at a high rate of speed to form the fibers. Molten material is distributed in a thin film on the surfaces of the rotors and then is thrown off by centrifugal force. As the material is discharged from the rotor, small globules develop on the rotors and form long, fibrous tails as they travel horizontally. Air or steam may be blown around the rotors to assist in fiberizing the material. A second fiberization method, the Downey process, uses a spinning concave rotor with air or steam attenuation. Molten material is

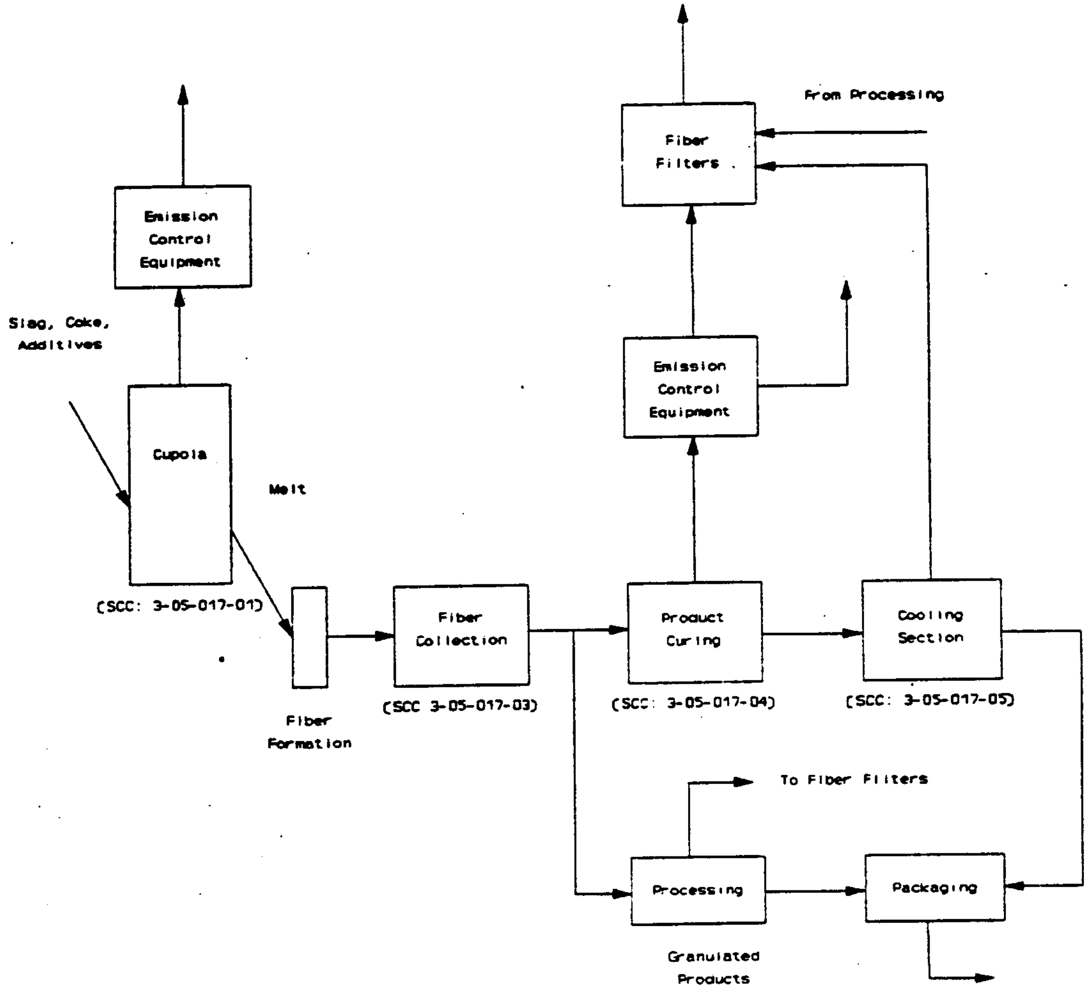


Figure 11.18-1. Mineral wool manufacturing process flow diagram. (Source Classification Codes in parentheses.)

distributed over the surface of the rotor, from which it flows up and over the edge and is captured and directed by a high-velocity stream of air or steam.

During the spinning process, not all globules that develop are converted into fiber. The nonfiberized globules that remain are referred to as "shot." In raw mineral wool, as much as half of the mass of the product may consist of shot. As shown in Figure 11.18-1, shot is usually separated from the wool by gravity immediately following fiberization.

Depending on the desired product, various chemical agents may be applied to the newly formed fiber immediately following the rotor. In almost all cases, an oil is applied to suppress dust and, to some degree, anneal the fiber. This oil can be either a proprietary product or a medium-weight fuel or lubricating oil. If the fiber is intended for use as loose wool or bulk products, no further chemical treatment is necessary. If the mineral wool product is required to have structural rigidity, as in batts and industrial felt, a binding agent is applied with or in place of the oil treatment. This binder is typically a phenol-formaldehyde resin that requires curing at elevated temperatures. Both the oil and the binder are applied by atomizing the liquids and spraying the agents to coat the airborne fiber.

After formation and chemical treatment, the fiber is collected in a blowchamber. Resin- and/or oil-coated fibers are drawn down on a wire mesh conveyor by fans located beneath the collector. The speed of the conveyor is set so that a wool blanket of desired thickness can be obtained.

Mineral wool containing the binding agent is carried by conveyor to a curing oven, where the wool blanket is compressed to the appropriate density and the binder is baked. Hot air, at a temperature of 150 to 320°C (300 to 600°F), is forced through the blanket until the binder has set. Curing time and temperature depend on the type of binder used and the mass rate through the oven. A cooling section follows the oven, where blowers force air at ambient temperatures through the wool blanket.

To make batts and industrial felt products, the cooled wool blanket is cut longitudinally and transversely to the desired size. Some insulation products are then covered with a vapor barrier of aluminum foil or asphalt-coated kraft paper on one side and untreated paper on the other side. The cutters, vapor barrier applicators, and conveyors are sometimes referred to collectively as a batt machine. Those products that do not require a vapor barrier, such as industrial felt and some residential insulation batts, can be packed for shipment immediately after cutting.

Loose wool products consist primarily of blowing wool and bulk fiber. For these products, no binding agent is applied, and the curing oven is eliminated. For granulated wool products, the fiber blanket leaving the blowchamber is fed to a shredder and pelletizer. The pelletizer forms small, 1-inch diameter pellets and separates shot from the wool. A bagging operation completes the processes. For other loose wool products, fiber can be transported directly from the blowchamber to a baler or bagger for packaging.

11.18.3 Emissions And Controls[1,13]

The sources of emissions in the mineral wool manufacturing industry are the cupola; binder storage, mixing, and application; the blow chamber; the curing oven; the mineral wool cooler; materials handling and bagging operations; and waste water treatment and storage. With the exception of lead, the industry emits the full range of criteria pollutants. Also, depending on the particular types of slag and binding agents used, the facilities may emit both metallic and organic hazardous air pollutants (HAPs).

The primary source of emissions in the mineral wool manufacturing process is the cupola. It is a significant source of particulate matter (PM) emissions and is likely to be a source of PM less than 10 micrometers (μm) in diameter (PM-10) emissions, although no particle size data are available. The cupola is also a potential source of HAP metal emissions attributable to the coke and slags used in the furnace. Coke combustion in the furnace produces carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxide (NO_x) emissions. Finally, because blast furnace slags contain sulfur, the cupola is also a source of sulfur dioxide (SO_2) and hydrogen sulfide (H_2S) emissions.

The blowchamber is a source of PM (and probably PM-10) emissions. Also, the annealing oils and binders used in the process can lead to VOC emissions from the process. Other sources of VOC emissions include batt application, the curing oven, and waste water storage and treatment. Finally, fugitive PM emissions can be generated during cooling, handling, and bagging operations. Tables 11.18-1 and 11.18-2 present emission factors for filterable PM emissions from various mineral wool manufacturing processes; Tables 11-18.3 and 11.18-4 show emission factors for CO, CO_2, SO_2, and sulfates; and Tables 11.18-5 and 11.18-6 present emission factors for NO_x, N_2O, H_2S and fluorides.

Mineral wool manufacturers use a variety of air pollution control techniques, but most are directed toward PM control with minimal control of other pollutants. The industry has given greatest attention to cupola PM control, with two-thirds of the cupolas in operation having fabric filter control systems. Some cupola exhausts are controlled by wet scrubbers and electrostatic precipitators (ESPs); cyclones are also used for cupola PM control either alone or in combination with other control devices. About half of the blow chambers in the industry also have some level of PM control, with the predominant control device being low-energy wet scrubbers. Cyclones and fabric filters have been used to a limited degree on blow chambers. Finally, afterburners have been used to control VOC emissions from blow chambers and curing ovens and CO emissions from cupolas.

Table 11.18-1 (Metric Units). EMISSION FACTORS FOR MINERAL WOOL MANUFACTURING[a]

Process	Filterable PM[b]	
	kg/Mg Of Product	EMISSION FACTOR RATING
Cupola[c] (SCC 3-05-017-01)	8.2	E
Cupola with fabric filter[d] (SCC 3-05-017-01)	0.051	D
Reverberatory furnace[e] (SCC 3-05-017-02)	2.4	E
Batt curing oven[e] (SCC 3-05-017-04)	1.8	E
Batt curing oven with ESP[f] (SCC 3-05-017-04)	0.36	D
Blow chamber[c] (SCC 3-05-017-03)	6.0	E
Blow chamber with wire mesh filter[g] (SCC 3-05-017-03)	0.45	D
Cooler[e] (SCC 3-05-017-05)	1.2	E

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] References 1,12. Activity level is assumed to be total feed charged.

[d] References 6,7,8,10,11. Activity level is total feed charged.

[e] Reference 12.

[f] Reference 9.

[g] Reference 7. Activity level is mass of molten mineral feed charged.

Table 11.18-2 (English Units). EMISSION FACTORS FOR MINERAL WOOL MANUFACTURING[a]

Process	Filterable PM[b]	
	lb/ton Of Product	EMISSION FACTOR RATING
Cupola[c] (SCC 3-05-017-01)	16	E
Cupola with fabric filter[d] (SCC 3-05-017-01)	0.10	D
Reverberatory furnace[e] (SCC 3-05-017-02)	4.8	E
Batt curing oven[e] (SCC 3-05-017-04)	3.6	E
Batt curing oven with ESP[f] (SCC 3-05-017-04)	0.72	D
Blow chamber[c] (SCC 3-05-017-03)	12	E
Blow chamber with wire mesh filter[g] (SCC 3-05-017-03)	0.91	D
Cooler[e] (SCC 3-05-017-05)	2.4	E

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Reference 1,12. Activity level is assumed to be total feed charged.

[d] References 6,7,8,10,11. Activity level is total feed charged.

[e] Reference 12.

[f] Reference 9.

[g] Reference 7. Activity level is mass of molten mineral feed charged.

Table 11.18-3 (Metric Units). EMISSION FACTORS FOR MINERAL WOOL MANUFACTURING[a]

Source	CO^b		$CO_2{}^b$		SO_2		SO_3	
	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING
Cupola (SCC 3-05-017 01)	125	D	260	D	4.0^c	D	3.2^d	E
Cupola with fabric filter (SCC 3-05-017-01)	NA		NA		NA		0.077^b	E
Batt curing oven (SCC 3-05-017-04)	ND		ND		0.58^d	E	ND	
Blow chamber (SCC 3-05-017-03)	ND		80^e	E	0.43^d	E	ND	
Cooler (SCC 3-05-017-05)	ND		ND		0.034^d	E	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. NA = not applicable. ND = no data.

[b] Reference 6.

[c] References 6,10,11.

[d] Reference 12.

[e] Reference 9.

Table 11.18-4 (English Units). EMISSION FACTORS FOR MINERAL WOOL MANUFACTURING[a]

	CO^b		CO_2[b]		SO_2		SO_3	
Source	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING
Cupola (SCC 3-05-017-01)	250	D	520	D	8.0[a]	D	6.3[d]	E
Cupola with fabric filter (SCC 3-05-017-01)	NA		NA		NA		0.15[b]	E
Batt curing oven (SCC 3-05-017-04)	ND		ND		1.2[d]	E	ND	
Blow chamber (SCC 3-05-017-03)	ND		160[c]	E	0.087[d]	E	ND	
Cooler (SCC 3-05-017-05)	ND		ND		0.068[d]	E	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. NA = not applicable. ND = no data.

[b] Reference 6.

[c] References 6,10,11.

[d] Reference 12.

[e] Reference 9.

Table 11.18-5 (Metric Units). EMISSION FACTORS FOR MINERAL WOOL MANUFACTURING[a]

Process	NO_x		N_2O		H_2S		Fluorides	
	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING	kg/mg Of Total Feed Charged	EMISSION FACTOR RATING	kg/Mg Of Total Feed Charged	EMISSION FACTOR RATING
Cupola (SCC 3-05-017-01)	0.8[b]	E	ND		1.5[b]	E	ND	
Cupola with fabric filter (SCC 3-05-017-01)	ND		ND		ND		0.019[c]	D
Cupola with fabric filter (SCC 3-05-017-01)	ND		ND		ND		0.19[d]	D
Batt curing oven (SCC 3-05-017-14)	ND		0.079	E	ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] Reference 1.

[c] References 10-11. Coke only used as fuel.

[d] References 10-11. Fuel combination of coke and aluminum smelting byproducts.

Table 11.18-6 (English Units). EMISSION FACTORS FOR MINERAL WOOL MANUFACTURING[a]

Process	NO_x		N_2O		H_2S		Fluorides	
	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING	lb/ton Of Total Feed Charged	EMISSION FACTOR RATING
Cupola (SCC 3-05-017-01)	1.6[b]	E	ND		3.0[b]	E	ND	
Cupola with fabric filter (SCC 3-05-017-01)	ND		ND		ND		0.038[c]	D
Cupola with fabric filter (SCC 3-05-017-01)	ND		ND		ND		0.38[d]	D
Batt curing oven (SCC 3-05-017-14)	ND		0.16	E	ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] Reference 1.

[c] References 10-11. Coke only used as fuel.

[d] References 10-11. Fuel combination of coke and aluminum smelting byproducts.

References For Section 11.18

1. *Source Category Survey: Mineral Wool Manufacturing Industry*, EPA-450/3-80-016, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1980.

2. *The Facts On Rocks And Slag Wool*, Pub. No. N 020, North American Insulation Manufacturers Association, Alexandria, VA, Undated.

3. ICF Corporation, *Supply Response To Residential Insulation Retrofit Demand*, Report to the Federal Energy Administration, Contract No. P-14-77-5438-0, Washington, DC, June 1977.

4. Personal communication between F. May, U.S.G. Corporation, Chicago, Illinois, and R. Marinshaw, Midwest Research Institute, Cary, NC, June 5, 1992.

5. Memorandum from K. Schuster, N. C. Department Of Environmental Management, to M. Aldridge, American Rockwool, April 25, 1988.

6. *Sulfur Oxide Emission Tests Conducted On The #1 And #2 Cupola Stacks In Leeds, Alabama For Rock Wool Company, November 8 & 9, 1988*, Guardian Systems, Inc., Leeds, AL, Undated.

7. *Particulate Emissions Tests For U. S. Gypsum Company On The Number 4 Dry Filter And Cupola Stack Located In Birmingham, Alabama On January 14, 1981*, Guardian Systems, Inc., Birmingham, AL, Undated.

8. Untitled Test Report, Cupolas Nos. 1, 2, and 3, U. S. Gypsum, Birmingham, AL, June 1979.

9. *Particulate Emission Tests On Batt Curing Oven For U. S. Gypsum, Birmingham, Alabama On October 31-November 1, 1977*, Guardian Systems, Inc., Birmingham, AL, Undated.

10. J. V. Apicella, *Particulate, Sulfur Dioxide, And Fluoride Emissions From Mineral Wool Emission, With Varying Charge Compositions, American Rockwool, Inc. Spring Hope, NC, 27882*, Alumina Company Of America, Alcoa Center, PA, June 1988.

11. J. V. Apicella, *Compliance Report On Particulate, Sulfur Dioxide, Fluoride, And Visual Emissions From Mineral Wool Production, American Rockwool, Inc., Spring Hope, NC, 27882*, Aluminum Company Of America, Alcoa Center, PA, February 1988.

12. J. L. Spinks, "Mineral Wool Furnaces", In: *Air Pollution Engineering Manual*, J. A. Danielson, ed., U. S. DHEW, PHS, National Center For Air Pollution Control, Cincinnati, OH, PHS Publication Number 999-AP-40, 1967, pp. 343-347.

13. Personal communication between M. Johnson, U. S. Environmental Protection Agency, Research Triangle Park, NC, and D. Bullock, Midwest Research Institute, Cary, NC, March 22, 1993.

11.19 Construction Aggregate Processing[1-2]

The construction aggregate industry covers a range of subclassifications of the nonmetallic minerals industry (see Section 11.24, Metallic Minerals Processing, for information on that similar activity). Many operations and processes are common to both groups, including mineral extraction from the earth, loading, unloading, conveying, crushing, screening, and loadout. Other operations are restricted to specific subcategories. These include wet and dry fine milling or grinding, air classification, drying, calcining, mixing, and bagging. The latter group of operations is not generally associated with the construction aggregate industry but can be conducted on the same raw materials used to produce aggregate. Two examples are processing of limestone and sandstone. Both substances can be used as construction materials and may be processed further for other uses at the same location. Limestone is a common source of construction aggregate, but it can be further milled and classified to produce agricultural limestone. Sandstone can be processed into construction sand and also can be wet and/or dry milled, dried, and air classified into industrial sand.

The construction aggregate industry can be categorized by source, mineral type or form, wet versus dry, washed or unwashed, and end uses, to name but a few. The industry is divided in this document into Section 11.19.1, Sand And Gravel Processing, and Section 11.19.2, Crushed Stone Processing. Sections on other categories of the industry will be published when data on these processes become available.

Uncontrolled construction aggregate processing can produce nuisance problems and can have an effect upon attainment of ambient particulate standards. However, the generally large particles produced often can be controlled readily. Some of the individual operations such as wet crushing and grinding, washing, screening, and dredging take place with "high" moisture (more than about 1.5 to 4.0 weight percent). Such wet processes do not generate appreciable particulate emissions.

References For Section 11.19

1. *Air Pollution Control Techniques For Nonmetallic Minerals Industry*, EPA-450/3-82-014, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1982.

2. *Review Emissions Data Base And Develop Emission Factors For The Construction Aggregate Industry*, Engineering-Science, Inc., Arcadia, CA, September 1984.

11.19.1 Sand And Gravel Processing

[Work In Progress]

11.19.2 Crushed Stone Processing

11.19.2.1 Process Description[1-2]

Major rock types processed by the rock and crushed stone industry include limestone, granite, dolomite, traprock, sandstone, quartz, and quartzite. Minor types include calcareous marl, marble, shell, and slate. Industry classifications vary considerably and, in many cases, do not reflect actual geological definitions.

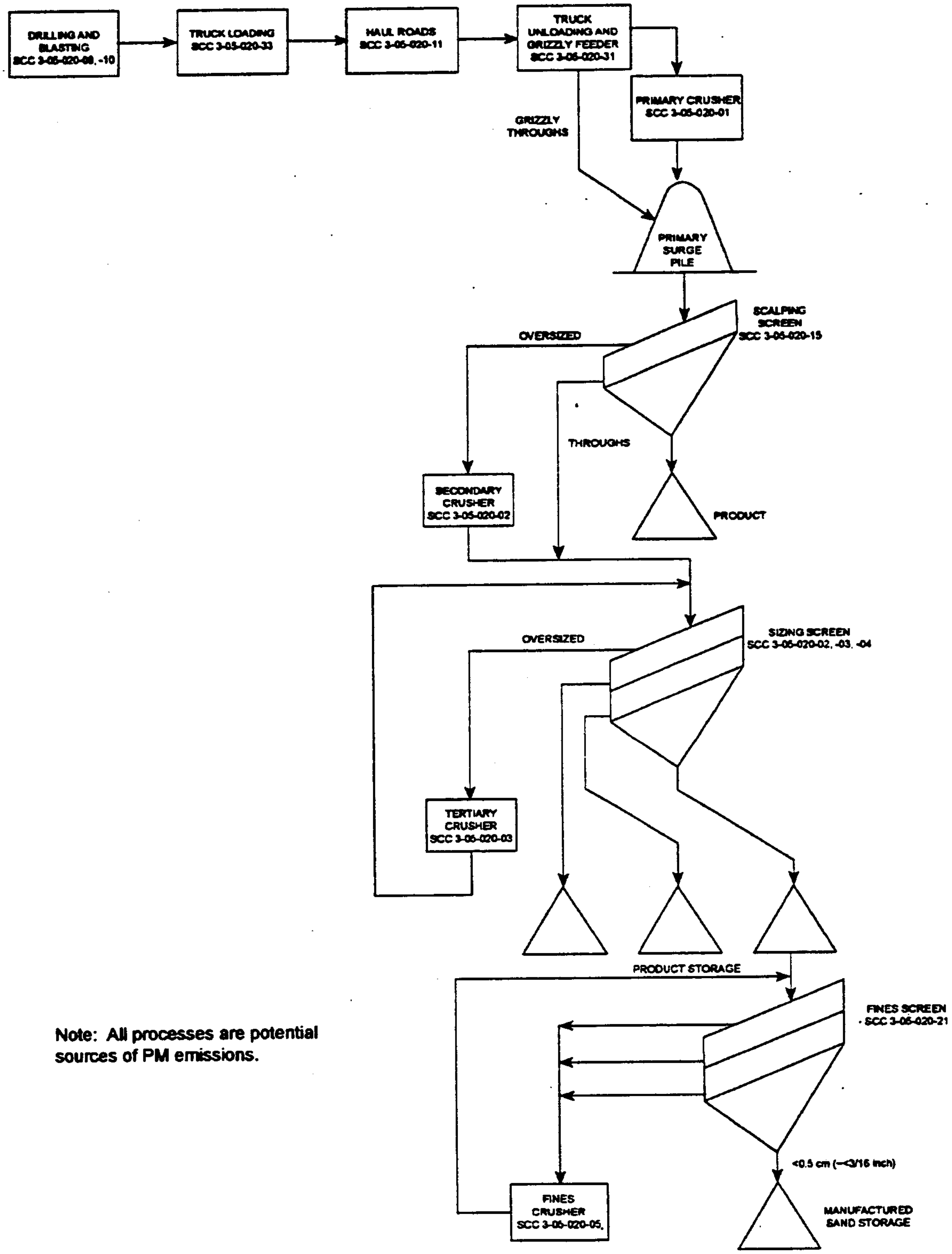
Rock and crushed stone products generally are loosened by drilling and blasting, then are loaded by power shovel or front-end loader into large haul trucks that transport the material to the processing operations. Techniques used for extraction vary with the nature and location of the deposit. Processing operations may include crushing, screening, size classification, material handling, and storage operations. All of these processes can be significant sources of PM and PM-10 emissions if uncontrolled.

Quarried stone normally is delivered to the processing plant by truck and is dumped into a hoppered feeder, usually a vibrating grizzly type, or onto screens, as illustrated in Figure 11.19.2-1. The feeder or screens separate large boulders from finer rocks that do not require primary crushing, thus reducing the load to the primary crusher. Jaw, impactor, or gyratory crushers are usually used for initial reduction. The crusher product, normally 7.5 to 30 centimeters (3 to 12 inches) in diameter, and the grizzly throughs (undersize material) are discharged onto a belt conveyor and usually are conveyed to a surge pile for temporary storage, or are sold as coarse aggregates.

The stone from the surge pile is conveyed to a vibrating inclined screen called the scalping screen. This unit separates oversized rock from the smaller stone. The undersize material from the scalping screen is considered to be a product stream and is transported to a storage pile and sold as base material. The stone that is too large to pass through the top deck of the scalping screen is processed in the secondary crusher. Cone crushers are commonly used for secondary crushing (although impact crushers are sometimes used), which typically reduces material to about 2.5 to 10 centimeters (1 to 4 inches). The material (throughs) from the second level of the screen bypasses the secondary crusher because it is sufficiently small for the last crushing step. The output from the secondary crusher and the throughs from the secondary screen are transported by conveyor to the tertiary circuit, which includes a sizing screen and a tertiary crusher.

Tertiary crushing is usually performed using cone crushers or other types of impactor crushers. Oversize material from the top deck of the sizing screen is fed to the tertiary crusher. The tertiary crusher output, which is typically about 0.50 to 2.5 centimeters (3/16th to 1 inch), is returned to the sizing screen. Various product streams with different size gradations are separated in the screening operation. The products are conveyed or trucked directly to finished product bins, open area stockpiles, or to other processing systems such as washing, air separators, and screens and classifiers (for the production of manufactured sand).

Some stone crushing plants produce manufactured sand. This is a small-sized rock product with a maximum size of 0.50 centimeters (3/16th inch). Crushed stone from the tertiary sizing screen is sized in a vibrating inclined screen (fines screen) with relatively small mesh sizes. Oversized material is processed in a cone crusher or a hammermill (fines crusher) adjusted to produce small diameter material. The output is then returned to the fines screen for resizing.



Note: All processes are potential sources of PM emissions.

Figure 11.19.2-1. Typical stone processing plant.[2]
(SCC = Source Classification Code.)

In certain cases, stone washing is required to meet particular end product specifications or demands as with concrete aggregate processing. Crushed and broken stone normally is not milled but is screened and shipped to the consumer after secondary or tertiary crushing.

11.19.2.2 Emissions And Controls[1-8]

Emissions of PM and PM-10 occur from a number of operations in stone quarrying and processing. A substantial portion of these emissions consists of heavy particles that may settle out within the plant. As in other operations, crushed stone emission sources may be categorized as either process sources or fugitive dust sources. Process sources include those for which emissions are amenable to capture and subsequent control. Fugitive dust sources generally involve the reentrainment of settled dust by wind or machine movement. Emissions from process sources should be considered fugitive unless the sources are vented to a baghouse or are contained in an enclosure with a forced-air vent or stack. Factors affecting emissions from either source category include the stone size distribution and surface moisture content of the stone processed; the process throughput rate; the type of equipment and operating practices used; and topographical and climatic factors.

Of geographic and seasonal factors, the primary variables affecting uncontrolled PM emissions are wind and material moisture content. Wind parameters vary with geographical location, season, and weather. It can be expected that the level of emissions from unenclosed sources (principally fugitive dust sources) will be greater during periods of high winds. The material moisture content also varies with geographic location, season, and weather. Therefore, the levels of uncontrolled emissions from both process emission sources and fugitive dust sources generally will be greater in arid regions of the country than in temperate ones, and greater during the summer months because of a higher evaporation rate.

The moisture content of the material processed can have a substantial effect on emissions. This effect is evident throughout the processing operations. Surface wetness causes fine particles to agglomerate on, or to adhere to, the faces of larger stones, with a resulting dust suppression effect. However, as new fine particles are created by crushing and attrition, and as the moisture content is reduced by evaporation, this suppressive effect diminishes and may disappear. Plants that use wet suppression systems (spray nozzles) to maintain relatively high material moisture contents can effectively control PM emissions throughout the process. Depending on the geographic and climatic conditions, the moisture content of mined rock may range from nearly zero to several percent. Because moisture content is usually expressed on a basis of overall weight percent, the actual moisture amount per unit area will vary with the size of the rock being handled. On a constant mass-fraction basis, the per-unit area moisture content varies inversely with the diameter of the rock. Therefore, the suppressive effect of the moisture depends on both the absolute mass water content and the size of the rock product. Typically, wet material contains 1.5 to 4 percent water or more.

A variety of material, equipment, and operating factors can influence emissions from crushing. These factors include (1) stone type, (2) feed size and distribution, (3) moisture content, (4) throughput rate, (5) crusher type, (6) size reduction ratio, and (7) fines content. Insufficient data are available to present a matrix of rock crushing emission factors detailing the above classifications and variables. Available data indicate that PM-10 emissions from limestone and granite processing operations are similar. Therefore, the emission factors developed from the emission data gathered at limestone and granite processing facilities are considered to be representative of typical crushed stone processing operations. Emission factors for filterable PM and PM-10 emissions from crushed stone processing operations are presented in Tables 11.19-1 (metric units) and 11.19-2 (English units).

Table 11.19.2-1 (Metric Units). EMISSION FACTORS FOR CRUSHED STONE PROCESSING OPERATIONS[a]

Source[b]	Total Particulate Matter	EMISSION FACTOR RATING	Total PM-10[c]	EMISSION FACTOR RATING
Screening (SCC 3-05-020-02,-03)	—[d]		0.0076[e]	C
Screening (controlled) (SCC 3-05-020-02-03)	—[d]		0.00042[e]	C
Primary crushing (SCC 3-05-020-01)	0.00035[f]	E	ND[g]	
Secondary crushing (SCC 3-05-020-02)	ND		ND[g]	
Tertiary crushing (SCC 3-05-020-03)	—[d]		0.0012[h]	C
Primary crushing (controlled) (SCC 3-05-020-01)	ND		ND[g]	
Secondary crushing (controlled) (SCC 3-05-020-02)	ND		ND[g]	
Tertiary crushing (controlled) (SCC 3-05-020-03)	—[d]		0.00029[h]	C
Fines crushing[j] (SCC 3-05-020-05)	—[d]		0.0075	E
Fines crushing (controlled)[j] (SCC 3-05-020-05)	—[d]		0.0010	E
Fines screening[j] (SCC 3-05-020-21)	—[d]		0.036	E
Fines screening (controlled)[j] (SCC 3-05-020-21)	—[d]		0.0011	E
Conveyor transfer point[k] (SCC 3-05-020-06)	—[d]		0.00072	D
Conveyor transfer point (controlled)[k] (SCC 3-05-020-06)	—[d]		$2.4\text{x}10^{-5}$	D
Wet drilling: unfragmented stone[m] (SCC 3-05-020-10)	ND		$4.0\text{x}10^{-5}$	E
Truck unloading: fragmented stone[m] (SCC 3-05-020-31)	ND		$8.0\text{x}10^{-6}$	E
Truck loading–conveyor: crushed stone[n] (SCC 3-05-020-32)	ND		$5.0\text{x}10^{-5}$	E

[a] Emission factors represent uncontrolled emissions unless noted. Emission factors in kg/Mg of material throughput. SCC = Source Classification Code. ND = no data.

[b] Controlled sources (with wet suppression) are those that are part of the processing plant that employs current wet suppression technology similar to the study group. The moisture content of the study group without wet suppression systems operating (uncontrolled) ranged from 0.21 to 1.3 percent and the same facilities operating wet suppression sytems (controlled) ranged from 0.55 to 2.88 percent. Due to carry over or the small amount of moisture required, it has been shown that each source, with the exception of crushers, does not need to employ direct water sprays. Although the moisture content was the only variable measured, other process features may have as much influence on emissions from a given source. Visual observations from each source under normal operating conditions are probably the best indicator of which emission factor is most appropriate. Plants that employ sub-standard control measures as indicated by visual observations should use the uncontrolled factor with an appropriate control efficiency that best reflects the effectiveness of the controls employed.

[c] Although total suspended particulate (TSP) is not a measurable property from a process, some states may require estimates of TSP emissions. No data are available to make these estimates. However, relative ratios in AP-42 Sections 13.2.2 and 13.2.4 indicate that TSP emission factors may be estimated by multiplying PM-10 by 2.1.

Table 11.19.2-1 (cont.).

[d] Emission factors for total particulate are not presented pending a re-evaluation of the EPA Method 201a test data and/or results of emission testing. This re-evaluation is expected to be completed by July 1995.

[e] References 9, 11, 15-16.

[f] Reference 1.

[g] No data available, but emission factors for PM-10 emission factors for tertiary crushing can be used as an upper limit for primary or secondary crushing.

[h] References 10-11, 15-16.

[j] Reference 12.

[k] References 13-14.

[m] Reference 3.

[n] Reference 4.

Table 11.19.2-2 (English Units). EMISSION FACTORS FOR CRUSHED STONE PROCESSING OPERATIONS[a]

Source[b]	Total Particulate Matter	EMISSION FACTOR RATING	Total PM-10[c]	EMISSION FACTOR RATING
Screening (SCC 3-05-020-02,-03)	—[d]		0.015[e]	C
Screening (controlled) (SCC 3-05-020-02-03)	—[d]		0.00084[e]	C
Primary crushing (SCC 3-05-020-01)	0.00070[f]	E	ND[g]	
Secondary crushing (SCC 3-05-020-02)	ND		ND[g]	
Tertiary crushing (SCC 3-05-020-03)	—[d]		0.0024[h]	C
Primary crushing (controlled) (SCC 3-05-020-01)	ND		ND[g]	NA
Secondary crushing (controlled) (SCC 3-05-020-02)	ND		ND[g]	NA
Tertiary crushing (controlled) (SCC 3-05-020-03)	—[d]		0.00059[h]	C
Fines crushing[j] (SCC 3-05-020-05)	—[d]		0.015	E
Fines crushing (controlled)[j] (SCC 3-05-020-05)	—[d]		0.0020	E
Fines screening[j] (SCC 3-05-020-21)	—[d]		0.071	E
Fines screening (controlled)[j] (SCC 3-05-020-21)	—[d]		0.0021	E
Conveyor transfer point[k] (SCC 3-05-020-06)	—[d]		0.0014	D
Conveyor transfer point (controlled)[k] (SCC 3-05-020-06)	—[d]		$4.8x10^{-5}$	D
Wet drilling: unfragmented stone[m] (SCC 3-05-020-10)	ND		$8.0x10^{-5}$	E
Truck unloading: fragmented stone[m] (SCC 3-05-020-31)	ND		$1.6x10^{-5}$	E
Truck loading—conveyor: crushed stone[n] (SCC 3-05-020-32)	ND		0.00010	E

[a] Emission factors represent uncontrolled emissions unless noted. Emission factors in lb/ton of material throughput. SCC = Source Classification Code. ND = no data.

[b] Controlled sources (with wet suppression) are those that are part of the processing plant that employs current wet suppression technology similar to the study group. The moisture content of the study group without wet suppression systems operating (uncontrolled) ranged from 0.21 to 1.3 percent and the same facilities operating wet suppression systems (controlled) ranged from 0.55 to 2.88 percent. Due to carry over or the small amount of moisture required, it has been shown that each source, with the exception of crushers, does not need to employ direct water sprays. Although the moisture content was the only variable measured, other process features may have as much influence on emissions from a given source. Visual observations from each source under normal operating conditions are probably the best indicator of which emission factor is most appropriate. Plants that employ sub-standard control measures as indicated by visual observations should use the uncontrolled factor with an appropriate control efficiency that best reflects the effectiveness of the controls employed.

[c] Although total suspended particulate (TSP) is not a measurable property from a process, some states may require estimates of TSP emissions. No data are available to make these estimates. However, relative ratios in AP-42 Sections 13.2.2 and 13.2.4 indicate that TSP emission factors may be estimated by multiplying PM-10 by 2.1.

Table 11.19.2-2 (cont.).

[d] Emission factors for total particulate are not presented pending a re-evaluation of the EPA Method 201a test data and/or results of emission testing. This re-evaluation is expected to be completed by July 1995.

[e] References 9, 11, 15-16.

[f] Reference 1.

[g] No data available, but emission factors for PM-10 emission factors for tertiary crushing can be used as an upper limit for primary or secondary crushing.

[h] References 10-11, 15-16.

[j] Reference 12.

[k] References 13-14.

[m] Reference 3.

[n] Reference 4.

Emission factor estimates for stone quarry blasting operations are not presented here because of the sparsity and unreliability of available test data. While a procedure for estimating blasting emissions is presented in Section 11.9, Western Surface Coal Mining, that procedure should not be applied to stone quarries because of dissimilarities in blasting techniques, material blasted, and size of blast areas. Milling of fines is not included in this section as this operation is normally associated with nonconstruction aggregate end uses and will be covered elsewhere when information is adequate. Emission factors for fugitive dust sources, including paved and unpaved roads, materials handling and transfer, and wind erosion of storage piles, can be determined using the predictive emission factor equations presented in AP-42 Section 13.2.

References For Section 11.19.2

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11.20 Lightweight Aggregate Manufacturing

11.20.1 Process Description[1,2]

Lightweight aggregate is a type of coarse aggregate that is used in the production of lightweight concrete products such as concrete block, structural concrete, and pavement. The Standard Industrial Classification (SIC) code for lightweight aggregate manufacturing is 3295; there currently is no Source Classification Code (SCC) for the industry.

Most lightweight aggregate is produced from materials such as clay, shale, or slate. Blast furnace slag, natural pumice, vermiculite, and perlite can be used as substitutes, however. To produce lightweight aggregate, the raw material (excluding pumice) is expanded to about twice the original volume of the raw material. The expanded material has properties similar to natural aggregate, but is less dense and therefore yields a lighter concrete product.

The production of lightweight aggregate begins with mining or quarrying the raw material. The material is crushed with cone crushers, jaw crushers, hammermills, or pugmills and is screened for size. Oversized material is returned to the crushers, and the material that passes through the screens is transferred to hoppers. From the hoppers, the material is fed to a rotary kiln, which is fired with coal, coke, natural gas, or fuel oil, to temperatures of about 1200°C (2200°F). As the material is heated, it liquefies and carbonaceous compounds in the material form gas bubbles, which expand the material; in the process, volatile organic compounds (VOC) are released. From the kiln, the expanded product (clinker) is transferred by conveyor into the clinker cooler where it is cooled by air, forming a porous material. After cooling, the lightweight aggregate is screened for size, crushed if necessary, stockpiled, and shipped. Figure 11.20-1 illustrates the lightweight aggregate manufacturing process.

Although the majority (approximately 90 percent) of plants use rotary kilns, traveling grates are also used to heat the raw material. In addition, a few plants process naturally occurring lightweight aggregate such as pumice.

11.20.2 Emissions And Controls[1]

Emissions from the production of lightweight aggregate consist primarily of particulate matter (PM), which is emitted by the rotary kilns, clinker coolers, and crushing, screening, and material transfer operations. Pollutants emitted as a result of combustion in the rotary kilns include sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), and VOCs. Chromium, lead, and chlorides also are emitted from the kilns. In addition, other metals including aluminum, copper, manganese, vanadium, and zinc are emitted in trace amounts by the kilns. However, emission rates for these pollutants have not been quantified. In addition to PM, clinker coolers emit CO_2 and VOCs. Emission factors for crushing, screening, and material transfer operations can be found in AP-42 Section 11.19.

Some lightweight aggregate plants fire kilns with material classified as hazardous waste under the Resource Conservation and Recovery Act. Emission data are available for emissions of hydrogen chloride, chlorine, and several metals from lightweight aggregate kilns burning hazardous waste. However, emission factors developed from these data have not been incorporated in this AP-42 section because the magnitude of emissions of these pollutants is largely a function of the waste fuel composition, which can vary considerably.

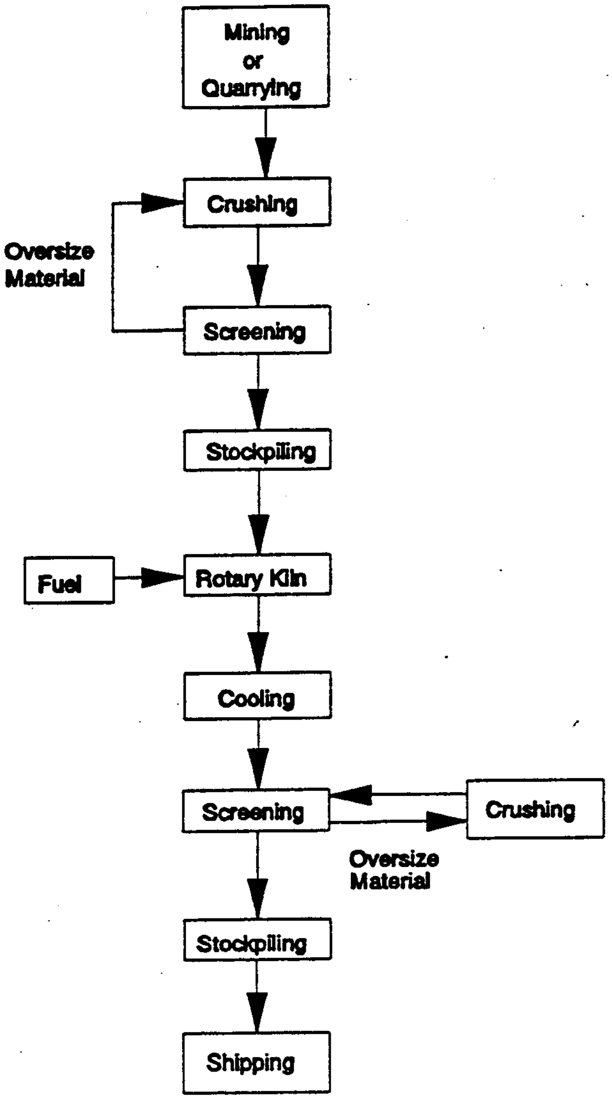

Figure 11.20-1. Process flow diagram for lightweight aggregate manufacturing.

Emissions from rotary kilns generally are controlled with wet scrubbers. However, fabric filters and electrostatic precipitators (ESP) are also used to control kiln emissions. Multiclones and settling chambers generally are the only types of controls for clinker cooler emissions.

Tables 11.20-1 and 11.20-2 summarize uncontrolled and controlled emission factors for PM emissions (both filterable and condensable) from rotary kilns and clinker coolers. Emission factors for SO_x, NO_x, CO, and CO_2 emissions from rotary kilns are presented in Tables 11.20-3 and 11.20-4, which also include an emission factor for CO_2 emissions from clinker coolers. Table 11.20-5 presents emission factors for total VOC (TVOC) emissions from rotary kilns. Size-specific PM emission factors for rotary kilns and clinker coolers are presented in Table 11.20-6.

Table 11.20-1 (Metric Units). EMISSION FACTORS FOR LIGHTWEIGHT AGGREGATE PRODUCTION[a]

Process	Filterable[b]				Condensable PM[c]			
	PM		PM-10		Inorganic		Organic	
	kg/Mg Of Feed	EMISSION FACTOR RATING	kg/Mg Of Feed	EMISSION FACTOR RATING	kg/Mg Of Feed	EMISSION FACTOR RATING	kg/Mg Of Feed	EMISSION FACTOR RATING
Rotary kiln	65[d]	D	ND		0.41[e]	D	0.0080[f]	D
Rotary kiln with scrubber	0.39[g]	C	0.15[h]	D	0.10[h]	D	0.0046[h]	D
Rotary kiln with fabric filter	0.13[i]	C	ND		0.070[j]	D	ND	
Rotary kiln with ESP	0.34[k]	D	ND		0.015[k]	D	ND	
Clinker cooler with settling chamber	0.14[l]	D	0.055[l]	D	0.0085[l]	D	0.00034[l]	D
Clinker coller with multiclone	0.15[m]	D	0.060[m]	D	0.0013[m]	D	0.0014[m]	D

[a] Factors represent uncontrolled emissions unless otherwise noted. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] References 3,7,14. Average of 3 tests that ranged from 6.5 to 170 kg/Mg.

[e] References 3,14.

[f] Reference 3.

[g] References 3,5,10,12-14.

[h] References 3,5.

[i] References 7,14,17-19.

[j] Reference 14.

[k] References 15,16.

[l] References 3,6.

[m] Reference 4.

Table 11.20-2 (English Units). EMISSION FACTORS FOR LIGHTWEIGHT AGGREGATE PRODUCTION[a]

	Filterable[b]				Condensable PM[c]			
	PM		PM-10		Inorganic		Organic	
Process	lb/ton Of Feed	EMISSION FACTOR RATING	lb/ton Of Feed	EMISSION FACTOR RATING	lb/ton Of Feed	EMISSION FACTOR RATING	lb/ton Of Feed	EMISSION FACTOR RATING
Rotary kiln	130[d]	D	ND		0.82[e]	D	0.016[f]	D
Rotary kiln with scrubber	0.78[g]	C	0.29[h]	D	0.19[h]	D	0.0092[h]	D
Rotary kiln with fabric filter	0.26[i]	C	ND		0.14[j]	D	ND	
Rotary kiln with ESP	0.67[k]	D	ND		0.031[k]	D	ND	
Clinker cooler with settling chamber	0.28[l]	D	0.11[l]	D	0.017[l]	D	0.00067[l]	D
Clinker cooler with multiclone	0.30[m]	D	0.12[m]	D	0.0025[m]	D	0.0027[m]	D

[a] Factors represent uncontrolled emissions unless otherwise noted. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] References 3,7,14. Average of 3 tests that ranged from 13 to 340 lb/ton.

[e] References 3,14.

[f] Reference 3.

[g] References 3,5,10,12-14.

[h] References 3,5.

[i] References 7,14,17-19.

[j] Reference 14.

[k] References 15,16.

[l] References 3,6.

[m] Reference 4.

Table 11.20-3 (Metric Units). EMISSION FACTORS FOR LIGHTWEIGHT AGGREGATE PRODUCTION[a]

Process	SO_x		NO_x		CO		CO_2	
	kg/Mg Of Feed	EMISSION FACTOR RATING	kg/Mg Of Feed	EMISSION FACTOR RATING	kg/Mg Of Feed	EMISSION FACTOR RATING	kg/Mg Of Feed	EMISSION FACTOR RATING
Rotary kiln	2.8[b]	C	ND		0.29[c]	C	240[d]	C
Rotary kiln with scrubber	1.7[e]	C	1.0[f]	D	ND		ND	
Clinker cooler with dry multicyclone	ND		ND		ND		22[g]	D

[a] Factors represent uncontrolled emissions unless otherwise noted. ND = no data.
[b] References 3,4,5,8.
[c] References 17,18,19.
[d] References 3,4,5,12,13,14,17,18,19
[e] References 3,4,5,9.
[f] References 3,4,5.
[g] Reference 4.

Table 11.20-4 (English Units). EMISSION FACTORS FOR LIGHTWEIGHT AGGREGATE PRODUCTION[a]

Process	SO_x		NO_x		CO		CO_2	
	lb/ton Of Feed	EMISSION FACTOR RATING	lb/ton Of Feed	EMISSION FACTOR RATING	lb/ton Of Feed	EMISSION FACTOR RATING	lb/ton Of Feed	EMISSION FACTOR RATING
Rotary kiln	5.6[b]	C	ND		0.59[c]	C	480[d]	C
Rotary kiln with scrubber	3.4[e]	C	1.9[f]	D	ND		ND	
Clinker cooler with dry multicyclone	ND		ND		ND		43[g]	D

[a] Factors represent uncontrolled emissions unless otherwise noted. ND = no data.
[b] References 3,4,5,8.
[c] References 17,18,19.
[d] References 3,4,5,12,13,14,17,18,19
[e] References 3,4,5,9.
[f] References 3,4,5.
[g] Reference 4.

Table 11.20-5 (Metric And English Units). EMISSION FACTORS FOR LIGHTWEIGHT AGGREGATE PRODUCTION[a]

Process	TVOCs		
	kg/Mg Of Feed	lb/ton Of Feed	EMISSION FACTOR RATING
Rotary kiln	ND	ND	D
Rotary kiln with scrubber	0.39[b]	0.78[b]	D

[a] Factors represent uncontrolled emissions unless otherwise noted. ND = no data.
[b] Reference 3.

Table 11.20-6 (Metric And English Units). PARTICULATE MATTER SIZE-SPECIFIC EMISSION FACTORS FOR EMISSIONS FROM ROTARY KILNS AND CLINKER COOLERS[a]

EMISSION FACTOR RATING: D

Diameter, micrometers	Cumulative % Less Than Diameter	Emission Factor	
		kg/Mg	lb/ton
Rotary Kiln With Scrubber[b]			
2.5	35	0.10	0.20
6.0	46	0.13	0.26
10.0	50	0.14	0.28
15.0	55	0.16	0.31
20.0	57	0.16	0.32
Clinker Cooler With Settling Chamber[c]			
2.5	9	0.014	0.027
6.0	21	0.032	0.063
10.0	35	0.055	0.11
15.0	49	0.080	0.16
20.0	58	0.095	0.19
Clinker Cooler With Multiclone[d]			
2.5	19	0.029	0.057
6.0	31	0.047	0.093
10.0	40	0.060	0.12
15.0	48	0.072	0.14
20.0	53	0.080	0.16

[a] Emission factors based on total feed.
[b] References 3,5.
[c] References 3,6.
[d] Reference 4.

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11.21 Phosphate Rock Processing

11.21.1 Process Description[1-5]

The separation of phosphate rock from impurities and nonphosphate materials for use in fertilizer manufacture consists of beneficiation, drying or calcining at some operations, and grinding. The Standard Industrial Classification (SIC) code for phosphate rock processing is 1475. The 6-digit Source Classification Code (SCC) for phosphate rock processing is 3-05-019.

Because the primary use of phosphate rock is in the manufacture of phosphatic fertilizer, only those phosphate rock processing operations associated with fertilizer manufacture are discussed here. Florida and North Carolina accounted for 94 percent of the domestic phosphate rock mined and 89 percent of the marketable phosphate rock produced during 1989. Other states in which phosphate rock is mined and processed include Idaho, Montana, Utah, and Tennessee. Alternative flow diagrams of these operations are shown in Figure 11.21-1.

Phosphate rock from the mines is first sent to beneficiation units to separate sand and clay and to remove impurities. Steps used in beneficiation depend on the type of rock. A typical beneficiation unit for separating phosphate rock mined in Florida begins with wet screening to separate pebble rock that is larger than 1.43 millimeters (mm) (0.056 inch [in.]) or 14 mesh, and smaller than 6.35 mm (0.25 in.) from the balance of the rock. The pebble rock is shipped as pebble product. The material that is larger than 0.85 mm (0.033 in.), or 20 mesh, and smaller than 14 mesh is separated using hydrocyclones and finer mesh screens and is added to the pebble product. The fraction smaller than 20 mesh is treated by 2-stage flotation. The flotation process uses hydrophilic or hydrophobic chemical reagents with aeration to separate suspended particles.

Phosphate rock mined in North Carolina does not contain pebble rock. In processing this type of phosphate, 10-mesh screens are used. Like Florida rock, the fraction that is less than 10 mesh is treated by 2-stage flotation, and the fraction larger than 10 mesh is used for secondary road building.

The 2 major western phosphate rock ore deposits are located in southeastern Idaho and northeastern Utah, and the beneficiation processes used on materials from these deposits differ greatly. In general, southeastern Idaho deposits require crushing, grinding, and classification. Further processing may include filtration and/or drying, depending on the phosphoric acid plant requirements. Primary size reduction generally is accomplished by crushers (impact) and grinding mills. Some classification of the primary crushed rock may be necessary before secondary grinding (rod milling) takes place. The ground material then passes through hydrocyclones that are oriented in a 3-stage countercurrent arrangement. Further processing in the form of chemical flotation may be required. Most of the processes are wet to facilitate material transport and to reduce dust.

Northeastern Utah deposits are a lower grade and harder than the southeastern Idaho deposits and require processing similar to that of the Florida deposits. Extensive crushing and grinding is necessary to liberate phosphate from the material. The primary product is classified with 150- to 200-mesh screens, and the finer material is disposed of with the tailings. The coarser fraction is processed through multiple steps of phosphate flotation and then diluent flotation. Further processing may include filtration and/or drying, depending on the phosphoric acid plant requirements. As is the case for southeastern Idaho deposits, most of the processes are wet to facilitate material transport and to reduce dust.

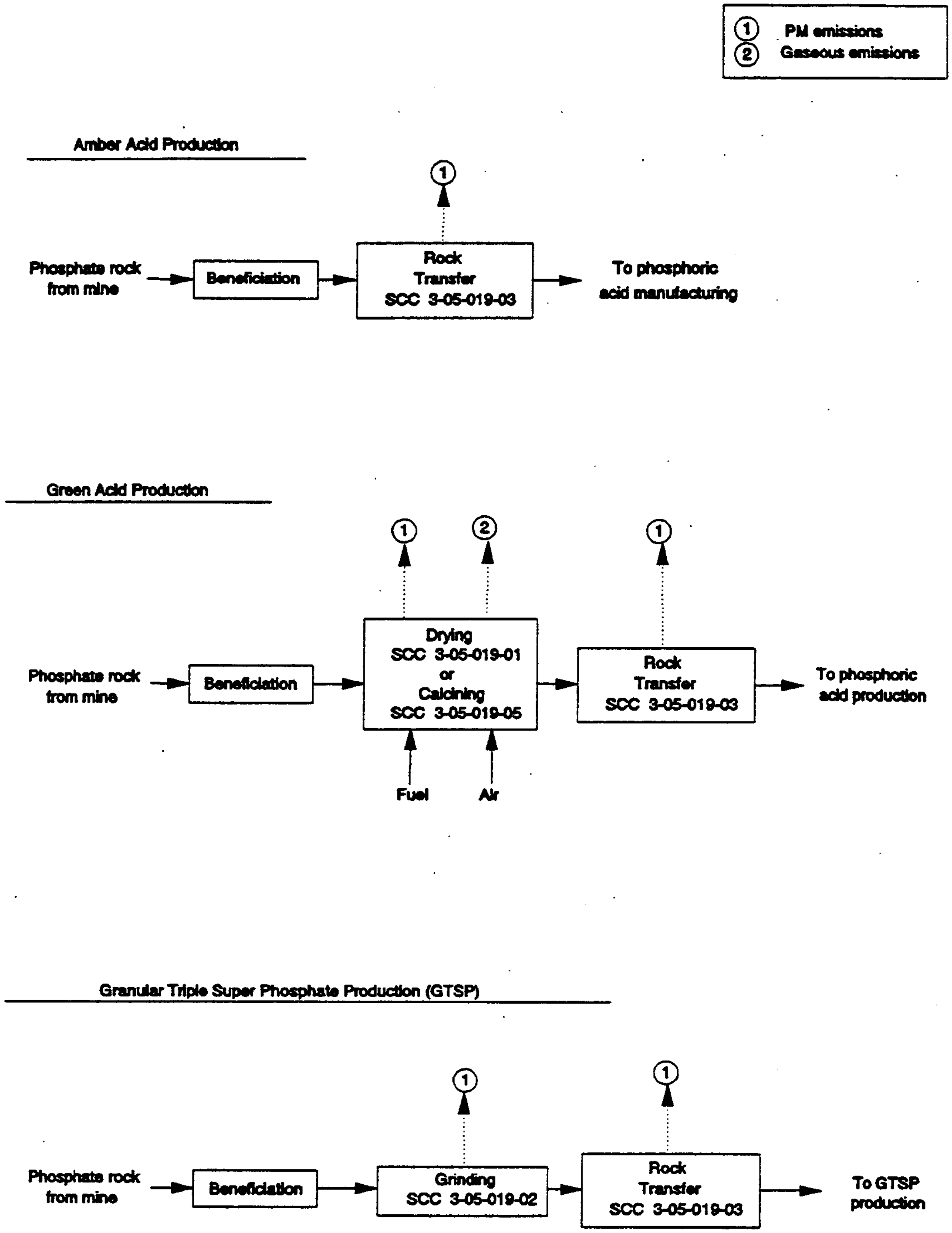

Figure 11.21-1. Alternative process flow diagrams for phosphate rock processing.

The wet beneficiated phosphate rock may be dried or calcined, depending on its organic content. Florida rock is relatively free of organics and is for the most part no longer dried or calcined. The rock is maintained at about 10 percent moisture and is stored in piles at the mine and/or chemical plant for future use. The rock is slurried in water and wet-ground in ball mills or rod mills at the chemical plant. Consequently, there is no significant emission potential from wet grinding. The small amount of rock that is dried in Florida is dried in direct-fired dryers at about 120°C (250°F), where the moisture content of the rock falls from 10 to 15 percent to 1 to 3 percent. Both rotary and fluidized bed dryers are used, but rotary dryers are more common. Most dryers are fired with natural gas or fuel oil (No. 2 or No. 6), with many equipped to burn more than 1 type of fuel. Unlike Florida rock, phosphate rock mined from other reserves contains organics and must be heated to 760 to 870°C (1400 to 1600°F) to remove them. Fluidized-bed calciners are most commonly used for this purpose, but rotary calciners are also used. After drying, the rock is usually conveyed to storage silos on weather-protected conveyors and, from there, to grinding mills. In North Carolina, a portion of the beneficiated rock is calcined at temperatures generally between 800 and 825°C (1480 and 1520°F) for use in "green" phosphoric acid production, which is used for producing super phosphoric acid and as a raw material for purified phosphoric acid manufacturing. To produce "amber" phosphoric acid, the calcining step is omitted, and the beneficiated rock is transferred directly to the phosphoric acid production processes. Phosphate rock that is to be used for the production of granular triple super phosphate (GTSP) is beneficiated, dried, and ground before being transferred to the GTSP production processes.

Dried or calcined rock is ground in roll or ball mills to a fine powder, typically specified as 60 percent by weight passing a 200-mesh sieve. Rock is fed into the mill by a rotary valve, and ground rock is swept from the mill by a circulating air stream. Product size classification is provided by a "revolving whizzer, which is mounted on top of the ball mill," and by an air classifier. Oversize particles are recycled to the mill, and product size particles are separated from the carrying air stream by a cyclone.

11.21.2 Emissions And Controls[1,3-9]

The major emission sources for phosphate rock processing are dryers, calciners, and grinders. These sources emit particulate matter (PM) in the form of fine rock dust and sulfur dioxide (SO_2). Beneficiation has no significant emission potential because the operations involve slurries of rock and water. The majority of mining operations in Florida handle only the beneficiation step at the mine; all wet grinding is done at the chemical processing facility.

Emissions from dryers depend on several factors including fuel types, air flow rates, product moisture content, speed of rotation, and the type of rock. The pebble portion of Florida rock receives much less washing than the concentrate rock from the flotation processes. It has a higher clay content and generates more emissions when dried. No significant differences have been noted in gas volume or emissions from fluid bed or rotary dryers. A typical dryer processing 230 megagrams per hour (Mg/hr) (250 tons per hour [ton/hr]) of rock will discharge between 31 and 45 dry normal cubic meters per second (dry normal m^3/sec) (70,000 and 100,000 dry standard cubic feet per minute [dscfm]) of gas, with a PM loading of 1,100 to 11,000 milligrams per dry normal cubic meters (mg/nm^3) (0.5 to 5 grains per dry standard cubic foot [gr/dscf]). Emissions from calciners consist of PM and SO_2 and depend on fuel type (coal or oil), air flow rates, product moisture, and grade of rock.

Phosphate rock contains radionuclides in concentrations that are 10 to 100 times the radionuclide concentration found in most natural material. Most of the radionuclides consist of uranium and its decay products. Some phosphate rock also contains elevated levels of thorium and its daughter products. The specific radionuclides of significance include uranium-238, uranium-234, thorium-230, radium-226, radon-222, lead-210, and polonium-210.

The radioactivity of phosphate rock varies regionally, and within the same region the radioactivity of the material may vary widely from deposit to deposit. Table 11.21-1 summarizes data on radionuclide concentrations (specific activities) for domestic deposits of phosphate rock in picocuries per gram (pCi/g). Materials handling and processing operations can emit radionuclides either as dust or in the case of radon-222, which is a decay product of uranium-238, as a gas. Phosphate dust particles generally have the same specific activity as the phosphate rock from which the dust originates.

Table 11.21-1. RADIONUCLIDE CONCENTRATIONS OF DOMESTIC PHOSPHATE ROCK[a]

Origin	Typical Concentration Values, pCi/g
Florida	48 to 143
Tennessee	5.8 to 12.6
South Carolina	267
North Carolina	5.86[b]
Arkansas, Oklahoma	19 to 22
Western States	80 to 123

[a] Reference 8, except where indicated otherwise. Specific activities in units of picocuries per gram.
[b] Reference 9.

Scrubbers are most commonly used to control emissions from phosphate rock dryers, but electrostatic precipitators are also used. Fabric filters are not currently being used to control emissions from dryers. Venturi scrubbers with a relatively low pressure loss (3,000 pascals [Pa] [12 in. of water]) may remove 80 to 99 percent of PM 1 to 10 micrometers (μm) in diameter, and 10 to 80 percent of PM less than 1 μm. High-pressure-drop scrubbers (7,500 Pa [30 in. of water]) may have collection efficiencies of 96 to 99.9 percent for PM in the size range of 1 to 10 μm and 80 to 86 percent for particles less than 1 μm. Electrostatic precipitators may remove 90 to 99 percent of all PM. Another control technique for phosphate rock dryers is use of the wet grinding process. In this process, rock is ground in a wet slurry and then added directly to wet process phosphoric acid reactors without drying.

A typical 45 Mg/hr (50 ton/hr) calciner will discharge about 13 to 27 dry normal m^3/sec (30,000 to 60,000 dscfm) of exhaust gas, with a PM loading of 0.5 to 5 gr/dscf. As with dryers, scrubbers are the most common control devices used for calciners. At least one operating calciner is equipped with a precipitator. Fabric filters could also be applied.

Oil-fired dryers and calciners have a potential to emit sulfur oxides when high-sulfur residual fuel oils are burned. However, phosphate rock typically contains about 55 percent lime (CaO), which reacts with the SO_2 to form calcium sulfites and sulfates and thus reduces SO_2 emissions. Dryers and calciners also emit fluorides.

A typical grinder of 45 Mg/hr (50 ton/hr) capacity will discharge about 1.6 to 2.5 dry normal m^3/sec (3,500 to 5,500 dscfm) of air containing 1.14 to 11.4 g/dry normal m^3 (0.5 to 5.0 gr/dscf) of PM. The air discharged is "tramp air," which infiltrates the circulating streams. To avoid fugitive emissions of rock dust, these grinding processes are operated at negative pressure. Fabric filters, and sometimes scrubbers, are used to control grinder emissions. Substituting wet grinding for conventional grinding would reduce the potential for PM emissions.

Emissions from material handling systems are difficult to quantify because several different systems are used to convey rock. Moreover, a large part of the emission potential for these operations is fugitives. Conveyor belts moving dried rock are usually covered and sometimes enclosed. Transfer points are sometimes hooded and evacuated. Bucket elevators are usually enclosed and evacuated to a control device, and ground rock is generally conveyed in totally enclosed systems with well defined and easily controlled discharge points. Dry rock is normally stored in enclosed bins or silos, which are vented to the atmosphere, with fabric filters frequently used to control emissions.

Table 11.21-2 summarizes emission factors for controlled emissions of SO_2 from phosphate rock calciners and for uncontrolled emissions of CO and CO_2 from phosphate rock dryers and calciners. Emission factors for PM emissions from phosphate rock dryers, grinders, and calciners are presented in Tables 11.21-3 and 11.21-4. Particle size distribution for uncontrolled filterable PM emissions from phosphate rock dryers and calciners are presented in Table 11.21-5, which shows that the size distribution of the uncontrolled calciner emissions is very similar to that of the dryer emissions. Tables 11.21-6 and 11.21-7 summarize emission factors for emissions of water-soluble and total fluorides from phosphate rock dryers and calciners. Emission factors for controlled and uncontrolled radionuclide emissions from phosphate rock grinders also are presented in Tables 11.21-6 and 11.21-7. Emission factors for PM emissions from phosphate rock ore storage, handling, and transfer can be developed using the equations presented in Section 13.2.4.

Table 11.21-2 (Metric And English Units). EMISSION FACTORS FOR PHOSPHATE ROCK PROCESSING[a]

EMISSIONS FACTOR RATING: D

Process	SO_2		CO_2		CO	
	kg/Mg Of Total Feed	lb/ton Of Total Feed	kg/Mg Of Total Feed	lb/ton Of Total Feed	kg/Mg Of Total Feed	lb/ton Of Total Feed
Dryer (SCC 3-05-019-01)	ND	ND	43[b]	86[b]	0.17[c]	0.34[c]
Calciner with scrubber (SCC 3-05-019-05)	0.0034[d]	0.0069	115[e]	230[e]	ND	ND

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.
[b] References 10,11.
[c] Reference 10.
[d] References 13,15.
[e] References 14-22.

Table 11.21-3 (Metric Units). EMISSION FACTORS FOR PHOSPHATE ROCK PROCESSING[a]

Process	Filterable PM[b]				Condensable PM[c]			
	PM		PM-10		Inorganic		Organic	
	kg/Mg Of Total Feed	EMISSION FACTOR RATING	kg/Mg Of Total Feed	EMISSION FACTOR RATING	kg/Mg Of Total Feed	EMISSION FACTOR RATING	kg/Mg Of Total Feed	EMISSION FACTOR RATING
Dryer (SCC 3-05-019-01)[d]	2.9	D	2.4	E	ND		ND	
Dryer with scrubber (SCC 3-05-019-01)[e]	0.035	D	ND		0.015	D	ND	
Dryer with ESP (SCC 3-05-019-01)[d]	0.016	D	ND		0.004	D	ND	
Grinder (SCC 3-05-019-02)[d]	0.8	C	ND		ND		ND	
Grinder with fabric filter (SCC 3-05-019-02)[f]	0.0022	D	ND		0.0011	D	ND	
Calciner (SCC 3-05-019-05)[d]	7.7	D	7.4	E	ND		ND	
Calciner with scrubber (SCC 3-05-019-05)	0.10[g]	C	ND		0.0079[g]	C	0.044[h]	D
Transfer and storage (SCC 3-05-019-__)[d]	2	E	ND		ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 1.

[e] References 1,10-11.

[f] References 1,11-12.

[g] References 1,14-22.

[h] References 14-22.

Table 11.21-4 (English Units). EMISSION FACTORS FOR PHOSPHATE ROCK PROCESSING[a]

Process	Filterable PM[b]				Condensable PM[c]			
	PM		PM-10		Inorganic		Organic	
	lb/ton Of Total Feed	EMISSION FACTOR RATING	lb/ton Of Total Feed	EMISSION FACTOR RATING	lb/ton Of Total Feed	EMISSION FACTOR RATING	lb/ton Of Total Feed	EMISSION FACTOR RATING
Dryer (SCC 3-05-019-01)[d]	5.7	D	4.8	E	ND		ND	
Dryer with scrubber (SCC 3-05-019-01)[e]	0.070	D	ND		0.030	D	ND	
Dryer with ESP (SCC 3-05-019-01)[d]	0.033	D	ND		0.008	D	ND	
Grinder (SCC 3-05-0190-2)[d]	1.5	C	ND		ND		ND	
Grinder with fabric filter (SCC 3-05-019-02)[f]	0.0043	D	ND		0.0021	D	ND	
Calciner (SCC 3-05-019-05)[d]	15	D	15	E	ND		ND	
Calciner with scrubber (SCC 3-05-019-05)	0.20[g]	C	ND		0.16[g]	C	0.088[h]	D
Transfer and storage (SCC 3-05-019-__)[d]	1	E	ND		ND		ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Condensable PM is that PM collected in the impinger portion of a PM sampling train.

[d] Reference 1.

[e] References 8,10-11.

[f] References 1,11-12.

[g] References 1,14-22.

[h] References 14-22.

Table 11.21-5. PARTICLE SIZE DISTRIBUTION OF FILTERABLE PARTICULATE EMISSIONS FROM PHOSPHATE ROCK DRYERS AND CALCINERS[a]

EMISSION FACTOR RATING: E

Diameter, μm	Percent Less Than Size	
	Dryers	Calciners
10	82	96
5	60	81
2	27	52
1	11	26
0.8	7	10
0.5	3	5

[a] Reference 1.

Table 11.21-6 (Metric Units). EMISSION FACTORS FOR PHOSPHATE ROCK PROCESSING[a]

Process	Fluoride, H_2O-Soluble		Fluoride, Total		Radionuclides[b]	
	kg/Mg Of Total Feed	EMISSION FACTOR RATING	kg/Mg Of Total Feed	EMISSION FACTOR RATING	pCi/Mg Of Total Feed	EMISSION FACTOR RATING
Dryer (SCC 3-05-019-01)[c]	0.00085	D	0.037	D	ND	
Dryer with scrubber (SCC 3-05-019-01)[d]	0.00048	D	0.0048	D	ND	
Grinder (SCC 3-05-019-02)[e]	ND		ND		800R	E
Grinder with fabric filter (SCC 3-05-019-02)[e]	ND		ND		5.2R	E
Calciner with scrubber (SCC 3-05-019-05)[f]	ND		0.00081	D	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] R is the radionuclide concentration (specific activity) of the phosphate rock. In units of pCi/Mg of feed.

[c] Reference 10.

[d] References 10-11.

[e] References 7-8.

[f] Reference 1.

Table 11.21-7 (English Units). EMISSION FACTORS FOR PHOSPHATE ROCK PROCESSING[a]

Process	Fluoride, H_2O-Soluble		Fluoride, Total		Radionuclides[b]	
	lb/ton Of Total Feed	EMISSION FACTOR RATING	lb/ton Of Total Feed	EMISSION FACTOR RATING	pCi/ton Of Total Feed	EMISSION FACTOR RATING
Dryer (SCC 3-05-019-01)[c]	0.0017	D	0.073	D	ND	
Dryer with scrubber (SCC 3-05-019-01)[d]	0.00095	D	0.0096	D	ND	
Grinder (SCC 3-05-019-02)[e]	ND		ND		730R	E
Grinder with fabric filter (SCC 3-05-019-02)[e]	ND		ND		4.7R	E
Calciner with scrubber (SCC 3-05-019-05)[f]	ND		0.0016	D	ND	

[a] Factors represent uncontrolled emissions unless otherwise noted. SCC = Source Classification Code. ND = no data.

[b] R is the radionuclide concentration (specific activity) of the phosphate rock. In units of pCi/Mg of feed.

[c] Reference 10.

[d] References 10-11.

[e] References 7-8.

[f] Reference 1.

The new source performance standard (NSPS) for phosphate rock plants was promulgated in April 1982 (40 CFR 60 Subpart NN). This standard limits PM emissions and opacity for phosphate rock calciners, dryers, and grinders and limits opacity for handling and transfer operations. The national emission standard for radionuclide emissions from elemental phosphorus plants was promulgated in December 1989 (40 CFR 61 Subpart K). This standard limits emissions of polonium-210 from phosphate rock calciners and nodulizing kilns at elemental phosphorus plants and requires annual compliance tests.

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11.22 Diatomite Processing

[Work In Progress]

11.23 Taconite Ore Processing

11.23.1 General[1-2]

More than two-thirds of the iron ore produced in the United States consists of taconite, a low-grade iron ore largely from deposits in Minnesota and Michigan, but from other areas as well. Processing of taconite consists of crushing and grinding the ore to liberate ironbearing particles, concentrating the ore by separating the particles from the waste material (gangue), and pelletizing the iron ore concentrate. A simplified flow diagram of these processing steps is shown in Figure 11.23-1.

Liberation -

The first step in processing crude taconite ore is crushing and grinding. The ore must be ground to a particle size sufficiently close to the grain size of the ironbearing mineral to allow for a high degree of mineral liberation. Most of the taconite used today requires very fine grinding. The grinding is normally performed in 3 or 4 stages of dry crushing, followed by wet grinding in rod mills and ball mills. Gyratory crushers are generally used for primary crushing, and cone crushers are used for secondary and tertiary fine crushing. Intermediate vibrating screens remove undersize material from the feed to the next crusher and allow for closed circuit operation of the fine crushers. The rod and ball mills are also in closed circuit with classification systems such as cyclones. An alternative is to feed some coarse ores directly to wet or dry semiautogenous or autogenous (using larger pieces of the ore to grind/mill the smaller pieces) grinding mills, then to pebble or ball mills. Ideally, the liberated particles of iron minerals and barren gangue should be removed from the grinding circuits as soon as they are formed, with larger particles returned for further grinding.

Concentration -

As the iron ore minerals are liberated by the crushing steps, the ironbearing particles must be concentrated. Since only about 33 percent of the crude taconite becomes a shippable product for iron making, a large amount of gangue is generated. Magnetic separation and flotation are most commonly used for concentration of the taconite ore.

Crude ores in which most of the recoverable iron is magnetite (or, in rare cases, maghemite) are normally concentrated by magnetic separation. The crude ore may contain 30 to 35 percent total iron by assay, but theoretically only about 75 percent of this is recoverable magnetite. The remaining iron is discarded with the gangue.

Nonmagnetic taconite ores are concentrated by froth flotation or by a combination of selective flocculation and flotation. The method is determined by the differences in surface activity between the iron and gangue particles. Sharp separation is often difficult.

Various combinations of magnetic separation and flotation may be used to concentrate ores containing various iron minerals (magnetite and hematite, or maghemite) and wide ranges of mineral grain sizes. Flotation is also often used as a final polishing operation on magnetic concentrates.

Pelletization -

Iron ore concentrates must be coarser than about No. 10 mesh to be acceptable as blast furnace feed without further treatment. The finer concentrates are agglomerated into small "green" pellets. This is normally accomplished by tumbling moistened concentrate with a balling drum or

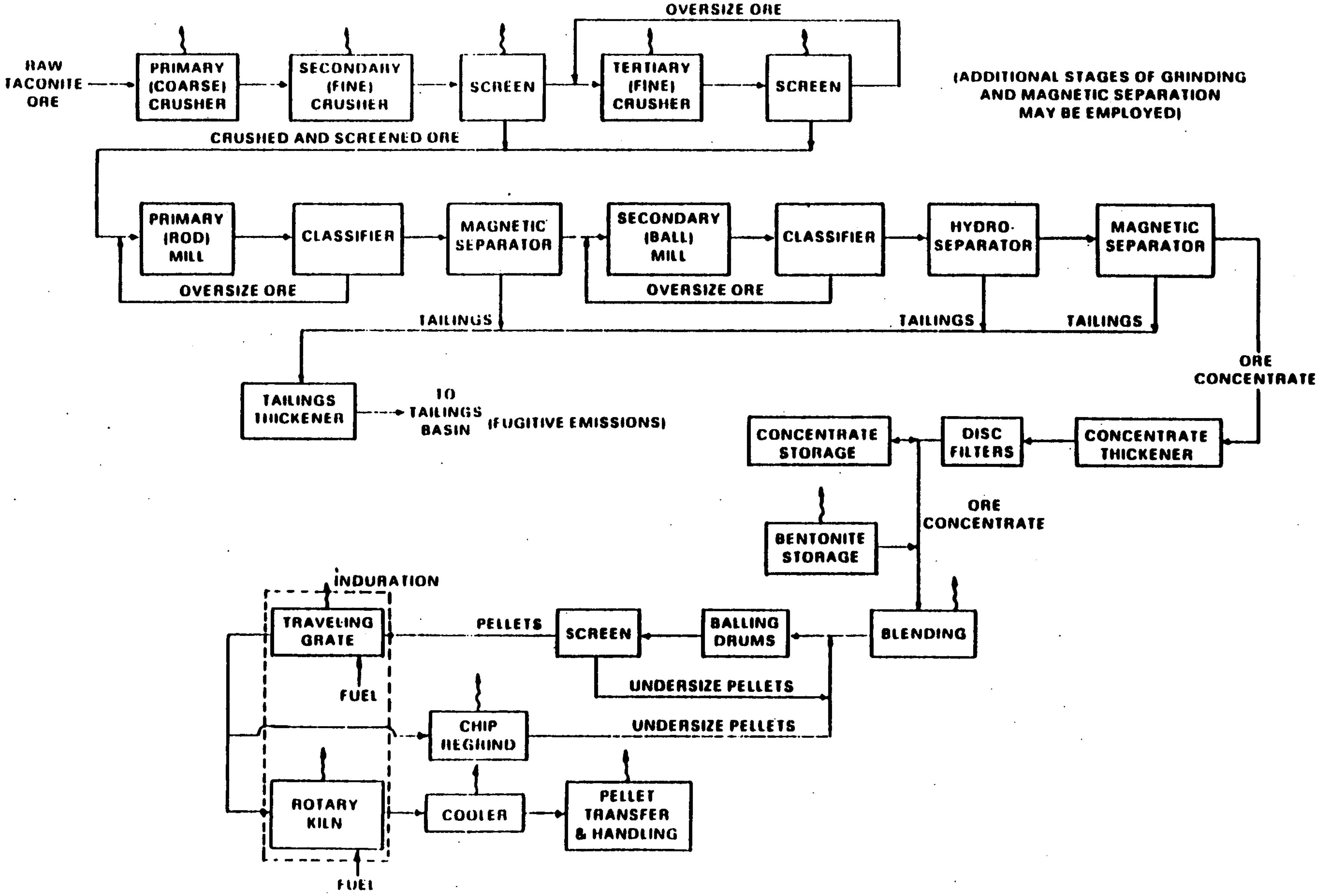

Figure 11.23-1. Taconite ore processing plant. (Process emissions are indicated by ↑.)

balling disc. A binder, usually powdered bentonite, may be added to the concentrate to improve ball formation and the physical qualities of the "green" balls. The bentonite is lightly mixed with the carefully moistened feed at 5 to 10 kilograms per megagram (kg/Mg) (10 to 20 pounds per ton [lb/ton]).

The pellets are hardened by a procedure called induration, the drying and heating of the green balls in an oxidizing atmosphere at incipient fusion temperature of 1290 to 1400°C (2350 to 2550°F), depending on the composition of the balls, for several minutes and then cooling. Four general types of indurating apparatus are currently used. These are the vertical shaft furnace, the straight grate, the circular grate, and grate/kiln. Most of the large plants and new plants use the grate/kiln. Natural gas dis most commonly used for pellet induration now, but probably not in the future. Heavy oil is being used at a few plants, and coal may be used at future plants.

In the vertical shaft furnace, the wet green balls are distributed evenly over the top of the slowly descending bed of pellets. A rising stream of hot gas of controlled temperature and composition flows counter to the descending bed of pellets. Auxiliary fuel combustion chambers supply hot gases midway between the top and bottom of the furnace. In the straight grate apparatus, a continuous bed of agglomerated green pellets is carried through various up and down flows of gases at different temperatures. The grate/kiln apparatus consists of a continuous traveling grate followed by a rotary kiln. Pellets indurated by the straight grate apparatus are cooled on an extension of the grate or in a separate cooler. The grate/kiln product must be cooled in a separate cooler, usually an annular cooler with counter-current airflow.

11.23.2 Emissions And Controls[1-4]

Emission sources in taconite ore processing plants are indicated in Figure 11.23-1. Particulate emissions also arise from ore mining operations. Emission factors for the major processing sources without controls are presented in Table 11.23-1, and control efficiencies in Table 11.23-2. Table 11.23-3 and Figure 11.23-2 present data on particle size distributions and corresponding size-specific emission factors for the controlled main waste gas stream from taconite ore pelletizing operations.

Table 11.23-1 (Metric And English Units). PARTICULATE EMISSION FACTORS FOR TACONITE ORE PROCESSING, WITHOUT CONTROLS[a]

EMISSION FACTOR RATING: D

Source	Emissions[b]	
	kg/Mg	lb/ton
Ore transfer	0.05	0.10
Coarse crushing and screening	0.10	0.20
Fine crushing	39.9	79.8
Bentonite transfer	0.02	0.04
Bentonite blending	0.11	0.22
Grate feed	0.32	0.64
Indurating furnace waste gas	14.6	29.2
Grate discharge	0.66	1.32
Pellet handling	1.7	3.4

[a] Reference 1. Median values.

[b] Expressed as units per unit weight of pellets produced.

Table 11.23-2. CONTROL EFFICIENCIES FOR COMBINATIONS OF CONTROL DEVICES AND SOURCES[a]

Control	Coarse Crushing	Ore Transfer	Fine Crushing	Bentonite Transfer	Bentonite Blending	Grate Feed	Grate Discharge	Waste Gas	Pellet Handling
Scrubber	$95(10)^f$ $91.6(4)^f$ $99(2)^m$	$99.5(18)^f$ $99(5)^f$ $97(4)^m$ $99(1)^m$	$99.5(5)^f$ $99.6(6)^f$ $97(10)^m$ $97(19)^e$	$98(1)^f$	$98.7(1)^f$ $99.3(1)^f$	$98.7(2)^f$ $98(1)^m$ $99(5)^e$	$99.3(2)^f$ $98(5)^m$ $99(1)^e$	$98.5(1)^e$ $89(1)^e$	$99.3(2)^f$ $99.7(1)^f$ $99(2)^f$ $97.5(1)^e$
Cyclone	$85(1)^f$	$95(2)^e$						$95 - 98(56)^f$	
Multiclone	$92(2)^f$ $88(2)^f$							$95 - 98(2)^f$	
Rotoclone	$91.6(4)^f$	$98(1)^f$	$99.7(7)^f$ $98.3(4)^f$						$98(1)^e$
Bag collector	$99(2)^m$ $99.9(2)^m$ $99(4)^e$ $99.9(2)^e$			$99(8)^e$	$99(2)^f$ $99.7(1)^f$				
Electrostatic precipitator								$98.9(2)^f$ $98.8(1)^e$	
Dry mechanical collector	$85(1)^f$	$85(1)^f$							
Centrifugal collector						$88(1)^f$ $98(1)^e$ $99.4(1)^e$	$88(1)^f$ $99.4(1)^e$		

[a] Reference 1. Control efficiencies are expressed as percent reduction. Numbers in parentheses are the number of indicated combinations with the stated efficiency. The letters m, f, e denote whether the stated efficiencies were based upon manufacturer's rating (m), field testing (f), or estimations (e). Blanks indicate that no such combinations of source and control technology are known to exist, or that no data on the efficiency of the combination are available.

Table 11.23-3 (Metric Units). PARTICLE SIZE DISTRIBUTIONS AND SIZE-SPECIFIC EMISSION FACTORS FOR CONTROLLED INDURATING FURNACE WASTE GAS STREAM FROM TACONITE ORE PELLETIZING[a]

SIZE-SPECIFIC EMISSION FACTOR RATING: D

Aerodynamic Particle Diameter, µm	Particle Size Distribution[b]		Size-Specific Emission Factor, kg/Mg[c]	
	Cyclone Controlled	Cyclone/ESP Controlled	Cyclone Controlled	Cyclone/ESP Controlled
2.5	17.4	48.0	0.16	0.012
6.0	25.6	71.0	0.23	0.018
10.0	35.2	81.5	0.31	0.021

[a] Reference 3. ESP = electrostatic precipitator. After cyclone control, mass emission factor is 0.89 kg/Mg, and after cyclone/ESP control, 0.025 kg/Mg. Mass and size-specific emission factors are calculated from data in Reference 3, and are expressed as kg particulate/Mg of pellets produced.

[b] Cumulative weight % < particle diameter.

[c] Size-specific emission factor = mass emission factor x particle size distribution, %/100.

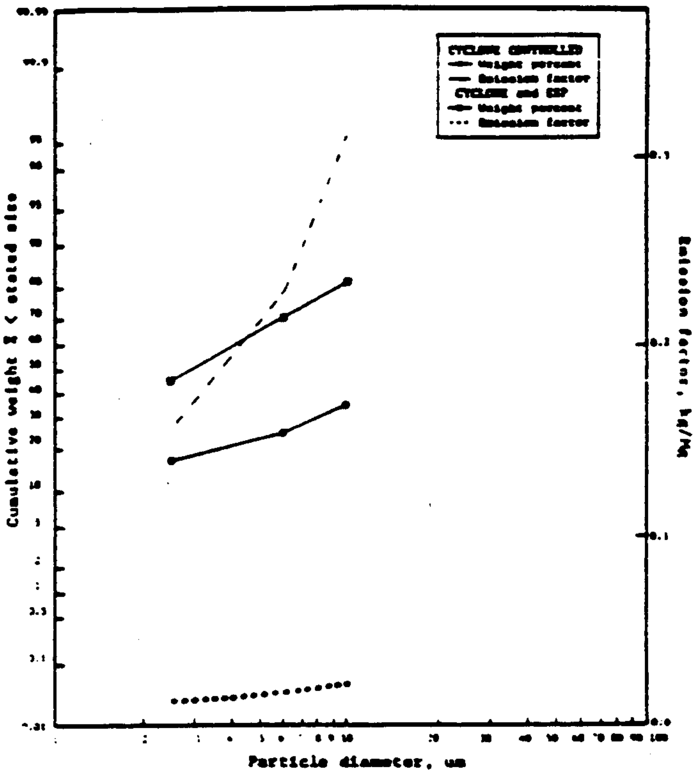

Figure 11.23-2. Particle size distributions and size-specific emission factors for indurating furnace waste gas stream from taconite ore pelletizing.

The taconite ore is handled dry through the crushing stages. All crushers, size classification screens, and conveyor transfer points are major points of particulate emissions. Crushed ore is normally wet ground in rod and ball mills. A few plants, however, use dry autogenous or semi-autogenous grinding and have higher emissions than do conventional plants. The ore remains wet through the rest of the beneficiation process (through concentrate storage, Figure 11.23-1) so particulate emissions after crushing are generally insignificant.

The first source of emissions in the pelletizing process is the transfer and blending of bentonite. There are no other significant emissions in the balling section, since the iron ore concentrate is normally too wet to cause appreciable dusting. Additional emission points in the pelletizing process include the main waste gas stream from the indurating furnace, pellet handling, furnace transfer points (grate feed and discharge), and for plants using the grate/kiln furnace, annular coolers. In addition, tailings basins and unpaved roadways can be sources of fugitive emissions.

Fuel used to fire the indurating furnace generates low levels of sulfur dioxide (SO_2) emissions. For a natural gas-fired furnace, these emissions are about 0.03 kilograms of SO_2 per megagram of pellets produced (0.06 lb/ton). Higher SO_2 emissions (about 0.06 to 0.07 kg/Mg, or 0.12 to 0.14 lb/ton) would result from an oil- or coal-fired furnace.

Particulate emissions from taconite ore processing plants are controlled by a variety of devices, including cyclones, multiclones, rotoclones, scrubbers, baghouses, and electrostatic precipitators. Water sprays are also used to suppress dusting. Annular coolers are generally left uncontrolled because their mass loadings of particulates are small, typically less than 0.11 grams per normal cubic meter (0.05 gr/scf).

The largest source of particulate emissions in taconite ore mines is traffic on unpaved haul roads.[4] Table 11.23-4 presents size-specific emission factors for this source determined through source testing at one taconite mine. Other significant particulate emission sources at taconite mines are wind erosion and blasting.[4]

Table 11.23-4 (Metric and English Units). UNCONTROLLED EMISSION FACTORS FOR HEAVY DUTY VEHICLE TRAFFIC ON HAUL ROADS AT TACONITE MINES[a]

Surface Material	Emission Factor By Aerodynamic Diameter, μm					Units	EMISSION FACTOR RATING
	<30	<15	<10	<5	<2.5		
Crushed rock and glacial till	3.1	2.2	1.7	1.1	0.62	kg/VKT	C
	11.0	7.9	6.2	3.9	2.2	lb/VMT	C
Crushed taconite and waste	2.6	1.9	1.5	0.9	0.54	kg/VKT	D
	9.3	6.6	5.2	3.2	1.9	lb/VMT	D

[a] Reference 4. Predictive emission factor equations, which provide generally more accurate estimates, are in Chapter 13. VKT = vehicle kilometers travelled. VMT = vehicle miles travelled.

Chapter 13 of this document. Each equation has been developed for a source operation defined by a single dust-generating mechanism common to many industries such as vehicle activity on unpaved roads. The predictive equation explains much of the observed variance in measured emission factors by relating emissions to parameters that characterize source conditions. These parameters may be grouped into 3 categories, (1) measures of source activity or energy expended, (i. e., the speed and weight of a vehicle on an unpaved road); (2) properties of the material being disturbed, (i. e., the content of suspendable fines in the surface material of an unpaved road); and (3) climatic parameters, such as the number of precipitation-free days per year, when emissions tend to a maximum.

Because the predictive equations allow for emission factor adjustment to specific source conditions, such equations should be used in place of the single-value factors for open dust sources in Tables 11.23-1 and 11.23-4 whenever emission estimates are needed for sources in a specific taconite ore mine or processing facility. One should remember that the generally higher quality ratings assigned to these equations apply only if (1) reliable values of correction parameters have been determined for the specific sources of interest, and (2) the correction parameter values lie within the ranges tested in developing the equations. In the event that site-specific values are not available, Chapter 13 lists measured properties of road surface and aggregate process materials found in taconite mining and processing facilities, and these can be used to estimate correction parameter values for the predictive emission factor equations. The use of mean correction parameter values from Chapter 13 reduces the quality ratings of the factor equations by 1 level.

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11.24 Metallic Minerals Processing

11.24.1 Process Description[1-6]

Metallic mineral processing typically involves the mining of ore from either open pit or underground mines; the crushing and grinding of ore; the separation of valuable minerals from matrix rock through various concentration steps; and at some operations, the drying, calcining, or pelletizing of concentrates to ease further handling and refining. Figure 11.24-1 is a general flow diagram for metallic mineral processing. Very few metallic mineral processing facilities will contain all of the operations depicted in this figure, but all facilities will use at least some of these operations in the process of separating valued minerals from the matrix rock.

The number of crushing steps necessary to reduce ore to the proper size vary with the type of ore. Hard ores, including some copper, gold, iron, and molybdenum ores, may require as much as a tertiary crushing. Softer ores, such as some uranium, bauxite, and titanium/zirconium ores, require little or no crushing. Final comminution of both hard and soft ores is often accomplished by grinding operations using media such as balls or rods of various materials. Grinding is most often performed with an ore/water slurry, which reduces particulate matter (PM) emissions to negligible levels. When dry grinding processes are used, PM emissions can be considerable.

After final size reduction, the beneficiation of the ore increases the concentration of valuable minerals by separating them from the matrix rock. A variety of physical and chemical processes is used to concentrate the mineral. Most often, physical or chemical separation is performed in an aqueous environment, which eliminates PM emissions, although some ferrous and titaniferous minerals are separated by magnetic or electrostatic methods in a dry environment.

The concentrated mineral products may be dried to remove surface moisture. Drying is most frequently done in natural gas-fired rotary dryers. Calcining or pelletizing of some products, such as alumina or iron concentrates, is also performed. Emissions from calcining and pelletizing operations are not covered in this section.

11.24.2 Process Emissions[7-9]

Particulate matter emissions result from metallic mineral plant operations such as crushing and dry grinding ore, drying concentrates, storing and reclaiming ores and concentrates from storage bins, transferring materials, and loading final products for shipment. Particulate matter emission factors are provided in Tables 11.24-1 and 11.24-2 for various metallic mineral process operations including primary, secondary, and tertiary crushing; dry grinding; drying; and material handling and transfer. Fugitive emissions are also possible from roads and open stockpiles, factors for which are in Section 13.2.

The emission factors in Tables 11.24-1 and 11.24-2 are for the process operations as a whole. At most metallic mineral processing plants, each process operation requires several types of equipment. A single crushing operation likely includes a hopper or ore dump, screen(s), crusher, surge bin, apron feeder, and conveyor belt transfer points. Emissions from these various pieces of equipment are often ducted to a single control device. The emission factors provided in Tables 11.24-1 and 11.24-2 for primary, secondary, and tertiary crushing operations are for process units that are typical arrangements of the above equipment.

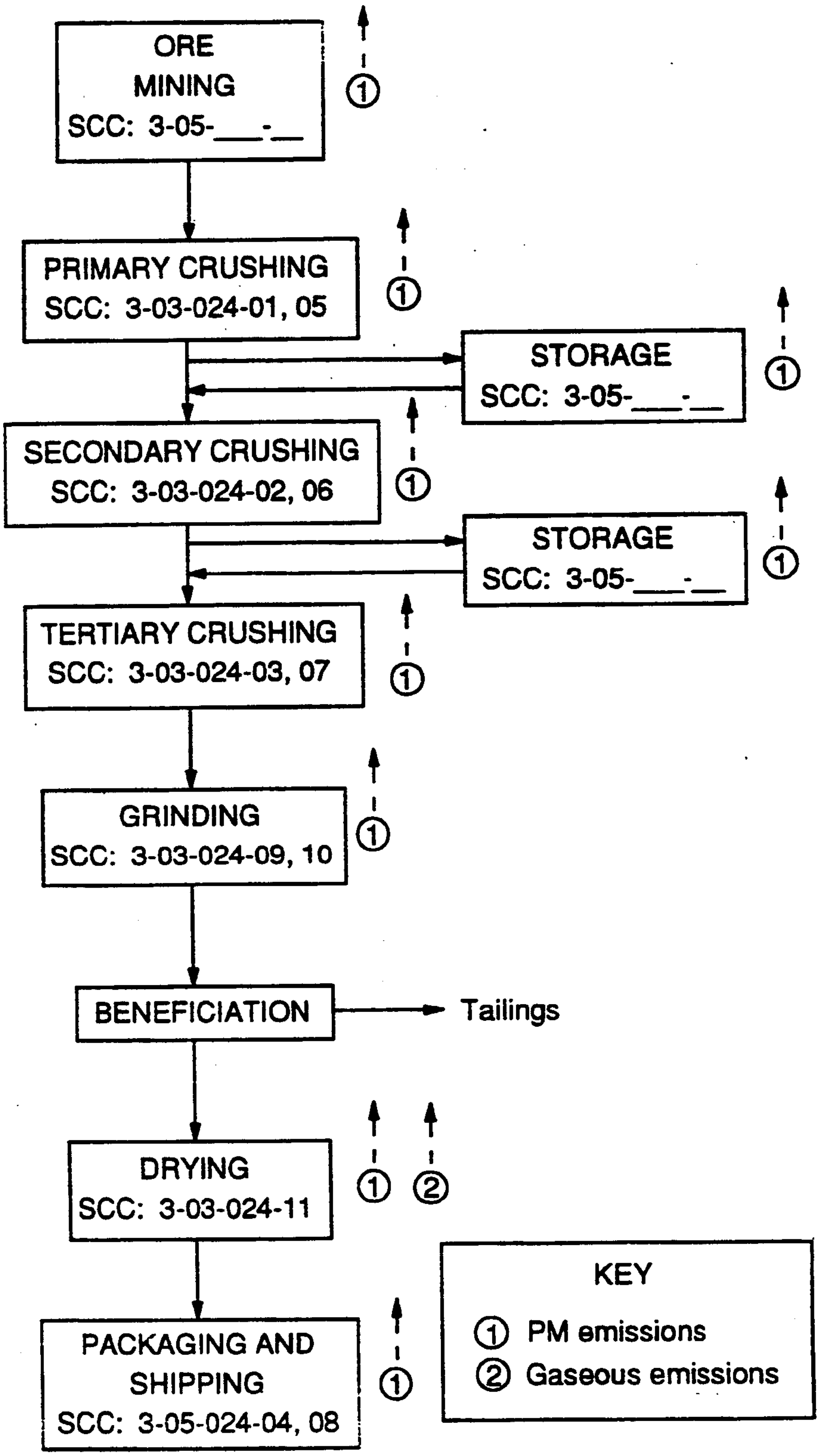

Figure 11.24-1. Process flow diagram for metallic mineral processing.

Table 11.24-1 (Metric Units). EMISSION FACTORS FOR METALLIC MINERALS PROCESSING[a]

EMISSION FACTOR RATINGS: (A-E) Follow The Emission Factor

Source	Filterable[b,c]			
	PM	RATING	PM-10	RATING
Low-moisture ore[c]				
Primary crushing (SCC 3-03-024-01)[d]	0.2	C	0.02	C
Secondary crushing (SCC 3-03-024-02)[d]	0.6	D	ND	
Tertiary crushing (SCC 3-03-024-03)[d]	1.4	E	0.08	E
Wet grinding	Neg		Neg	
Dry grinding with air conveying and/or air classification (SCC 3-03-024-09)[e]	14.4	C	13	C
Dry grinding without air conveying and/or air classification (SCC 3-03-024-10)[e]	1.2	D	0.16	D
Drying--all minerals except titanium/zirconium sands (SCC 3-03-024-11)[f]	9.8	C	5.9	C
Drying--titanium/zirconium with cyclones (SCC 3-03-024-11)[f]	0.3	C	ND	C
Material handling and transfer--all minerals except bauxite (SCC 3-03-024-04)[g]	0.06	C	0.03	C
Material handling and transfer--bauxite/alumina (SCC 3-03-024-04)[g,h]	0.6	C	ND	
High-moisture ore[c]				
Primary crushing (SCC 3-03-024-05)[d]	0.01	C	0.004	C
Secondary crushing (SCC 3-03-024-06)[d]	0.03	D	0.012	D
Tertiary crushing (SCC 3-03-024-07)[d]	0.03	E	0.01	E
Wet grinding	Neg		Neg	
Dry grinding with air conveying and/or air classification (SCC 3-03-024-09)[e]	14.4	C	13	C
Dry grinding without air conveying and/or air classification (SCC 3-03-024-10)[e]	1.2	D	0.16	D
Drying--all minerals except titanium/zirconium sands (SCC 3-03-024-11)[f]	9.8	C	5.9	C
Drying--titanium/zirconium with cyclones (SCC 3-03-024-11)[f]	0.3	C	ND	
Material handling and transfer--all minerals except bauxite (SCC 3-03-024-08)[g]	0.005	C	0.002	C
Material handling and transfer--bauxite/alumina (SCC 3-03-024-08)[g,h]	ND		ND	

[a] References 9-12; factors represent uncontrolled emissions unless otherwise noted; controlled emission factors are discussed in Section 11.24.3. All emission factors are in kg/Mg of material processed unless noted. SCC = Source Classification Code. Neg = negligible. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Defined in Section 11.24.2.

[d] Based on weight of material entering primary crusher.

[e] Based on weight of material entering grinder; emission factors are the same for both low-moisture and high-moisture ore because material is usually dried before entering grinder.

[f] Based on weight of material exiting dryer; emission factors are the same for both high-moisture and low-moisture ores; SO_x emissions are fuel dependent (see Chapter 1); NO_x emissions depend on burner design and combustion temperature (see Chapter 1).

[g] Based on weight of material transferred; applies to each loading or unloading operation and to each conveyor belt transfer point.

[h] Bauxite with moisture content as high as 15 to 18% can exhibit the emission characteristics of low-moisture ore; use low-moisture ore emission factor for bauxite unless material exhibits obvious sticky, nondusting characteristics.

Table 11.24-2 (English Units). EMISSION FACTORS FOR METALLIC MINERALS PROCESSING[a,b]

EMISSION FACTOR RATINGS: (A-E) Follow The Emission Factor

Source	Filterable[b,c]			
	PM	RATING	PM-10	RATING
Low-moisture ore[c]				
Primary crushing (SCC 3-03-024-01)[d]	0.5	C	0.05	C
Secondary crushing (SCC 303-024-02)[d]	1.2	D	ND	
Tertiary crushing (SCC 3-03-024-03)[d]	2.7	E	0.16	E
Wet grinding	Neg		Neg	
Dry grinding with air conveying and/or air classification (SCC 3-03-024-09)[e]	28.8	C	26	C
Dry grinding without air conveying and/or air classification (SCC 3-03-024-10)[e]	2.4	D	0.31	D
Drying—all minerals except titanium/zirconium sands (SCC 3-03-024-11)[f]	19.7	C	12	C
Drying—titanium/zirconium with cyclones (SCC 3-03-024-11)[f]	0.5	C	ND	C
Material handling and transfer—all minerals except bauxite (SCC 3-03-024-04)[g]	0.12	C	0.06	C
Material handling and transfer—bauxite/alumina (SCC 3-03-024-04)[g,h]	1.1	C	ND	
High-moisture ore[c]				
Primary crushing (SCC 3-03-024-05)[d]	0.02	C	0.009	C
Secondary crushing (SCC 3-03-024-06)[d]	0.05	D	0.02	D
Tertiary crushing (SCC 3-03-024-07)[d]	0.06	E	0.02	E
Wet grinding	Neg		Neg	
Dry grinding with air conveying and/or air classification (SCC 3-03-024-09)[e]	28.8	C	26	C
Dry grinding without air conveying and/or air classification (SCC 3-03-024-10)[e]	2.4	D	0.31	D
Drying—all minerals except titanium/zirconium sands (SCC 3-03-024-11)[f]	19.7	C	12	C
Drying—titanium/zirconium with cyclones (SCC 3-03-024-11)[f]	0.5	C	ND	
Material handling and transfer—all minerals except bauxite (SCC 3-03-024-08)[g]	0.01	C	0.004	C
Material handling and transfer—bauxite/alumina (SCC 3-03-024-08)[g,h]	ND		ND	

[a] References 9-12; factors represent uncontrolled emissions unless otherwise noted; controlled emission factors are discussed in Section 11.24.3. All emission factors are in lb/ton of material processed unless noted. SCC = Source Classification Code. Neg = negligible. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Defined in Section 11.24.2.

[d] Based on weight of material entering primary crusher.

[e] Based on weight of material entering grinder; emission factors are the same for both low-moisture and high-moisture ore because material is usually dried before entering grinder.

[f] Based on weight of material exiting dryer; emission factors are the same for both high-moisture and low-moisture ores; SO_x emissions are fuel dependent (see Chapter 1); NO_x emissions depend on burner design and combustion temperature (see Chapter 1).

[g] Based on weight of material transferred; applies to each loading or unloading operation and to each conveyor belt transfer point.

[h] Bauxite with moisture content as high as 15 to 18% can exhibit the emission characteristics of low-moisture ore; use low-moisture ore emission factor for bauxite unless material exhibits obvious sticky, nondusting characteristics.

Emission factors are provided in Tables 11.24-1 and 11.24-2 for two types of dry grinding operations: those that involve air conveying and/or air classification of material and those that involve screening of material without air conveying. Grinding operations that involve air conveying and air classification usually require dry cyclones for efficient product recovery. The factors in Tables 11.24-1 and 11.24-2 are for emissions after product recovery cyclones. Grinders in closed circuit with screens usually do not require cyclones. Emission factors are not provided for wet grinders because the high-moisture content in these operations can reduce emissions to negligible levels.

The emission factors for dryers in Tables 11.24-1 and 11.24-2 include transfer points integral to the drying operation. A separate emission factor is provided for dryers at titanium/zirconium plants that use dry cyclones for product recovery and for emission control. Titanium/zirconium sand-type ores do not require crushing or grinding, and the ore is washed to remove humic and clay material before concentration and drying operations.

At some metallic mineral processing plants, material is stored in enclosed bins between process operations. The emission factors provided in Tables 11.24-1 and 11.24-2 for the handling and transfer of material should be applied to the loading of material into storage bins and the transferring of material from the bin. The emission factor will usually be applied twice to a storage operation: once for the loading operation and once for the reclaiming operation. If material is stored at multiple points in the plant, the emission factor should be applied to each operation and should apply to the material being stored at each bin. The material handling and transfer factors do not apply to small hoppers, surge bins, or transfer points that are integral with crushing, drying, or grinding operations.

At some large metallic mineral processing plants, extensive material transfer operations with numerous conveyor belt transfer points may be required. The emission factors for material handling and transfer should be applied to each transfer point that is not an integral part of another process unit. These emission factors should be applied to each such conveyor transfer point and should be based on the amount of material transferred through that point.

The emission factors for material handling can also be applied to final product loading for shipment. Again, these factors should be applied to each transfer point, ore dump, or other point where material is allowed to fall freely.

Test data collected in the mineral processing industries indicate that the moisture content of ore can have a significant effect on emissions from several process operations. High moisture generally reduces the uncontrolled emission rates, and separate emission rates are provided for primary crushers, secondary crushers, tertiary crushers, and material handling and transfer operations that process high-moisture ore. Drying and dry grinding operations are assumed to produce or to involve only low-moisture material.

For most metallic minerals covered in this section, high-moisture ore is defined as ore whose moisture content, as measured at the primary crusher inlet or at the mine, is 4 weight percent or greater. Ore defined as high-moisture at the primary crusher is presumed to be high-moisture ore at any subsequent operation for which high-moisture factors are provided unless a drying operation precedes the operation under consideration. Ore is defined as low-moisture when a dryer precedes the operation under consideration or when the ore moisture at the mine or primary crusher is less than 4 weight percent.

Separate factors are provided for bauxite handling operations because some types of bauxite with a moisture content as high as 15 to 18 weight percent can still produce relatively high emissions during material handling procedures. These emissions could be eliminated by adding sufficient moisture to the ore, but bauxite then becomes so sticky that it is difficult to handle. Thus, there is some advantage to keeping bauxite in a relatively dusty state, and the low-moisture emission factors given represent conditions fairly typical of the industry.

Particulate matter size distribution data for some process operations have been obtained for control device inlet streams. Since these inlet streams contain PM from several activities, a variability has been anticipated in the calculated size-specific emission factors for PM.

Emission factors for PM equal to or less than 10 μm in aerodynamic diameter (PM-10) from a limited number of tests performed to characterize the processes are presented in Table 11.24-1.

In some plants, PM emissions from multiple pieces of equipment and operations are collected and ducted to a control device. Therefore, examination of reference documents is recommended before applying the factors to specific plants.

Emission factors for PM-10 from high-moisture primary crushing operations and material handling and transfer operations were based on test results usually in the 30 to 40 weight percent range. However, high values were obtained for high-moisture ore at both the primary crushing and the material handling and transfer operations, and these were included in the average values in the table. A similarly wide range occurred in the low-moisture drying operation.

Several other factors are generally assumed to affect the level of emissions from a particular process operation. These include ore characteristics such as hardness, crystal and grain structure, and friability. Equipment design characteristics, such as crusher type, could also affect the emissions level. At this time, data are not sufficient to quantify each of these variables.

11.24.3 Controlled Emissions[7-9]

Emissions from metallic mineral processing plants are usually controlled with wet scrubbers or baghouses. For moderate to heavy uncontrolled emission rates from typical dry ore operations, dryers, and dry grinders, a wet scrubber with pressure drop of 1.5 to 2.5 kilopascals (kPa) (6 to 10 inches of water) will reduce emissions by approximately 95 percent. With very low uncontrolled emission rates typical of high-moisture conditions, the percentage reduction will be lower (approximately 70 percent).

Over a wide range of inlet mass loadings, a well-designed and maintained baghouse will reduce emissions to a relatively constant outlet concentration. Such baghouses tested in the mineral processing industry consistently reduce emissions to less than 0.05 gram per dry standard cubic meter (g/dscm) (0.02 grains per dry standard cubic foot [gr/dscf]), with an average concentration of 0.015 g/dscm (0.006 gr/dscf). Under conditions of moderate to high uncontrolled emission rates of typical dry ore facilities, this level of controlled emissions represents greater than 99 percent removal of PM emissions. Because baghouses reduce emissions to a relatively constant outlet concentration, percentage emission reductions would be less for baghouses on facilities with a low level of uncontrolled emissions.

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11.25 Clay Processing

11.25.1 Process Description[1-4]

Clay is defined as a natural, earthy, fine-grained material, largely of a group of crystalline hydrous silicate minerals known as clay minerals. Clay minerals are composed mainly of silica, alumina, and water, but they may also contain appreciable quantities of iron, alkalies, and alkaline earths. Clay is formed by the mechanical and chemical breakdown of rocks. The six-digit Source Classification Codes (SCC) for clay processing are as follows: .SCC 3-05-041 for kaolin processing, SCC 3-05-042 for ball clay processing, SCC 3-05-043 for fire clay processing, SCC 3-05-044 for bentonite processing, SCC 3-05-045 for fuller's earth processing, and SCC 3-05-046 for common clay and shale processing.

Clays are categorized into six groups by the U. S. Bureau Of Mines. The categories are kaolin, ball clay, fire clay, bentonite, fuller's earth, and common clay and shale. Kaolin, or china clay, is defined as a white, claylike material composed mainly of kaolinite, which is a hydrated aluminum silicate ($Al_2O_3 \bullet 2SiO_2 \bullet 2H_2O$), and other kaolin-group minerals. Kaolin has a wide variety of industrial applications including paper coating and filling, refractories, fiberglass and insulation, rubber, paint, ceramics, and chemicals. Ball clay is a plastic, white-firing clay that is composed primarily of kaolinite and is used mainly for bonding in ceramic ware, primarily dinnerware, floor and wall tile, pottery, and sanitary ware. Fire clays are composed primarily of kaolinite, but also may contain several other materials including diaspore, burley, burley-flint, ball clay, and bauxitic clay and shale. Because of their ability to withstand temperatures of 1500°C (2700°F) or higher, fire clays generally are used for refractories or to raise vitrification temperatures in heavy clay products. Bentonite is a clay composed primarily of smectite minerals, usually montmorillonite, and is used largely in drilling muds, in foundry sands, and in pelletizing taconite iron ores. Fuller's earth is defined as a nonplastic clay or claylike material that typically is high in magnesia and has specialized decolorizing and purifying properties. Fuller's earth, which is very similar to bentonite, is used mainly as absorbents of pet waste, oil, and grease. Common clay is defined as a plastic clay or claylike material with a vitrification point below 1100°C (2000°F). Shale is a laminated sedimentary rock that is formed by the consolidation of clay, mud, or silt. Common clay and shale are composed mainly of illite or chlorite, but also may contain kaolin and montmorillonite.

Most domestic clay is mined by open-pit methods using various types of equipment, including draglines, power shovels, front-end loaders, backhoes, scraper-loaders, and shale planers. In addition, some kaolin is extracted by hydraulic mining and dredging. Most underground clay mines are located in Pennsylvania, Ohio, and West Virginia, where the clays are associated with coal deposits. A higher percentage of fire clay is mined underground than other clays, because the higher quality fire clay deposits are found at depths that make open-pit mining less profitable.

Clays usually are transported by truck from the mine to the processing plants, many of which are located at or near the mine. For most applications, clays are processed by mechanical methods, such as crushing, grinding, and screening, that do not appreciably alter the chemical or mineralogical properties of the material. However, because clays are used in such a wide range of applications, it is often necessary to use other mechanical and chemical processes, such as drying, calcining, bleaching, blunging, and extruding to prepare the material for use.

Primary crushing reduces material size from as much as one meter to a few centimeters in diameter and typically is accomplished using jaw or gyratory crushers. Rotating pan crushers, cone crushers, smooth roll crushers, toothed roll crushers, and hammer mills are used for secondary crushing, which further reduces particle size to 3 mm (0.1 in.) or less. For some applications, tertiary size reduction is necessary and is accomplished by means of ball, rod, or pebble mills, which are often combined with air separators. Screening typically is carried out by means of two or more multi-deck sloping screens that are mechanically or electromagnetically vibrated. Pug mills are used for blunging, and rotary, fluid bed, and vibrating grate dryers are used for drying clay materials. At most plants that calcine clay, rotary or flash calciners are used. However, multiple hearth furnaces often are used to calcine kaolin.

Material losses through basic mechanical processing generally are insignificant. However, material losses for processes such as washing and sizing can reach 30 to 40 percent. The most significant processing losses occur in the processing of kaolin and fuller's earth. The following paragraphs describe the steps used to process each of the six categories of clay. Table 11.25-1 summarizes these processes by clay type.

Kaolin -

Kaolin is both dry- and wet-processed. The dry process is simpler and produces a lower quality product than the wet process. Dry-processed kaolin is used mainly in the rubber industry, and to a lesser extent, for paper filling and to produce fiberglass and sanitary ware. Wet-processed kaolin is used extensively in the paper manufacturing industry. A process flow diagram for kaolin mining and dry processing is presented in Figure 11.25-1, and Figure 11.25-2 illustrates the wet processing of kaolin.

In the dry process, the raw material is crushed to the desired size, dried in rotary dryers, pulverized and air-floated to remove most of the coarse grit. Wet processing of kaolin begins with blunging to produce a slurry, which then is fractionated into coarse and fine fractions using centrifuges, hydrocyclones, or hydroseparators. At this step in the process, various chemical methods, such as bleaching, and physical and magnetic methods, may be used to refine the material. Chemical processing includes leaching with sulfuric acid, followed by the addition of a strong reducing agent such as hydrosulfite. Before drying, the slurry is filtered and dewatered by means of a filter press, centrifuge, rotary vacuum filter, or tube filter. The filtered dewatered slurry material may be shipped or further processed by drying in apron, rotary, or spray dryers. Following the drying step, the kaolin may be calcined for use as filler or refractory material. Multiple hearth furnaces are most often used to calcine kaolin. Flash and rotary calciners also are used.

Ball Clay -

Mined ball clay, which typically has a moisture content of approximately 28 percent, first is stored in drying sheds until the moisture content decreases to 20 to 24 percent. The clay then is shredded in a disintegrator into small pieces 1.3 to 2.5 centimeters (cm) (0.5 to 1 in.) in thickness. The shredded material then is either dried or ground in a hammer mill. Material exiting the hammer mill is mixed with water and bulk loaded as a slurry for shipping. Figure 11.25-3 depicts the process flow for ball clay processing.

Indirect rotary or vibrating grate dryers are used to dry ball clay. Combustion gases from the firebox pass through an air-to-air heat exchanger to heat the drying air to a temperature of approximately 300°C (570°F). The clay is dried to a moisture content of 8 to 10 percent. Following drying, the material is ground in a roller mill and shipped. The ground ball clay may also be mixed with water as a slurry for bulk shipping.

Table 11.25-1. CLAY PROCESSING OPERATIONS

Process	Kaolin	Ball Clay	Fire Clay	Bentonite	Fuller's Earth	Common Clay And Shale
Mining	X	X	X	X	X	X
Stockpiling	X	X	X	X	X	X
Crushing	X	X	X	X	X	X
Grinding	X	X	X	X	X	X
Screening	X		X		X	X
Mixing	X	X				X
Blunging	X				X	X
Air flotation	X	X				
Slurrying	X	X				
Extruding					X	X
Drying	X		X	X	X	X
Calcining	X		X			
Packaging	X	X	X	X	X	
Other	Water fractionation, magnetic separation, acid treatment, bleaching	Shredding, pulverizing	Weathering, blending	Cation exchange, granulating, air classifying	Dispersing	

Fire Clay -

Figure 11.25-4 illustrates the process flow for fire clay processing. Mined fire clay first is transported to the processing plant and stockpiled. In some cases, the crude clay is weathered for 6 to 12 months, depending on the type of fire clay. Freezing and thawing break the material up, resulting in smaller particles and improved plasticity. The material then is crushed and ground. At this stage in the process, the clay has a moisture content of 10 to 15 percent. For certain applications, the clay is dried in mechanical dryers to reduce the moisture content of the material to 7 percent or less. Typically, rotary and vibrating grate dryers fired with natural gas or fuel oil are used for drying fire clay.

To increase the refractoriness of the material, fire clay often is calcined. Calcining eliminates moisture and organic material and causes a chemical reaction to occur between the alumina and silica in the clay, rendering a material (mullite) that is harder, denser, and more easily crushed than

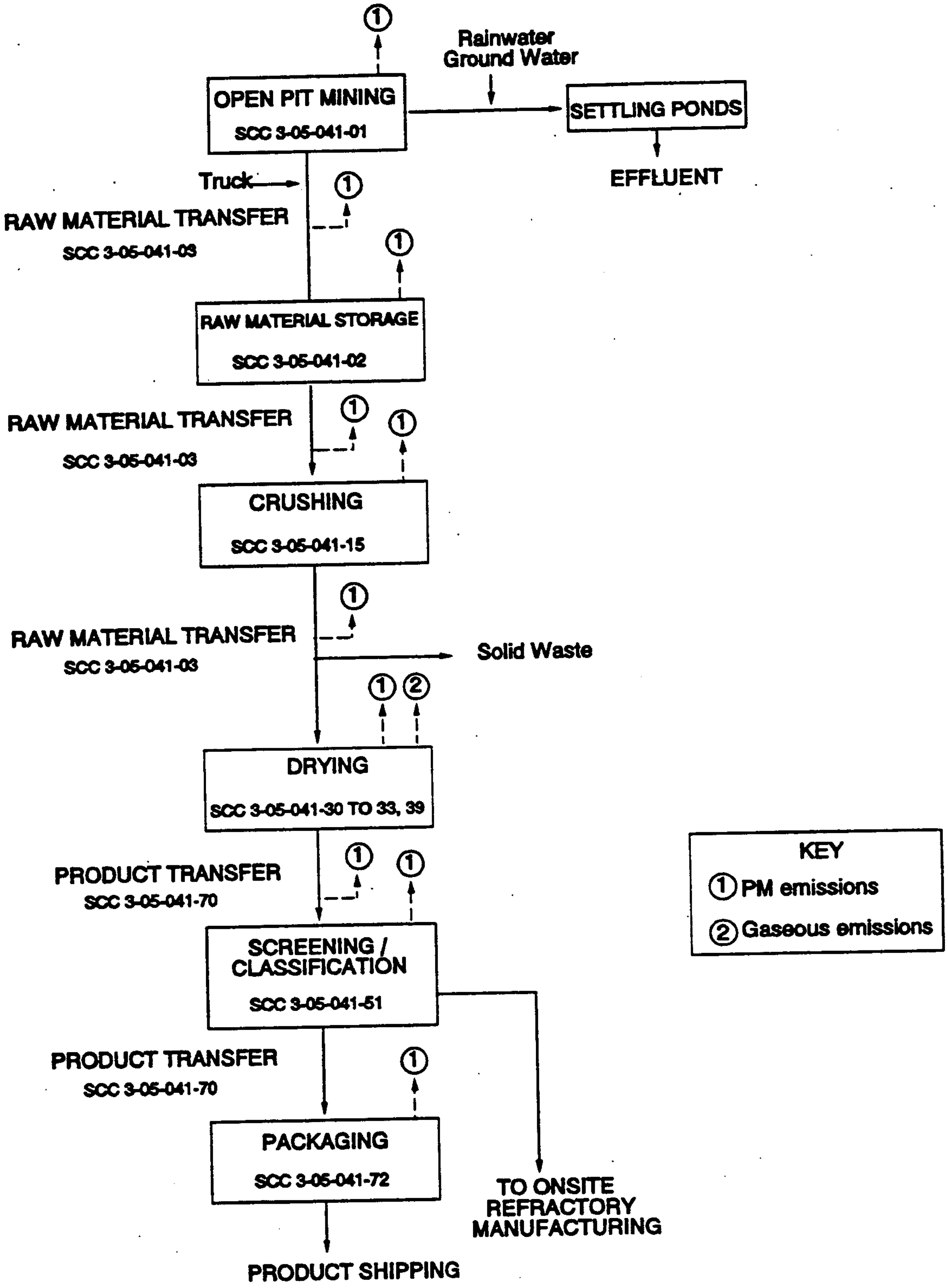

Figure 11.25-1. Process flow diagram for kaolin mining and dry processing. (SCC = Source Classification Code.)

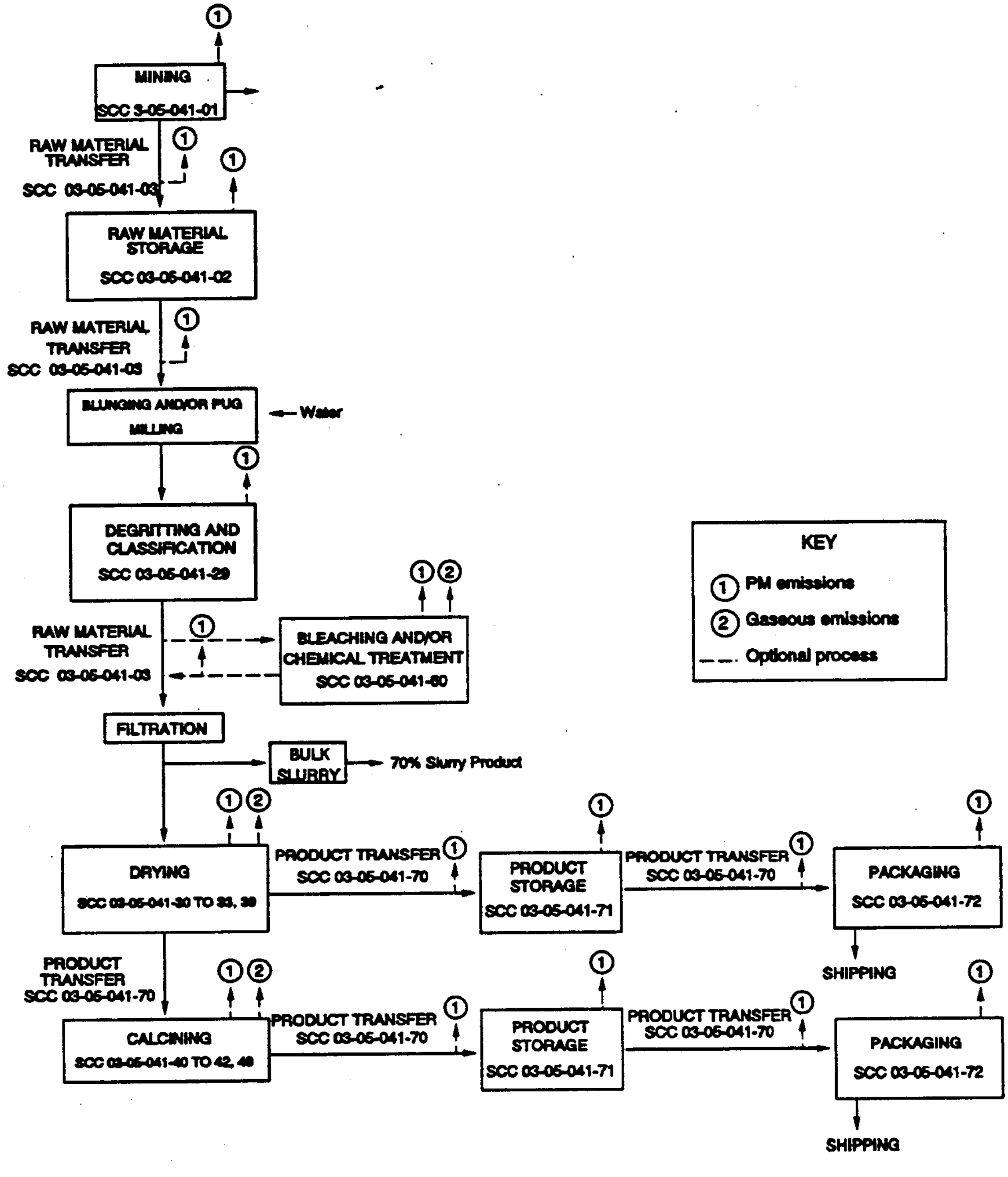

Figure 11.25-2. Process flow diagram for wet process kaolin for high grade products. (SCC = Source Classification Code.)

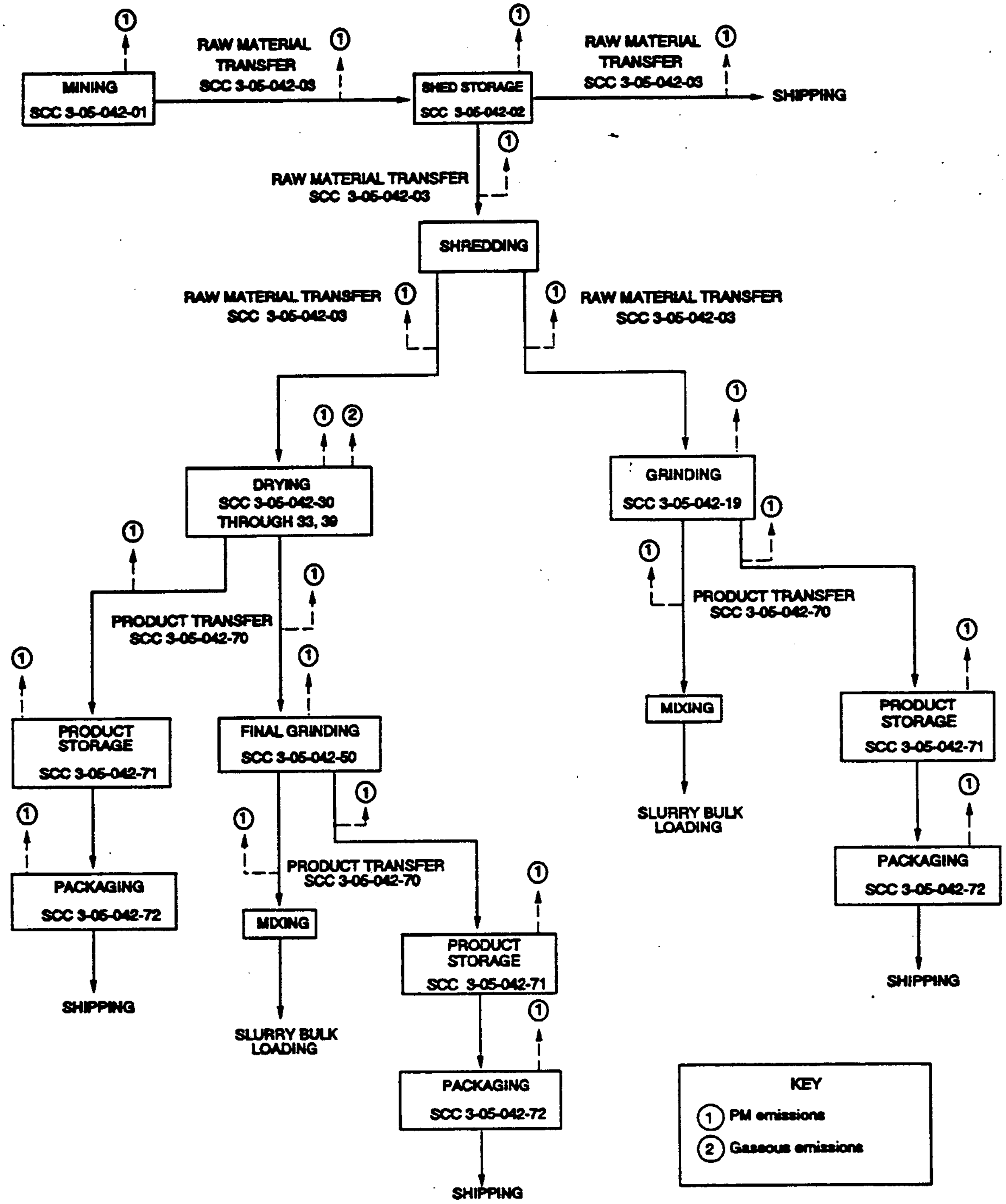

Figure 11.25-3. Process flow diagram for ball clay processing.
(SCC = Source Classification Code.)

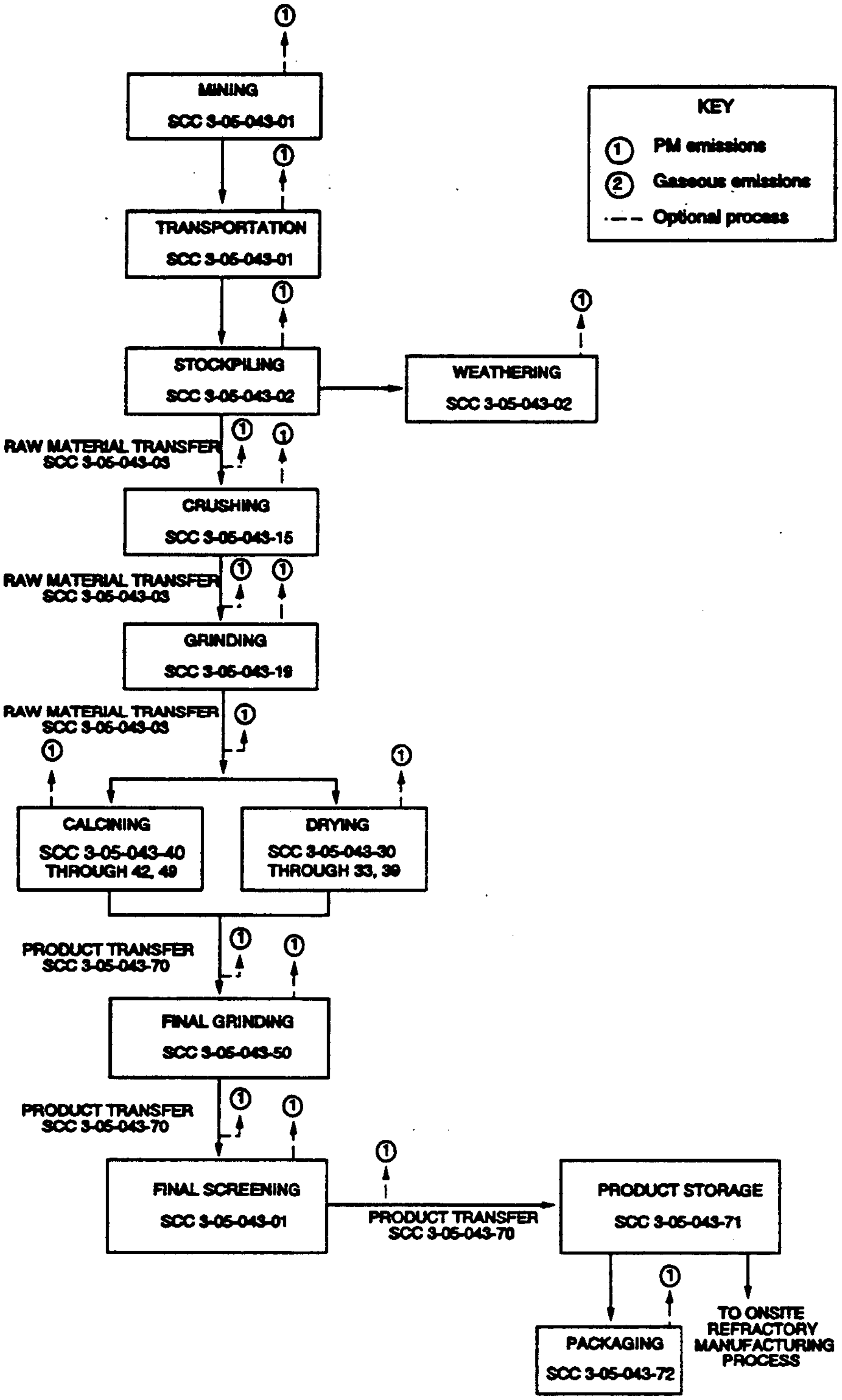

Figure 11.25-4. Process flow diagram for fire clay processing.
(SCC = Source Classification Code.)

uncalcined fire clay. After the clay is dried and/or calcined, the material is crushed, ground, and screened. After screening, the processed fire clay may be blended with other materials, such as organic binders, before to being formed in the desired shapes and fired.

Bentonite -

A flow diagram for bentonite processing is provided in Figure 11.25-5. Mined bentonite first is transported to the processing plant and stockpiled. If the raw clay has a relatively high moisture content (30 to 35 percent), the stockpiled material may be plowed to facilitate air drying to a moisture content of 16 to 18 percent. Stockpiled bentonite may also be blended with other grades of bentonite to produce a uniform material. The material then is passed through a grizzly and crusher to reduce the clay pieces to less than 2.5 cm (1 in.) in size. Next, the crushed bentonite is dried in rotary or fluid bed dryers fired with natural gas, oil, or coal to reduce the moisture content to 7 to 8 percent. The temperatures in bentonite dryers generally range from 900°C (1650°F) at the inlet to 100 to 200°C (210 to 390°F) at the outlet. The dried material then is ground by means of roller or hammer mills. At some facilities which produce specialized bentonite products, the material is passed through an air classifier after being ground. Soda ash also may be added to the processed material to improve the swelling properties of the clay.

Fuller's Earth -

A flow diagram for fuller's earth processing is provided in Figure 11.25-6. After being mined, fuller's earth is transported to the processing plant, crushed, ground, and stockpiled. Before drying, fuller's earth is fed into secondary grinders to reduce further the size of the material. At some plants, the crushed material is fed into a pug mill, mixed with water, and extruded to improve the properties needed for certain end products. The material then is dried in rotary or fluid bed dryers fired with natural gas or fuel oil. Drying reduces the moisture content to 0 to 10 percent from its initial moisture content of 40 to 50 percent. The temperatures in fuller's earth dryers depend on the end used of the product. For colloidal grades of fuller's earth, drying temperatures of approximately 150°C (300°F) are used, and for absorbent grades, drying temperatures of 650°C (1200°F) are typical. In some plants, fuller's earth is calcined rather than dried. In these cases, an operating temperature of approximately 675°C (1250°F) is used. The dried or calcined material then is ground by roller or hammer mills and screened.

Common Clay And Shale -

Figure 11.25-7 depicts common clay and shale processing. Common clay and shale generally are mined, processed, formed, and fired at the same site to produce the end product. Processing generally begins with primary crushing and stockpiling. The material then is ground and screened. Oversize material may be further ground to produce particles of the desired size. For some applications, common clay and shale are dried to reduce the moisture content to desired levels. Further processing may include blunging or mixing with water in a pug mill, extruding, and firing in a kiln, depending on the type of end product.

11.25.2 Emissions And Controls[3,9-10]

The primary pollutants of concern in clay processing operations are particulate matter (PM) and PM less than 10 micrometers (PM-10). Particulate matter is emitted from all dry mechanical processes, such as crushing, screening, grinding, and materials handling and transfer operations. The emissions from dryers and calciners include products of combustion, such as carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x), in addition to filterable and condensible PM. Volatile organic compounds associated with the raw materials and the fuel also may be emitted from drying and calcining.

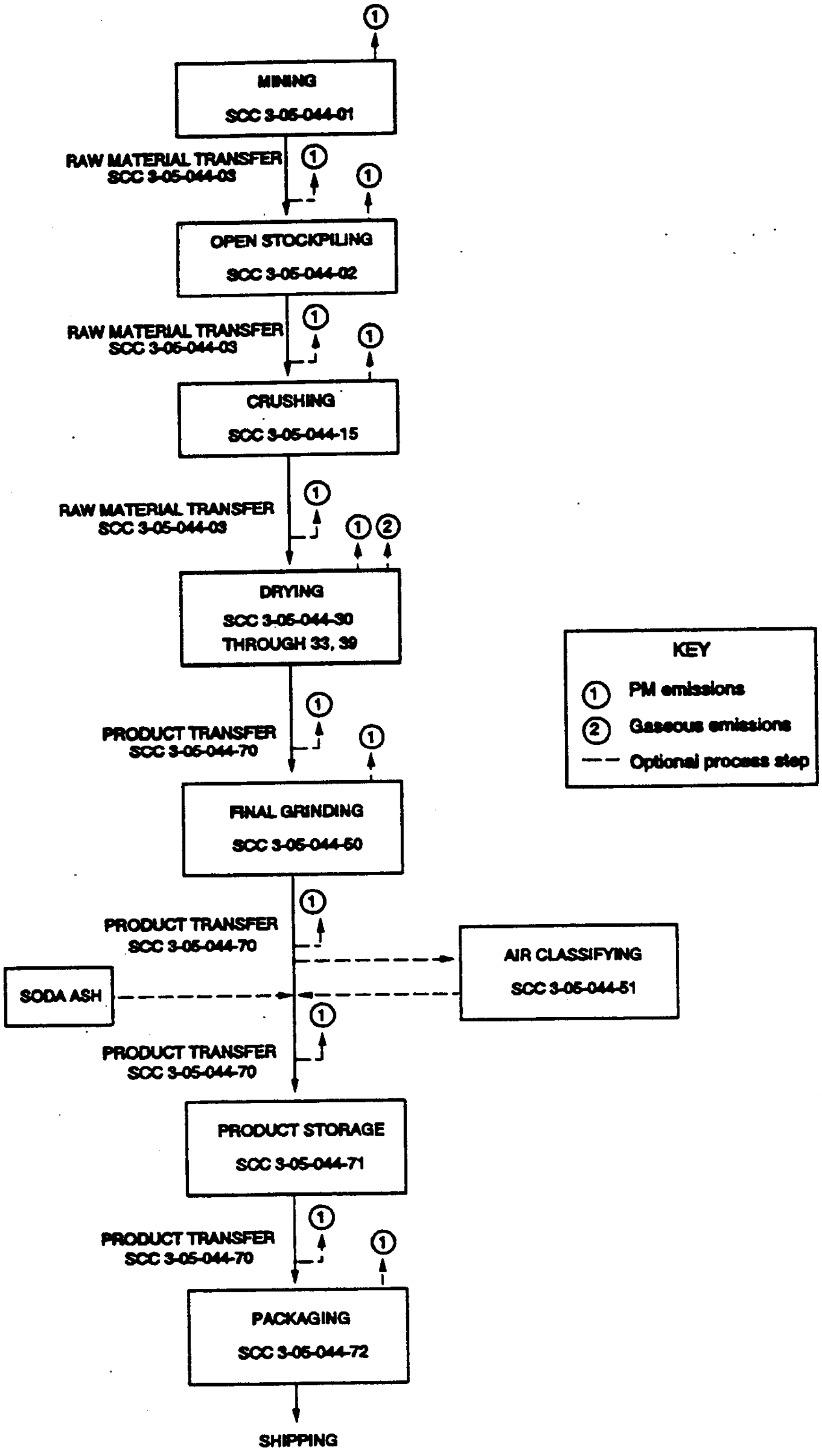

Figure 11.25-5. Process flow diagram for bentonite processing.
(SCC = Source Classification Code.)

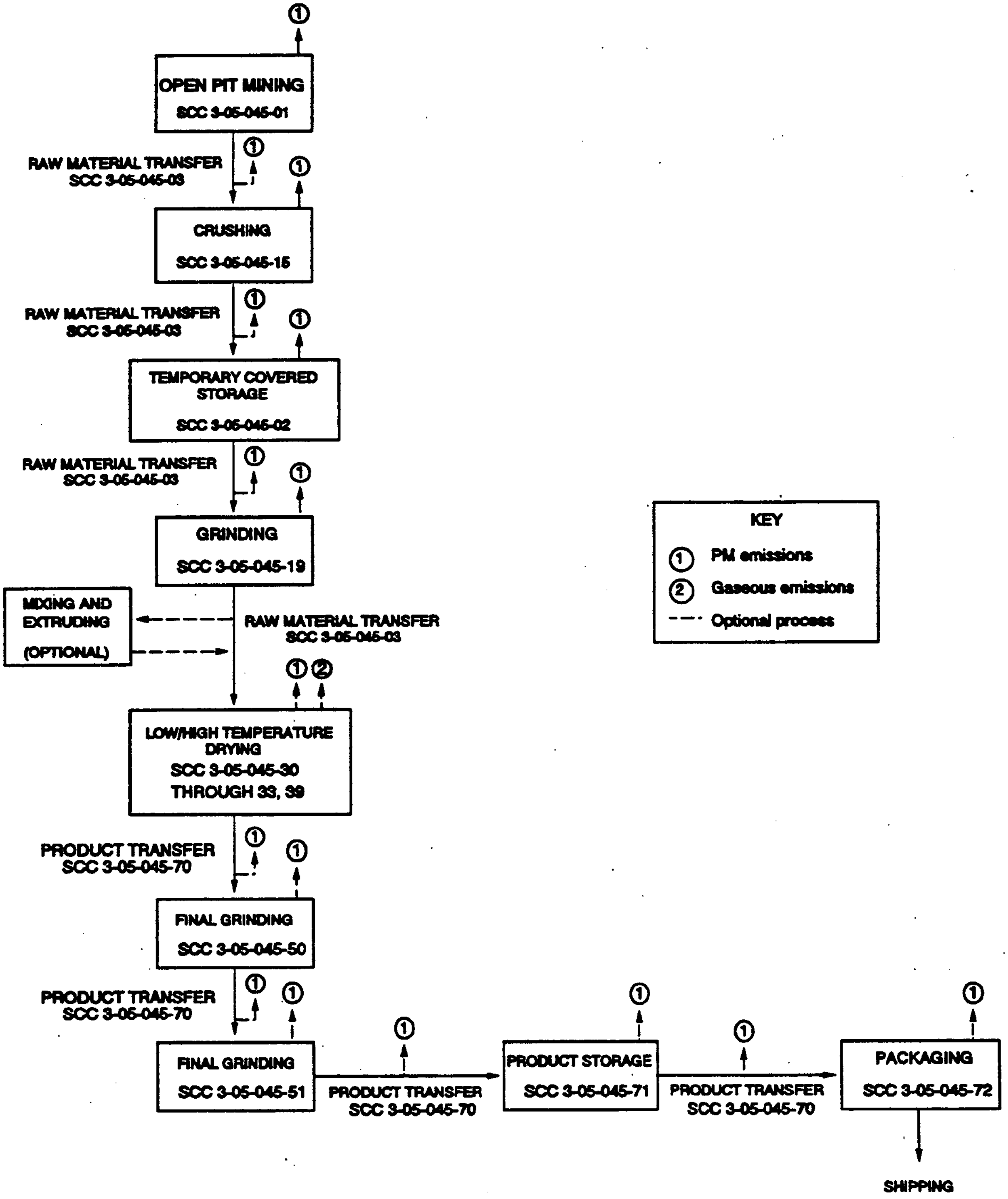

Figure 11.25-6. Process flow diagram for fuller's earth processing.
(SCC = Source Classification Code.)

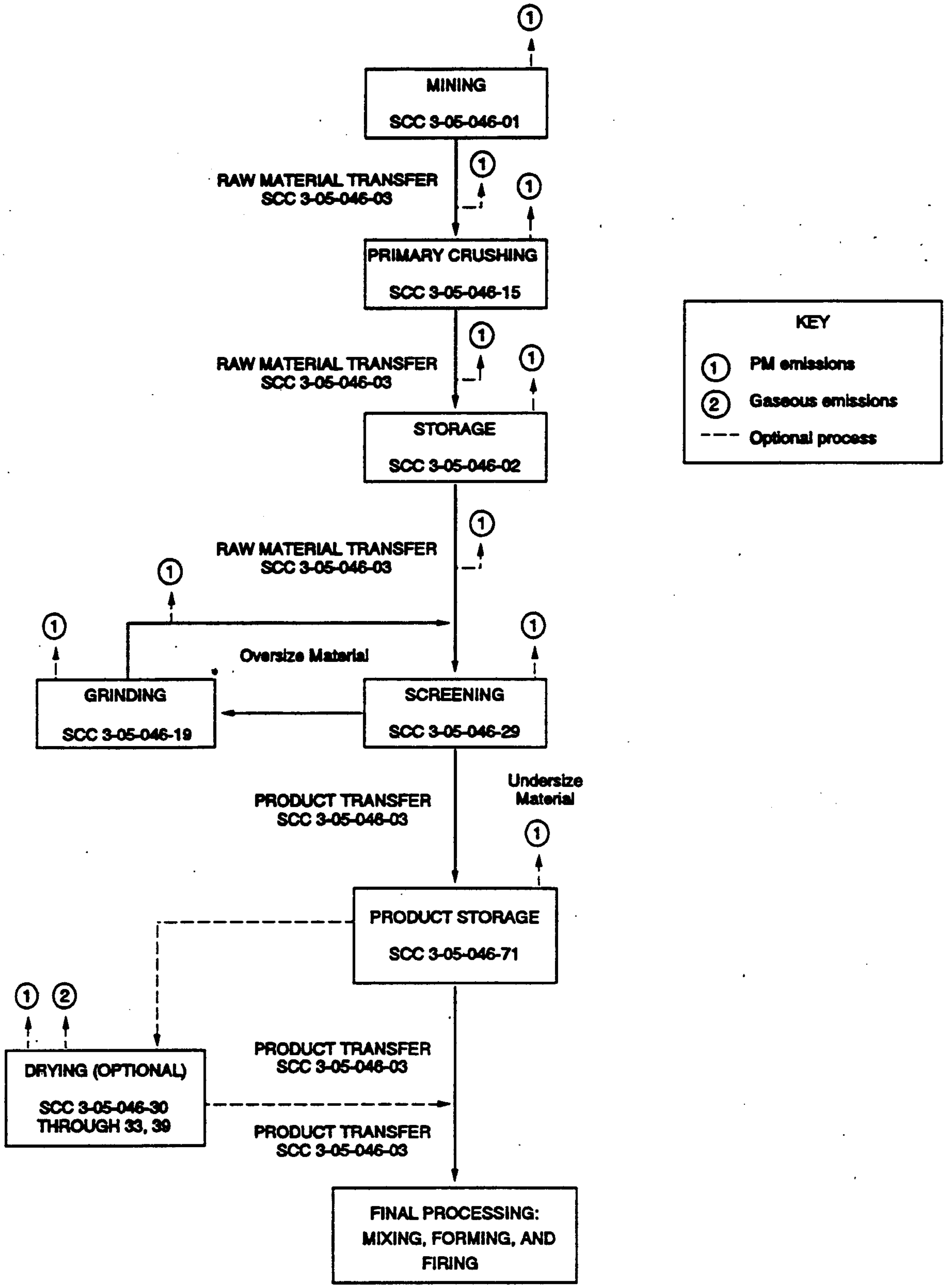

Figure 11.25-7. Process flow diagram for common clay and shale processing. (SCC = Source Classification Code.)

Cyclones, wet scrubbers, and fabric filters are the most commonly used devices to control PM emissions from most clay processing operations. Cyclones often are used for product recovery from mechanical processes. In such cases, the cyclones are not considered to be an air pollution control device. Electrostatic precipitators also are used at some facilities to control PM emissions.

Tables 11.25-2 (metric units) and 11.25-3 (English units) present the emission factors for kaolin processing, and Table 11.25-4 presents particle size distributions for kaolin processing. Table 11.25-5 (metric and English units) presents the emission factors for ball clay processing. Emission factors for fire clay processing are presented in Tables 11.25-6 (metric units) and 11.25-7 (English units). Table 11.25-8 presents the particle size distributions for fire clay processing. Emission factors for bentonite processing are presented in Tables 11.25-9 (metric units) and 11.25-10 (English units), and Table 11.25-11 presents the particle size distribution for bentonite processing. Emission factors for processing common clay and shale to manufacture bricks are presented in AP-42 Section 11.3, "Bricks And Related Clay Products". No data are available for processing common clay and shale for other applications.

No data are available also for individual sources of emissions from fuller's earth processing operations. However, data from one fuller's earth plant indicate the following emission factors for combined sources controlled with multiclones and wet scrubbers: for fuller's earth dried from approximately 50 percent to approximately 12 percent, 0.69 kg/Mg (1.4 lb/ton) for filterable PM and 310 kg/Mg (610 lb/ton) for CO_2 emissions from a rotary dryer, rotary cooler, and packaging warehouse. For fuller's earth dried from approximately 12 percent to 1 to 2 percent, assume 0.32 kg/Mg (0.63 lb/ton) for filterable PM emissions from a rotary dryer, rotary cooler, grinding and screening operations, and packaging warehouse. It should be noted that the sources tested may not be representative of current fuller's earth processing operations.

Table 11.25-2 (Metric Units). EMISSION FACTORS FOR KAOLIN PROCESSING[a]

EMISSION FACTOR RATING: D

Source	Filterable PM[b]	Filterable PM-10[c]	CO_2
Spray dryer with fabric filter (SCC 3-05-041-31)	0.12[d]	ND	81[e]
Apron dryer (SCC 3-05-041-32)	0.62[f]	ND	140[f]
Multiple hearth furnace (SCC 3-05-041-40)	17[g]	8.2[g]	140[g]
Multiple hearth furnace with venturi scrubber (SCC 3-05-041-40)	0.12[g]	ND	NA
Flash calciner (SCC 3-05-041-42)	550[g]	280[g]	260[g]
Flash calciner with fabric filter (SCC 3-05-041-42)	0.028[g]	0.023[g]	NA

[a] Factors are kg/Mg produced. Emissions are uncontrolled, unless noted. SCC = Source Classification Code. ND = no data. NA = not applicable, control device has negligible effects on CO_2 emissions.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Based on filterable PM emission factor and particle size data.

[d] References 3,5.

[e] Reference 5.

[f] Reference 6.

[g] Reference 8.

Table 11.25-3 (English Units). EMISSION FACTORS FOR KAOLIN PROCESSING[a]

EMISSION FACTOR RATING: D

Source	Filterable PM[b]	Filterable PM-10[c]	CO_2
Spray dryer with fabric filter (SCC 3-05-041-31)	0.23[d]	ND	160[e]
Apron dryer (SCC 3-05-041-32)	1.2[f]	ND	280[f]
Multiple hearth furnace (SCC 3-05-041-40)	34[g]	16[g]	280[g]
Multiple hearth furnace with venturi scrubber (SCC 3-05-041-40)	0.23[g]	ND	NA
Flash calciner (SCC 3-05-041-42)	1,100[g]	560[g]	510[g]
Flash calciner with fabric filter (SCC 3-05-041-42)	0.055[g]	0.046[g]	NA

[a] Factors are kg/Mg produced. Emissions are uncontrolled, unless noted. SCC = Source Classification Code. ND = no data. NA = not applicable, control device has negligible effects on CO_2 emissions.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Based on filterable PM emission factor and particle size data.

[d] References 3,5.

[e] Reference 5.

[f] Reference 6.

[g] Reference 8.

Table 11.25-4. PARTICLE SIZE DISTRIBUTIONS FOR KAOLIN PROCESSING[a]

Particle Size, μm	Cumulative Percent Less Than Size		
	Multiple Hearth Furnace, Uncontrolled (SCC 3-05-041-40)	Flash Calciner (SCC 3-05-041-42)	
		Uncontrolled	With Fabric Filter
1.0	5.65	ND	26.93
1.25	8.21	11.14	31.88
2.5	22.99	25.32	55.29
6.0	42.1	44.65	77.34
10	47.22	50.87	88.31
15	52.02	55.35	94.77
20	56.61	59.45	96.56

[a] Reference 8. SCC = Source Classification Code. ND = no data.

Table 11.25-5 (Metric And English Units). EMISSION FACTORS FOR BALL CLAY PROCESSING[a]

EMISSION FACTOR RATING: D

Source	Filterable PM[b]	
	kg/Mg	lb/ton
Vibrating grate dryer with fabric filter (SCC 3-05-042-33)	0.071	0.14

[a] Reference 3. Factors are kg/Mg and lb/ton of ball clay processed. SCC = Source Classification Code.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

Table 11.25-6 (Metric Units). EMISSION FACTORS FOR FIRE CLAY PROCESSING[a]

EMISSION FACTOR RATING: D

Process	SO_2	NO_x	CO_2	Filterable[b]	
				PM	PM-10
Rotary dryer[c] (SCC 3-05-043-30)	ND	ND	15[b]	33	8.1
Rotary dryer with cyclone[c] (SCC 3-05-043-30)	ND	ND	ND	5.6	2.6
Rotary dryer with cyclone and wet scrubber[c] (SCC 3-05-043-30)	ND	ND	ND	0.052	ND
Rotary calciner (SCC 3-05-043-40)	ND	ND	300[c]	62[d]	14[e]
Rotary calciner with multiclone (SCC 3-05-043-40)	ND	ND	ND	31[f]	ND
Rotary calciner with multiclone and wet scrubber (SCC 3-05-043-40)	3.8[d]	0.87[d]	ND	0.15[d]	0.031[e]

[a] Factors are kg/Mg of raw material feed. Emissions are uncontrolled, unless noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Reference 11.

[d] References 12-13.

[e] Reference 12.

[f] Reference 13.

Table 11.25-7 (English Units). EMISSION FACTORS FOR FIRE CLAY PROCESSING[a]

EMISSION FACTOR RATING: D

Process	SO_2	NO_x	CO_2	Filterable[b]	
				PM	PM-10
Rotary dryer[c] (SCC 3-05-043-30)	ND	ND	30	65	16
Rotary dryer with cyclone[c] (SCC 3-05-043-30)	ND	ND	ND	11	5.1
Rotary dryer with cyclone and wet scrubber[c] (SCC 3-05-043-30)	ND	ND	ND	0.11	ND
Rotary calciner (SCC 3-05-043-40)	ND	ND	600[e]	120[d]	30[e]
Rotary calciner with multiclone (SCC 3-05-043-40)	ND	ND	ND	61[f]	ND
Rotary calciner with multiclone and wet scrubber (SCC 3-05-043-40)	7.6[d]	1.7[d]	ND	0.30[d]	0.062[e]

[a] Factors are kg/Mg of raw material feed. Emissions are uncontrolled, unless noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train. PM-10 values are based on cascade impaction particle size distribution.

[c] Reference 11.

[d] References 12-13.

[e] Reference 12.

[f] Reference 13.

Table 11.25-8. PARTICLE SIZE DISTRIBUTIONS FOR FIRE CLAY PROCESSING[a]

EMISSION FACTOR RATING: D

Diameter (μm)	Uncontrolled	Multiclone Controlled	Cyclone Controlled	Cyclone/Scrubber Controlled
	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter	Cumulative % Less Than Diameter
Rotary Dryers (SCC 3-05-043-30)[b]				
2.5	2.5	ND	14	ND
6.0	10	ND	31	ND
10.0	24	ND	46	ND
15.0	37	ND	60	ND
20.0	51	ND	68	ND
Rotary Calciners (SCC 3-05-43-40)[c]				
1.0	3.1	13	ND	31
1.25	4.1	14	ND	43
2.5	6.9	23	ND	46
6.0	17	39	ND	55
10.0	34	50	ND	69
15.0	50	63	ND	81
20.0	62	81	ND	91

[a] For filterable PM only. SCC = Source Classification Code. ND = no data.

[b] Reference 11.

[c] References 12-13 (uncontrolled). Reference 12 (multiclone-controlled). Reference 13 (cyclone/scrubber-controlled).

Table 11.25-9 (Metric Units). EMISSION FACTORS FOR BENTONITE PROCESSING[a]

Source	Filterable PM[b]	EMISSION FACTOR RATING	PM-10[c]	EMISSION FACTOR RATING
Rotary dryer (SCC 3-05-044-30)	140	D	10	D
Rotary dryer with fabric filter (SCC 3-05-044-30)	0.050	D	0.037	D
Rotary dryer with ESP (SCC 3-05-044-30)	0.016	E	ND	

[a] Reference 3. Factors are kg/Mg produced. Emissions are uncontrolled, unless noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Based on filterable PM emission factor and particle size data.

Table 11.25-10 (English Units). EMISSION FACTORS FOR BENTONITE PROCESSING[a]

Source	Filterable PM[b]	EMISSION FACTOR RATING	PM-10[c]	EMISSION FACTOR RATING
Rotary dryer (SCC 3-05-044-30)	290	D	20	D
Rotary dryer with fabric filter (SCC 3-05-044-30)	0.10	D	0.074	D
Rotary dryer with ESP (SCC 3-05-044-30)	0.033	E	ND	

[a] Reference 3. Factors are kg/Mg produced. Emissions are uncontrolled, unless noted. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or before the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Based on filterable PM emission factor and particle size data.

Table 11.25-11. PARTICLE SIZE DISTRIBUTIONS FOR BENTONITE PROCESSING[a]

Particle Size, μm	Cumulative Percent Less Than Size Rotary Dryer, Uncontrolled (SCC 3-05-044-30)	Cumulative Percent Less Than Size Rotary Dryer With Fabric Filter (SCC 3-05-044-30)
1.0	0.2	2.5
1.25	0.3	3.0
2.5	0.8	12
6.0	2.2	44
10.0	7.0	74
15.0	12	92
20.0	25	97

[a] Reference 3. SCC = Source Classification Code.

References For Section 11.25

1. S. H. Patterson and H. H. Murray, "Clays", *Industrial Minerals And Rocks, Volume 1*, Society Of Mining Engineers, New York, 1983.

2. R. L. Virta, *Annual Report 1991: Clays (Draft)*, Bureau Of Mines, U. S. Department Of The Interior, Washington, DC, September 1992.

3. *Calciners And Dryers In Mineral Industries - Background Information For Proposed Standards*, EPA-450/3-85-025a, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1985.

4. J. T. Jones and M. F. Berard, *Ceramics, Industrial Processing And Testing*, Iowa State University Press, Ames, IA, 1972.

5. *Report On Particulate Emissions From No. 3 Spray Dryer, American Industrial Clay Company, Sandersonville, Georgia*, July 21, 1975.

6. *Report On Particulate Emissions From Apron Dryer, American Industrial Clay Company, Sandersonville, Georgia*, July 21, 1975.

7. *Emission Test Report: Thiele Kaolin, Sandersonville, Georgia*, EMB-78-NMM-7, Emission Measurement Branch, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1979.

8. *Emission Test Report: Plant A*, ESD Project No. 81/08, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1983.

9. *Source Test Report, Plant B, Kiln Number 2 Outlet*, Technical Services, Inc., Jacksonville, FL, February 1979.

10. *Source Test Report, Plant B, Number 1 Kiln Outlet Particulate Emissions*, Technical Services, Inc., Jacksonville, FL, February 1979.

11. *Calciners And Dryers Emission Test Report, North American Refractories Company, Farber, Missouri*, EMB - 84-CDR-14, Emission Measurement Branch, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1984.

12. *Emission Test Report: Plant A*, ESD Project No. 81/08, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 13, 1983.

13. *Calciners And Dryers Emission Test Report, A. P. Green Company, Mexico, Missouri*, EMB-83-CDR-1, Emission Measurement Branch, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1983.

11.26 Talc Processing

11.26.1 Process Description[1-4]

Talc, which is a soft, hydrous magnesium silicate ($3MgO \cdot 4SiO_2 \cdot H_2O$), is used in a wide range of industries including the manufacture of ceramics, paints, paper, and asphalt roofing. The end-uses for talc are determined by variables such as chemical and mineralogical composition, particle size and shape, specific gravity, hardness, and color. The Standard Industrial Classification (SIC) code for talc mining is 1499 (miscellaneous nonmetallic minerals, except fuels), and the SIC code for talc processing is 3295 (minerals and earths, ground or otherwise treated). There is no Source Classification Code (SCC) for the source category.

Most domestic talc is mined from open-pit operations; over 95 percent of the talc ore produced in the United States comes from open-pit mines. Mining operations usually consist of conventional drilling and blasting methods. The softness of talc makes it easier to mine and process than most other minerals.

Figure 11.26-1 is a process flow diagram for a typical U.S. talc plant. Talc ore generally is hauled to the plant by truck from a nearby mine. The ore is crushed and screened, and coarse (oversize) material is returned to the crusher. Rotary dryers may be used to dry the material. Secondary grinding is achieved with pebble mills or roller mills, producing a product that is 44 to 149 micrometers (μm) (325 to 100 mesh) in size. Hammer mills or jet air mills may be used to produce additional final products. Air classifiers (separators), generally in closed-circuit with the mills, separate the material into coarse, coarse-plus-fine, and fine fractions. The coarse and coarse-plus-fine fractions then are stored as products. The fines may be concentrated using a shaking table (tabling process) to separate product containing small quantities of nickel, iron, cobalt, or other minerals and then undergo a one-step flotation process. The resultant talc slurry is dewatered and filtered prior to passing through a flash dryer. The flash-dried product is then stored for shipment, or it may be further ground to meet customer specifications.

Talc deposits mined in the southwestern United States contain organic impurities and must be calcined prior to additional processing to yield a product with uniform chemical and physical properties. Generally, a separate product will be used to produce the calcined talc. Prior to calcining, the mined ore passes through a crusher and is ground to a specified screen size. After calcining in a rotary kiln, the material passes through a rotary cooler. The cooled calcine (zero percent free water) is then stored for shipment, or it may be further processed. Calcined talc may be mixed with dried talc from other product lines and passed through a roller mill prior to bulk shipping.

11.26.2 Emissions And Controls[1,2,4,5]

The primary pollutant of concern in talc processing is particulate matter (PM) and PM less than 10 μm (PM-10). Particulate matter is emitted from drilling, blasting, crushing, screening, grinding, drying, calcining, classifying, and materials handling and transfer operations. Particulate matter emissions may include trace amounts of several inorganic compounds that are listed hazardous air pollutants (HAP) including chromium, cobalt, manganese, nickel, and phosphorus.

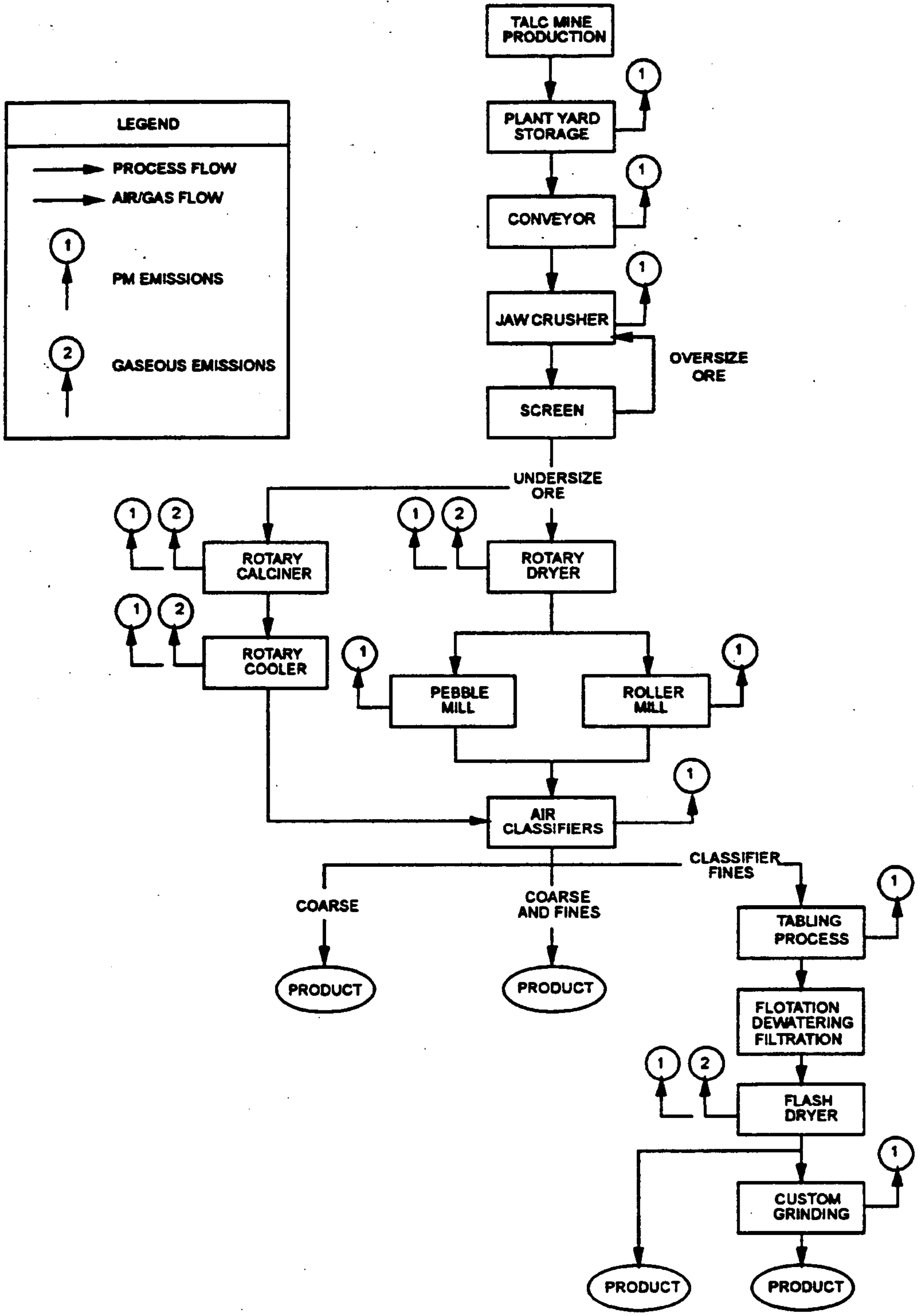

Figure 11.26-1. Process flow diagram for talc processing.[1,4]

The emissions from dryers and calciners include products of combustion such as carbon monoxide, carbon dioxide, nitrogen oxides, and sulfur oxides, in addition to filterable and condensable PM. Volatile organic compounds also are emitted from the drying and calcining of southwestern United States talc deposits, which generally contain organic impurities.

Emissions from talc dryers and calciners are typically controlled with fabric filters. Fabric filters also are used at some facilities to control emissions from mechanical processes such as crushing and grinding.

Due to a lack of available data, no emission factors for talc processing are presented.

References For Section 11.26

1. *Calciners And Dryers In Mineral Industries--Background Information For Proposed Standards*, EPA-450/3-025a, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1985.

2. L. A. Roe and R. H. Olson, "Talc", *Industrial Rocks And Minerals, Volume I*, Society of Mining Engineers, NY, 1983.

3. R. L. Virta, *The Talc Industry-An Overview*, Information Circular 9220, Bureau of Mines, U. S. Department of the Interior, Washington, DC, 1989.

4. Written communication from B. Virta, Bureau of Mines, U. S. Department of the Interior, Washington, D.C., to R. Myers, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 28, 1994.

5. *Emission Study At A Talc Crushing And Grinding Facility, Eastern Magnesia Talc Company, Johnson, Vermont, October 19-21, 1976*, Report No. 76-NMM-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1977.

11.27 Feldspar Processing

11.27.1 General[1]

Feldspar consists essentially of aluminum silicates combined with varying percentages of potassium, sodium, and calcium, and it is the most abundant mineral of the igneous rocks. The two types of feldspar are soda feldspar (7 percent or higher Na_2O) and potash feldspar (8 percent or higher K_2O). Feldspar-silica mixtures can occur naturally, such as in sand deposits, or can be obtained from flotation of mined and crushed rock.

11.27.2 Process Description [1-2]

Conventional open-pit mining methods including removal of overburden, drilling and blasting, loading, and transport by trucks are used to mine ores containing feldspar. A froth flotation process is used for most feldspar ore beneficiation. Figure 11.27-1 shows a process flow diagram of the flotation process. The ore is crushed by primary and secondary crushers and ground by jaw crushers, cone crushers, and rod mills until it is reduced to less than 841 μm (20 mesh). Then the ore passes to a three-stage, acid-circuit flotation process.

An amine collector that floats off and removes mica is used in the first flotation step. Also, sulfuric acid, pine oil, and fuel oil are added. After the feed is dewatered in a classifier or cyclone to remove reagents, sulfuric acid is added to lower the pH. Petroleum sulfonate (mahogany soap) is used to remove iron-bearing minerals. To finish the flotation process, the discharge from the second flotation step is dewatered again, and a cationic amine is used for collection as the feldspar is floated away from quartz in an environment of hydrofluoric acid (pH of 2.5 to 3.0).

If feldspathic sand is the raw material, no size reduction may be required. Also, if little or no mica is present, the first flotation step may be bypassed. Sometimes the final flotation stage is omitted, leaving a feldspar-silica mixture (often referred to as sandspar), which is usually used in glassmaking.

From the completed flotation process, the feldspar float concentrate is dewatered to 5 to 9 percent moisture. A rotary dryer is then used to reduce the moisture content to 1 percent or less. Rotary dryers are the most common dryer type used, although fluid bed dryers are also used. Typical rotary feldspar dryers are fired with No. 2 oil or natural gas, operate at about 230°C (450°F), and have a retention time of 10 to 15 minutes. Magnetic separation is used as a backup process to remove any iron minerals present. Following the drying process, dry grinding is sometimes performed to reduce the feldspar to less than 74 μm (200 mesh) for use in ceramics, paints, and tiles. Drying and grinding are often performed simultaneously by passing the dewatered cake through a rotating gas-fired cylinder lined with ceramic blocks and charged with ceramic grinding balls. Material processed in this manner must then be screened for size or air classified to ensure proper particle size.

11.27.2 Emissions And Controls

The primary pollutant of concern that is emitted from feldspar processing is particulate matter (PM). Particulate matter is emitted by several feldspar processing operations, including crushing, grinding, screening, drying, and materials handling and transfer operations.

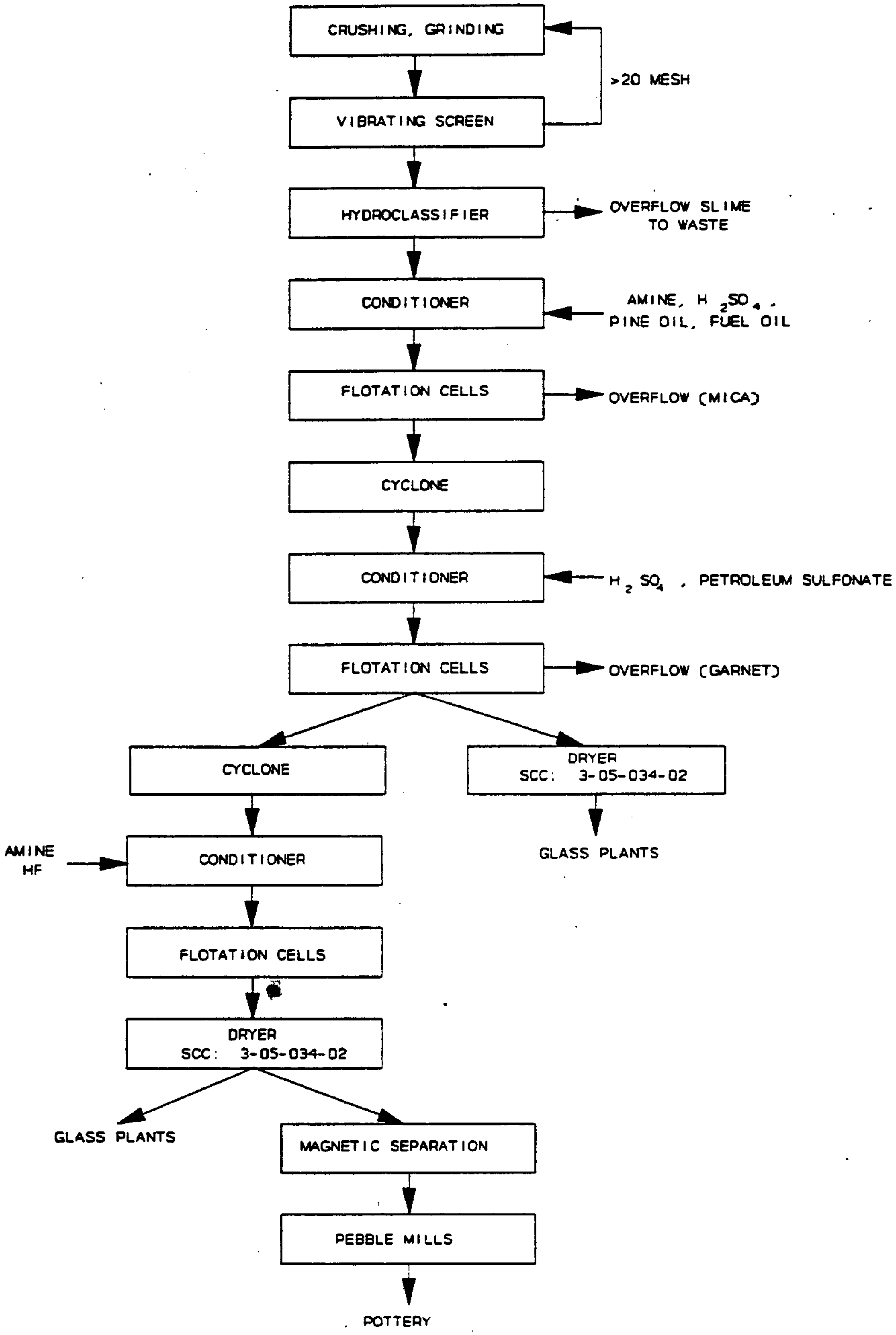

Figure 11.27-1. Feldspar flotation process.[1]

Emissions from dryers typically are controlled by a combination of a cyclone or a multiclone and a scrubber system. Particulate matter emissions from crushing and grinding generally are controlled by fabric filters.

Table 11.27-1 presents controlled emission factors for filterable PM from the drying process. Table 11.27-2 presents emission factors for CO_2 from the drying process. The controls used in feldspar processing achieve only incidental control of CO_2.

Table 11.27-1 (Metric And English Units). EMISSION FACTORS FOR FILTERABLE PARTICULATE MATTER[a]

Process	Filterable Particulate		
	kg/Mg Feldspar Dried	lb/Ton Feldspar Dried	EMISSION FACTOR RATING
Dryer with scrubber and demister[b] (SCC 3-05-034-02)	0.60	1.2	D
Dryer with mechanical collector and scrubber[c,d] (SCC 3-05-034-02)	0.041	0.081	D

[a] SCC = Source Classification Code
[b] Reference 4.
[c] Reference 3.
[d] Reference 5.

Table 11.27-2 (Metric And English Units). EMISSION FACTOR FOR CARBON DIOXIDE[a]

Process	Carbon Dioxide		
	kg/Mg Feldspar Dried	lb/Ton Feldspar Dried	EMISSION FACTOR RATING
Dryer with multiclone and scrubber[b] (SCC 3-05-034-02)	51	102	D

[a] SCC = Source Classification Code.
[b] Scrubbers may achieve incidental control of CO_2 emissions. Multiclones do not control CO_2 emissions.

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11.28 Vermiculite Processing

[Work In Progress]

11.29 Alumina Manufacturing

[Work In Progress]

11.30 Perlite Processing

11.30.1 Process Description[1,2]

Perlite is a glassy volcanic rock with a pearl-like luster. It usually exhibits numerous concentric cracks that cause it to resemble an onion skin. A typical perlite sample is composed of 71 to 75 percent silicon dioxide, 12.5 to 18.0 percent alumina, 4 to 5 percent potassium oxide, 1 to 4 percent sodium and calcium oxides, and trace amounts of metal oxides.

Crude perlite ore is mined, crushed, dried in a rotary dryer, ground, screened, and shipped to expansion plants. Horizontal rotary or vertical stationary expansion furnaces are used to expand the processed perlite ore.

The normal size of crude perlite expanded for use in plaster aggregates ranges from plus 250 micrometers (μm) (60 mesh) to minus 1.4 millimeters (mm) (12 mesh). Crude perlite expanded for use as a concrete aggregate ranges from 1 mm (plus 16 mesh) to 0.2 mm (plus 100 mesh). Ninety percent of the crude perlite ore expanded for horticultural uses is greater than 841 μm (20 mesh).

Crude perlite is mined using open-pit methods and then is moved to the plant site where it is stockpiled. Figure 11.30-1 is a flow diagram of crude ore processing. The first processing step is to reduce the diameter of the ore to approximately 1.6 centimeters (cm) (0.6 inch [in.]) in a primary jaw crusher. The crude ore is then passed through a rotary dryer, which reduces the moisture content from between 4 and 10 percent to less than 1 percent.

After drying, secondary grinding takes place in a closed-circuit system using screens, air classifiers, hammer mills, and rod mills. Oversized material produced from the secondary circuit is returned to the primary crusher. Large quantities of fines, produced throughout the processing stages, are removed by air classification at designated stages. The desired size processed perlite ore is stored until it is shipped to an expansion plant.

At the expansion plants, the processed ore is either preheated or fed directly to the furnace. Preheating the material to approximately 430°C (800°F) reduces the amount of fines produced in the expansion process, which increases usable output and controls the uniformity of product density. In the furnace, the perlite ore reaches a temperature of 760 to 980°C (1400 to 1800°F), at which point it begins to soften to a plastic state where the entrapped combined water is released as steam. This causes the hot perlite particles to expand 4 to 20 times their original size. A suction fan draws the expanded particles out of the furnace and transports them pneumatically to a cyclone classifier system to be collected. The air-suspended perlite particles are also cooled as they are transported to the collection equipment. The cyclone classifier system collects the expanded perlite, removes the excessive fines, and discharges gases to a baghouse or wet scrubber for air pollution control.

The grades of expanded perlite produced can also be adjusted by changing the heating cycle, altering the cutoff points for size collection, and blending various crude ore sizes. All processed products are graded for specific uses and are usually stored before being shipped. Most production rates are less than 1.8 megagrams per hour (Mg/hr) (2 tons/hr), and expansion furnace temperatures range from 870 to 980°C (1600 to 1800°F). Natural gas is typically used for fuel, although No. 2 fuel oil and propane are occasionally used. Fuel consumption varies from 2,800 to 8,960 kilojoules per kilogram (kJ/kg) (2.4×10^6 to 7.7×10^6 British thermal units per ton [Btu/ton]) of product.

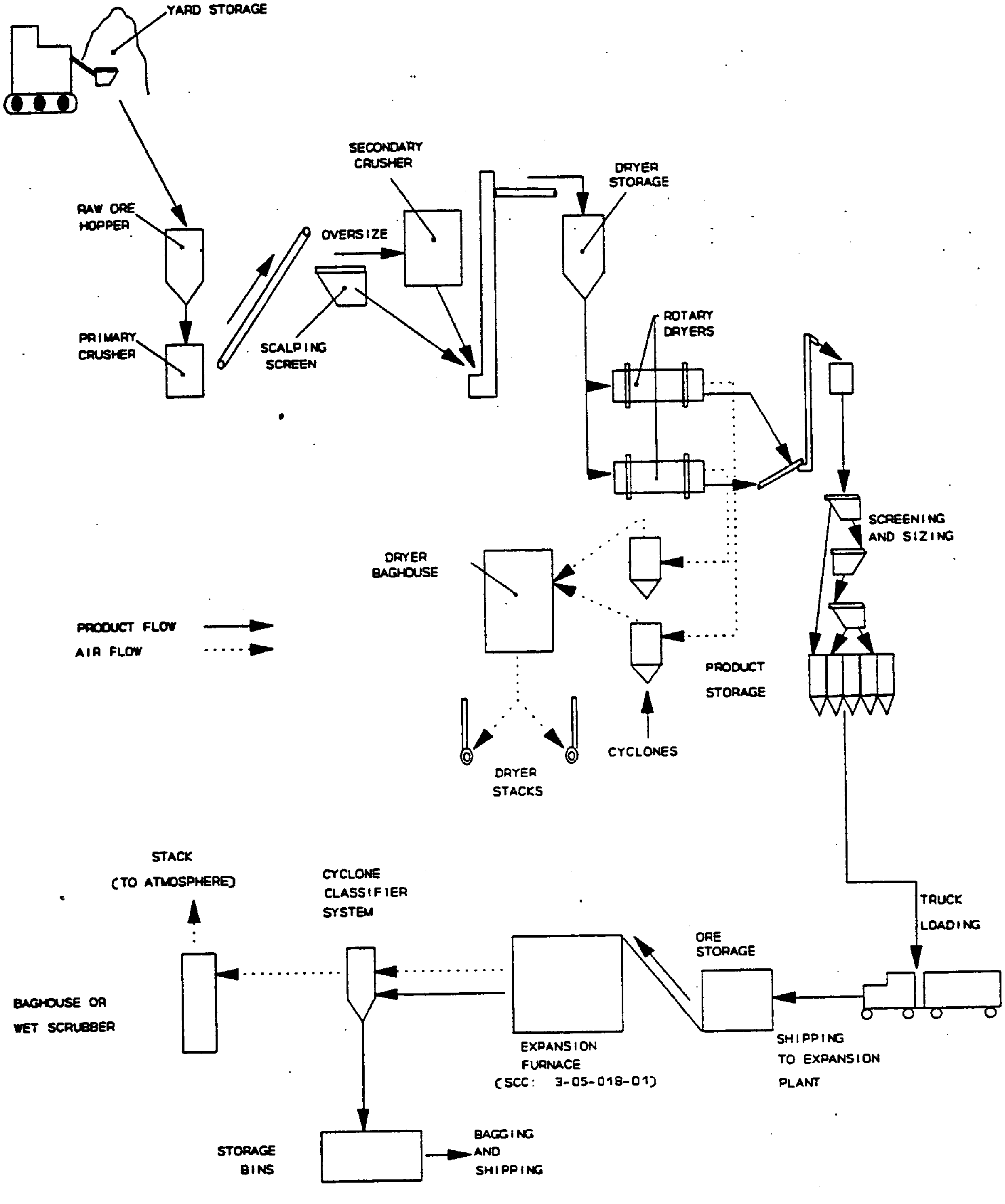

Figure 11.30-1. Flow diagram for perlite processing.[1]
(Source Classification Code in parentheses.)

11.30.2 Emissions And Controls[1,3-11]

The major pollutant of concern emitted from perlite processing facilities is particulate matter (PM). The dryers, expansion furnaces, and handling operations can all be sources of PM emissions. Emissions of nitrogen oxides from perlite expansion and drying generally are negligible. When sulfur-containing fuels are used, sulfur dioxide (SO_2) emissions may result from combustion sources. However, the most common type of fuel used in perlite expansion furnaces and dryers is natural gas, which is not a significant source of SO_2 emissions.

Test data from one perlite plant indicate that perlite expansion furnaces emit a number of trace elements including aluminum, calcium, chromium, fluorine, iron, lead, magnesium, manganese, mercury, nickel, titanium, and zinc. However, because the data consist of a single test run, emission factors were not developed for these elements. The sample also was analyzed for beryllium, uranium, and vanadium, but these elements were not detected.

To control PM emissions from both dryers and expansion furnaces, the majority of perlite plants use baghouses, some use cyclones either alone or in conjunction with baghouses, and a few use scrubbers. Frequently, PM emissions from material handling processes and from the dryers are controlled by the same device. Large plants generally have separate fabric filters for dryer emissions, whereas small plants often use a common fabric filter to control emissions from dryers and materials handling operations. In most plants, fabric filters are preceded by cyclones for product recovery. Wet scrubbers are also used in a small number of perlite plants to control emissions from perlite milling and expansion sources.

Table 11.30-1 presents emission factors for filterable PM and CO_2 emissions from the expanding and drying processes.

Table 11.30-1 (Metric And English Units). EMISSION FACTORS FOR PERLITE PROCESSING[a]

EMISSION FACTOR RATING: D

Process	Filterable PM[b]		CO_2	
	kg/Mg Perlite Expanded	lb/ton Perlite Expanded	kg/Mg Perlite Expanded	lb/ton Perlite Expanded
Expansion furnace (SCC 3-05-018-01)	ND	ND	420[c]	850[c]
Expansion furnace with wet cyclone (SCC 3-05-018-01)	1.1[d]	2.1[d]	NA	NA
Expansion furnace with cyclone and baghouse (SCC 3-05-018-01)	0.15[e]	0.29[e]	NA	NA
Dryer (SCC 3-05-018-__)	ND	ND	16[f]	31[f]
Dryer with baghouse (SCC 3-05-018-__)	0.64[f]	1.3[f]	NA	NA
Dryer with cyclones and baghouses (SCC 3-05-018-__)	0.13[g]	0.25[g]	NA	NA

[a] All emission factors represent controlled emissions. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Reference 4.

[d] Reference 11.

[e] References 4,8.

[f] Reference 10.

[g] References 7,9.

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11.31 Abrasives Manufacturing

11.31.1 General[1]

The abrasives industry is composed of approximately 400 companies engaged in the following separate types of manufacturing: abrasive grain manufacturing, bonded abrasive product manufacturing, and coated abrasive product manufacturing. Abrasive grain manufacturers produce materials for use by the other abrasives manufacturers to make abrasive products. Bonded abrasives manufacturing is very diversified and includes the production of grinding stones and wheels, cutoff saws for masonry and metals, and other products. Coated abrasive products manufacturers include those facilities that produce large rolls of abrasive-coated fabric or paper, known as jumbo rolls, and those facilities that manufacture belts and other products from jumbo rolls for end use.

The six-digit Source Classification Codes (SCC) for the industry are 3-05-035 for abrasive grain processing, 3-05-036 for bonded abrasives manufacturing, and 3-05-037 for coated abrasives manufacturing.

11.31.2 Process Description[1-7]

The process description is broken into three distinct segments discussed in the following sections: production of the abrasive grains, production of bonded abrasive products, and production of coated abrasive products.

Abrasive Grain Manufacturing -

The most commonly used abrasive materials are aluminum oxides and silicon carbide. These synthetic materials account for as much as 80 to 90 percent of the total quantity of abrasive grains produced domestically. Other materials used for abrasive grains are cubic boron nitride (CBN), synthetic diamonds, and several naturally occurring minerals such as garnet and emery. The use of garnet as an abrasive grain is decreasing. Cubic boron nitride is used for machining the hardest steels to precise forms and finishes. The largest application of synthetic diamonds has been in wheels for grinding carbides and ceramics. Natural diamonds are used primarily in diamond-tipped drill bits and saw blades for cutting or shaping rock, concrete, grinding wheels, glass, quartz, gems, and high-speed tool steels. Other naturally occurring abrasive materials (including garnet, emery, silica sand, and quartz) are used in finishing wood, leather, rubber, plastics, glass, and softer metals.

The following paragraphs describe the production of aluminum oxide, silicon carbide, CBN, and synthetic diamond.

1. Silicon carbide. Silicon carbide (SiC) is manufactured in a resistance arc furnace charged with a mixture of approximately 60 percent silica sand and 40 percent finely ground petroleum coke. A small amount of sawdust is added to the mix to increase its porosity so that the carbon monoxide gas formed during the process can escape freely. Common salt is added to the mix to promote the carbon-silicon reaction and to remove impurities in the sand and coke. During the heating period, the furnace core reaches approximately 2200°C (4000°F), at which point a large portion of the load crystallizes. At the end of the run, the furnace contains a core of loosely knit silicon carbide crystals surrounded by unreacted or partially reacted raw materials. The silicon carbide crystals are removed to begin processing into abrasive grains.

2. Aluminum oxide. Fused aluminum oxide (Al_2O_3) is produced in pot-type, electric-arc furnaces with capacities of several tons. Before processing, bauxite, the crude raw material, is calcined at about 950°C (1740°F) to remove both free and combined water. The bauxite is then mixed with ground coke (about 3 percent) and iron borings (about 2 percent). An electric current is applied and the intense heat, on the order of 2000°C (3700°F), melts the bauxite and reduces the impurities that settle to the bottom of the furnace. As the fusion process continues, more bauxite mixture is added until the furnace is full. The furnace is then emptied and the outer impure layer is stripped off. The core of aluminum oxide is then removed to be processed into abrasive grains.

3. Cubic boron nitride. Cubic boron nitride is synthesized in crystal form from hexagonal boron nitride, which is composed of atoms of boron and nitrogen. The hexagonal boron nitride is combined with a catalyst such as metallic lithium at temperatures in the range of 1650°C (3000°F) and pressures of up to 6,895,000 kilopascals (kPa) (1,000,000 pounds per square inch [psi]).

4. Synthetic diamond. Synthetic diamond is manufactured by subjecting graphite in the presence of a metal catalyst to pressures in the range of 5,571,000 to 13,100,000 kPa (808,000 to 1,900,000 psi) at temperatures in the range of 1400 to 2500°C (2500 to 4500°F).

Abrasive Grain Processing -

Abrasive grains for both bonded and coated abrasive products are made by graded crushing and close sizing of either natural or synthetic abrasives. Raw abrasive materials first are crushed by primary crushers and are then reduced by jaw crushers to manageable size, approximately 19 millimeters (mm) (0.75 inches [in]). Final crushing is usually accomplished with roll crushers that break up the small pieces into a usable range of sizes. The crushed abrasive grains are then separated into specific grade sizes by passing them over a series of screens. If necessary, the grains are washed in classifiers to remove slimes, dried, and passed through magnetic separators to remove iron-bearing material, before the grains are again closely sized on screens. This careful sizing is necessary to prevent contamination of grades by coarser grains. Sizes finer than 0.10 millimeter (mm) (250 grit) are separated by hydraulic flotation and sedimentation or by air classification. Figure 11.31-1 presents a process flow diagram for abrasive grain processing.

Bonded Abrasive Products Manufacturing -

The grains in bonded abrasive products are held together by one of six types of bonds: vitrified or ceramic (which account for more than 50 percent of all grinding wheels), resinoid (synthetic resin), rubber, shellac, silicate of soda, or oxychloride of magnesium. Figure 11.31-2 presents a process flow diagram for the manufacturing of vitrified bonded abrasive products.

Measured amounts of prepared abrasive grains are moistened and mixed with porosity media and bond material. Porosity media are used for creating voids in the finished wheels and consist of filler materials, such as paradichlorobenzene (moth ball crystals) or walnut shells, that are vaporized during firing. Feldspar and clays generally are used as bond materials in vitrified wheels. The mix is moistened with water or another temporary binder to make the wheel stick together after it is pressed. The mix is then packed and uniformly distributed into a steel grinding wheel mold, and compressed in a hydraulic press under pressures varying from 1,030 to 69,000 kPa (150 to 10,000 psi). If there is a pore-inducing media in the mix such as paradichlorobenzene, it is removed in a steam autoclave. Prior to firing, smaller wheels are dried in continuous dryers; larger wheels are dried in humidity-controlled, intermittent dry houses.

Most vitrified wheels are fired in continuous tunnel kilns in which the molded wheels ride through the kiln on a moving belt. However, large wheels are often fired in bell or periodic kilns. In the firing process, the wheels are brought slowly to temperatures approaching 1400°C (2500°F)

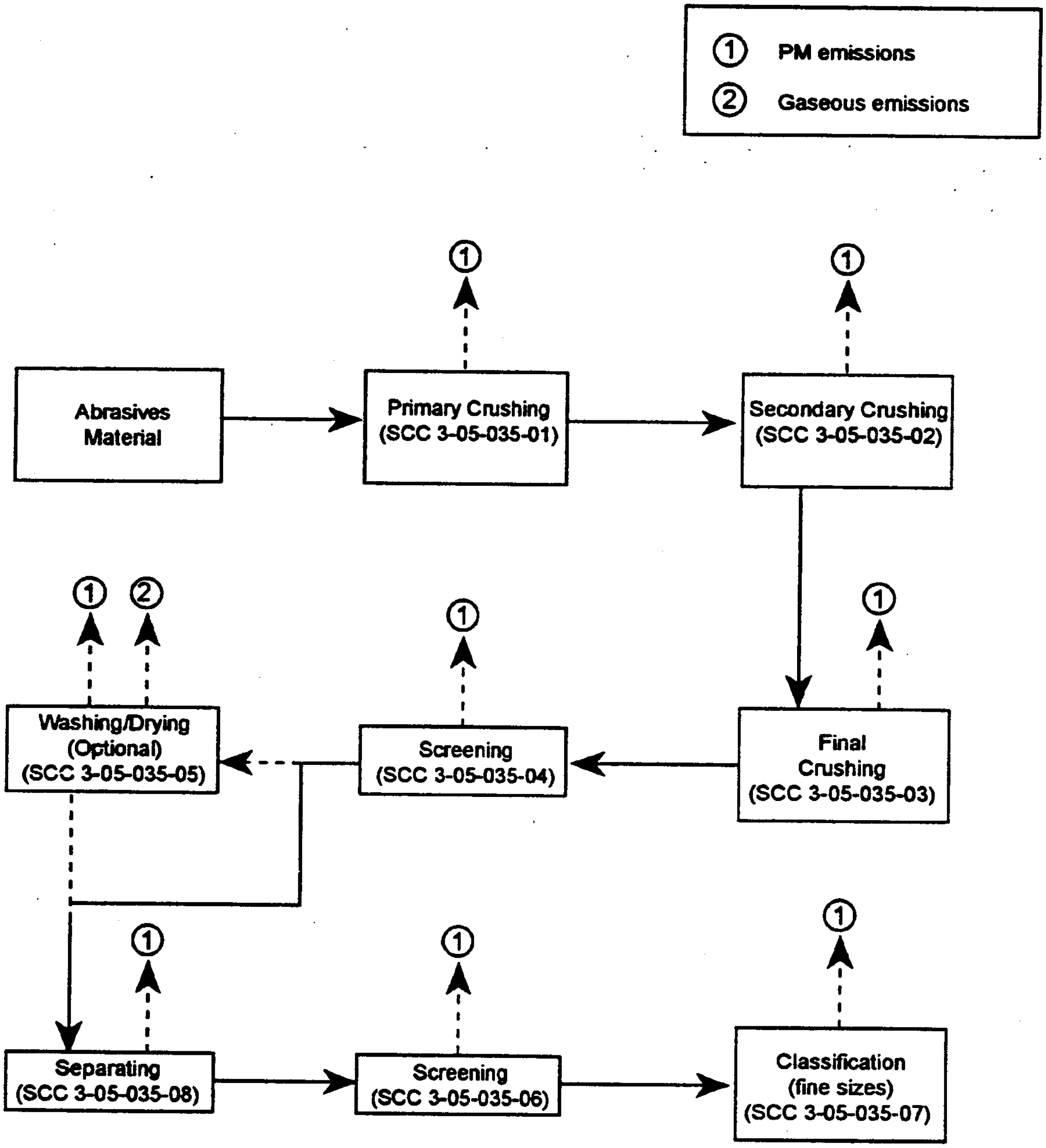

Figure 11.31-1. Process flow diagram for abrasive grain processing.
(Source Classification Codes in parentheses.)

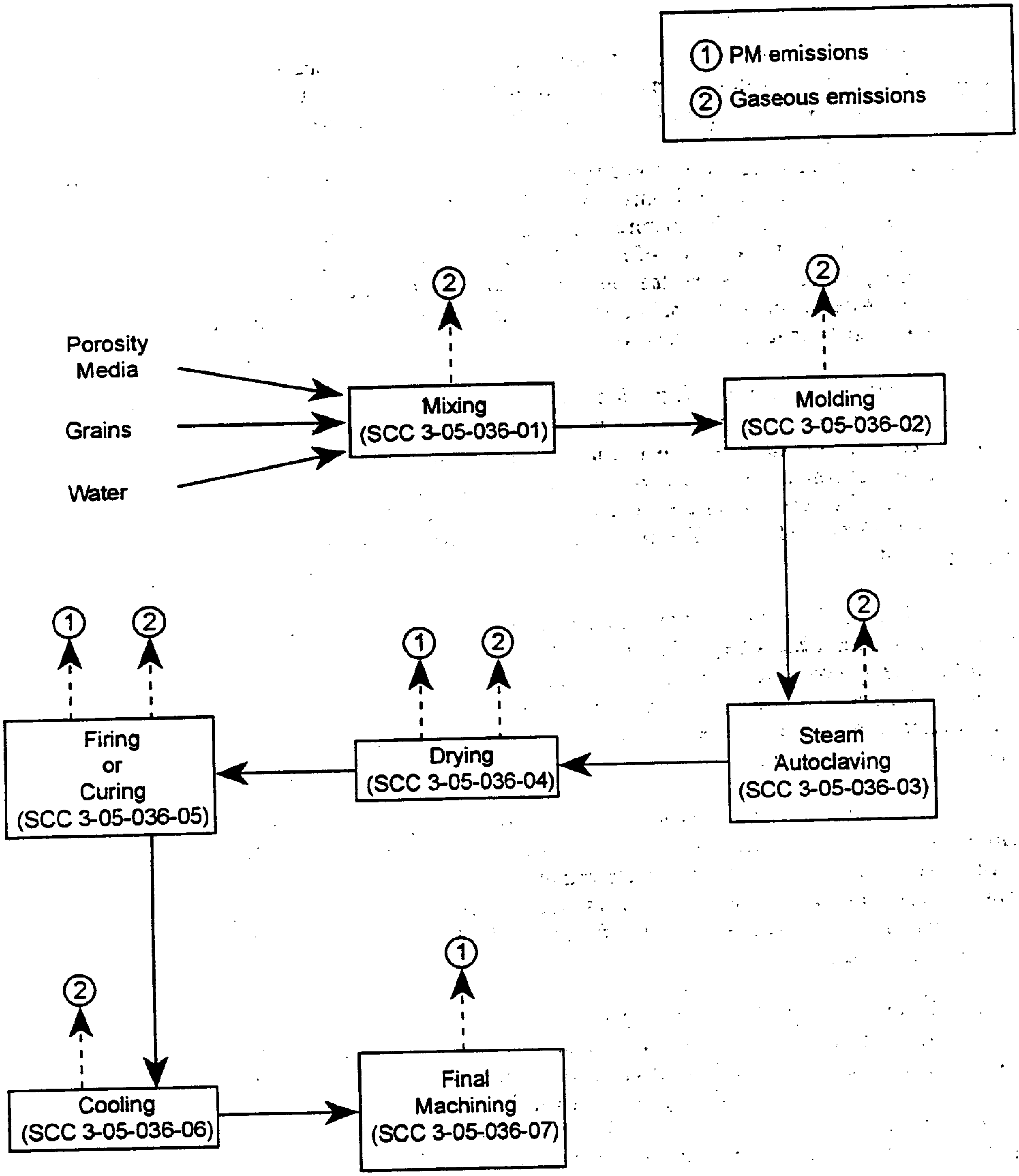

Figure 11.31-2. Process flow diagram for the manufacturing of vitrified bonded abrasive products. (Source Classification Codes in parentheses.)

for as long as several days depending on the size of the grinding wheels and the charge. This slow temperature ramp fuses the clay bond mixture so that each grain is surrounded by a hard glass-like bond that has high strength and rigidity. The wheels are then removed from the kiln and slowly cooled.

After cooling, the wheels are checked for distortion, shape, and size. The wheels are then machined to final size, balanced, and overspeed tested to ensure operational safety. Occasionally wax and oil, rosin, or sulfur are applied to improve the cutting effectiveness of the wheel.

Resin-bonded wheels are produced similarly to vitrified wheels. A thermosetting synthetic resin, in liquid or powder form, is mixed with the abrasive grain and a plasticizer (catalyst) to allow the mixture to be molded. The mixture is then hydraulically pressed to size and cured at 150 to 200°C (300 to 400°F) for a period of from 12 hours to 4 or 5 days depending on the size of the wheel. During the curing period, the mold first softens and then hardens as the oven reaches curing temperature. After cooling, the mold retains its cured hardness. The remainder of the production process is similar to that for vitrified wheels.

Rubber-bonded wheels are produced by selecting the abrasive grain, sieving it, and kneading the grain into a natural or synthetic rubber. Sulfur is added as a vulcanizing agent and then the mix is rolled between steel calendar rolls to form a sheet of the required thickness. The grinding wheels are cut out of the rolled sheet to a specified diameter and hole size. Scraps are kneaded, rolled, and cut out again. Then the wheels are vulcanized in molds under pressure in ovens at approximately 150 to 175°C (300 to 350°F). The finishing and inspection processes are similar to those for other types of wheels.

Shellac-bonded wheels represent a small percentage of the bonded abrasives market. The production of these wheels begins by mixing abrasive grain with shellac in a steam-heated mixer, which thoroughly coats the grain with the bond material (shellac). Wheels 3 mm (0.125 in.) thick or less are molded to exact size in heated steel molds. Thicker wheels are hot-pressed in steel molds. After pressing, the wheels are set in quartz sand and baked for a few hours at approximately 150°C (300°F). The finishing and inspection processes are similar to those for other types of wheels.

In addition to grinding wheels, bonded abrasives are formed into blocks, bricks, and sticks for sharpening and polishing stones such as oil stones, scythe stones, razor and cylinder hones. Curved abrasive blocks and abrasive segments are manufactured for grinding or polishing curved surfaces. Abrasive segments can also be combined into large wheels such as pulpstones. Rubber pencil and ink erasers contain abrasive grains; similar soft rubber wheels, sticks, and other forms are made for finishing soft metals.

Coated Abrasive Products Manufacturing -

Coated abrasives consist of sized abrasive grains held by a film of adhesive to a flexible backing. The backing may be film, cloth, paper, vulcanized fiber, or a combination of these materials. Various types of resins, glues, and varnishes are used as adhesives or bonds. The glue is typically animal hide glue. The resins and varnishes are generally liquid phenolics or ureas, but depending on the end use of the abrasive, they may be modified to yield shorter or longer drying times, greater strength, more flexibility, or other required properties. Figure 11.31-3 presents a process flow diagram for the manufacturing of coated abrasive products.

The production of coated abrasive products begins with a length of backing, which is passed through a printing press that imprints the brand name, manufacturer, abrasive, grade number, and other identifications on the back. Jumbo rolls typically are 1.3 m (52 in.) wide by 1,372 m

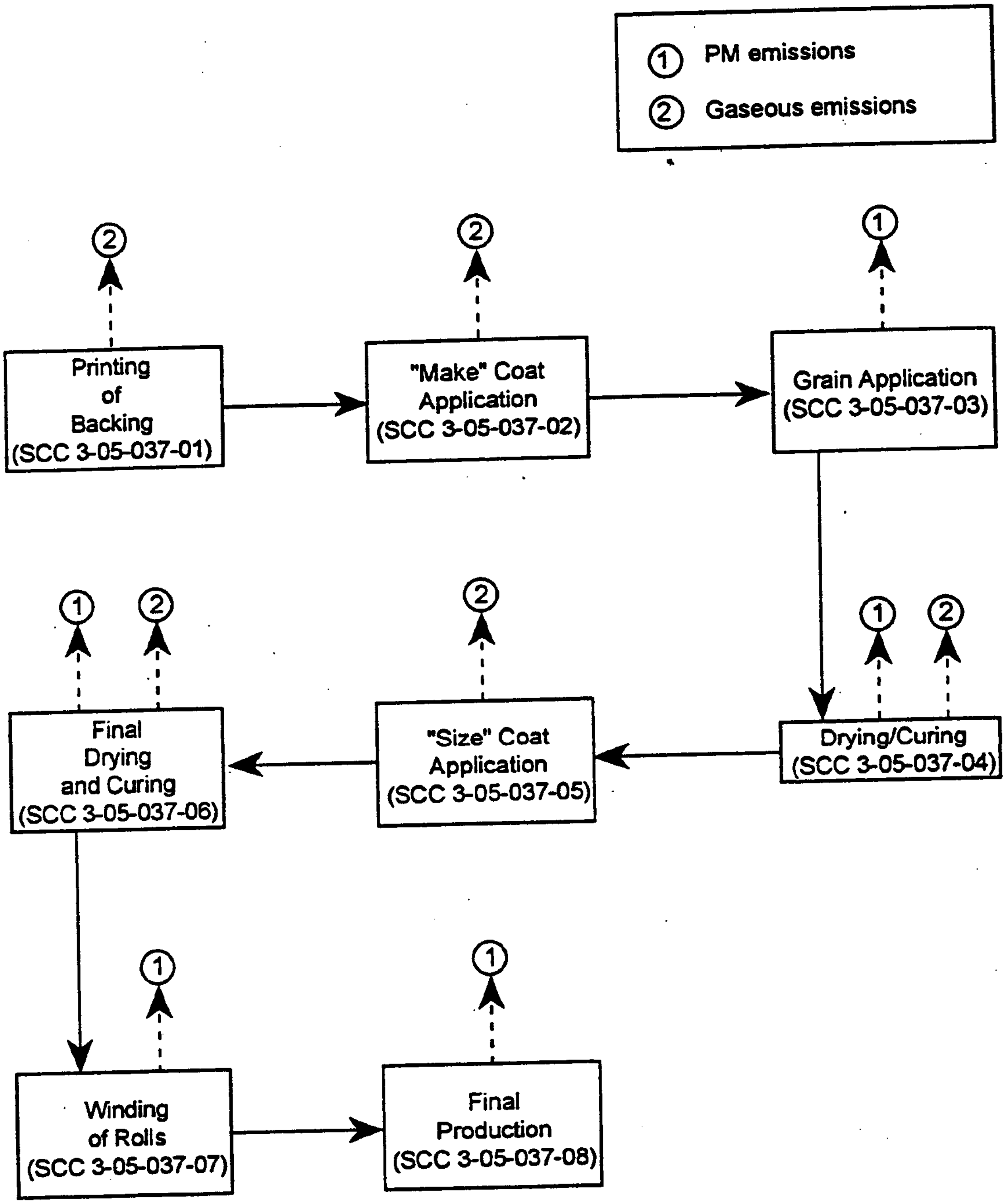

Figure 11.31-3. Process flow diagram for the manufacturing of coated abrasive products. (Source Classification Codes in parentheses.)

(1,500 yards [yd]) to 2,744 m (3,000 yd) in length. The shorter lengths are used for fiber-backed products, and the longer lengths are used for film-backed abrasives. Then the backing receives the first application of adhesive bond, the "make" coat, in a carefully regulated film, varying in concentration and quantity according to the particle size of the abrasive to be bonded. Next, the selected abrasive grains are applied either by a mechanical or an electrostatic method. Virtually all of the abrasive grain used for coated abrasive products is either silicon carbide or aluminum oxide, augmented by small quantities of natural garnet or emery for woodworking, and minute amounts of diamond or CBN.

In mechanical application, the abrasive grains are poured in a controlled stream onto the adhesive-impregnated backing, or the impregnated backing is passed through a tray of abrasive thereby picking up the grains. In the electrostatic method, the adhesive-impregnated backing is passed adhesive-coated side down over a tray of abrasive grains, while at the same time passing an electric current through the abrasive. The electrostatic charge induced by the current causes the grains to imbed upright in the wet bond on the backing. In effect the sharp cutting edges of the grain are bonded perpendicular to the backing. It also causes the individual grains to be spaced more evenly due to individual grain repulsion. The amount of abrasive grains deposited on the backing can be controlled extremely accurately by adjusting the abrasive stream and manipulating the speed of the backing sheet through the abrasive.

After the abrasive is applied, the product is carried by a festoon conveyor system through a drying chamber to the sizing unit, where a second layer of adhesive, called the size coat or sand size, is applied. The size coat unites with the make coat to anchor the abrasive grains securely. The coated material is then carried by another longer festoon conveyor through the final drying and curing chamber in which the temperature and humidity are closely controlled to ensure uniform drying and curing. When the bond is properly dried and cured, the coated abrasive is wound into jumbo rolls and stored for subsequent conversion into marketable forms of coated abrasives. Finished coated abrasives are available as sheets, rolls, belts, discs, bands, cones, and many other specialized forms.

11.31.3 Emissions And Controls[1,7]

Little information is available on emissions from the manufacturing of abrasive grains and products. However, based on similar processes in other industries, some assumptions can be made about the types of emissions that are likely to result from abrasives manufacturing.

Emissions from the production of synthetic abrasive grains, such as aluminum oxide and silicon carbide, are likely to consist primarily of particulate matter (PM), PM less than 10 micrometers (PM-10), and carbon monoxide (CO) from the furnaces. The PM and PM-10 emissions are likely to consist of filterable, inorganic condensable, and organic condensable PM. The addition of salt and sawdust to the furnace charge for silicon carbide production is likely to result in emissions of chlorides and volatile organic compounds (VOC). Aluminum oxide processing takes place in an electric arc furnace and involves temperatures up to 2600°C (4710°F) with raw materials of bauxite ore, silica, coke, iron borings, and a variety of minerals that include chromium oxide, cryolite, pyrite, and silane. This processing is likely to emit fluorides, sulfides, and metal constituents of the feed material. In addition, nitrogen oxides (NO_x) are emitted from the Solgel method of producing aluminum oxide.

The primary emissions from abrasive grain processing consist of PM and PM-10 from the crushing, screening, classifying, and drying operations. Particulate matter also is emitted from materials handling and transfer operations. Table 11.31-1 presents emission factors for filterable PM and CO_2 emissions from grain drying operations in metric and English units. Table 11.31-2

Table 11.31-1 (Metric And English Units). EMISSION FACTORS FOR ABRASIVE MANUFACTURING[a]

EMISSION FACTOR RATING: E

Process	Filterable PM[b]		CO_2	
	kg/Mg	lb/ton	kg/Mg	lb/ton
Rotary dryer, sand blasting grit, with wet scrubber (SCC 3-05-035-05)	ND	ND	22[c]	43[c]
Rotary dryer, sand blasting grit, with fabric filter (SCC 3-05-035-05)	0.0073[d]	0.015[d]	ND	ND

[a] Emission factors in kg/Mg and lb/ton of grit fed into dryer. SCC = Source Classification Code. ND = no data.

[b] Filterable PM is that PM collected on or prior to the filter of an EPA Method 5 (or equivalent) sampling train.

[c] Reference 9.

[d] Reference 8.

Table 11.31-2 (Metric And English Units). EMISSION FACTORS FOR ABRASIVE MANUFACTURING[a]

EMISSION FACTOR RATING: E

Source	Pollutant	Emission Factor	
		kg/Mg	lb/ton
Rotary dryer: sand blasting grit, with wet scrubber (SCC 3-05-035-05)	Antimony	4.0×10^{-5}	8.1×10^{-5}
	Arsenic	0.00012	0.00024
	Beryllium	4.1×10^{-6}	8.2×10^{-6}
	Lead	0.0022	0.0044
	Cadmium	0.00048	0.00096
	Chromium	0.00023	0.00045
	Manganese	3.1×10^{-5}	6.1×10^{-5}
	Mercury	8.5×10^{-7}	1.7×10^{-6}
	Thallium	4.0×10^{-5}	8.1×10^{-5}
	Nickel	0.0013	0.0026

[a] Reference 9. Emission factors in kg/Mg and lb/ton of grit fed into dryer. SCC = Source Classification Code.

presents emission factors developed from the results of a metals analysis conducted on a rotary dryer controlled by a wet scrubber.

Emissions generated in the production of bonded abrasive products may involve a small amount of dust generated by handling the loose abrasive, but careful control of sizes of abrasive particles limits the amount of fine particulate that can be entrained in the ambient air. However, for products made from finer grit sizes--less than 0.13 mm (200 grit)--PM emissions may be a significant problem. The main emissions from production of grinding wheels are generated during the curing of the bond structure for wheels. Heating ovens or kilns emit various types of VOC depending upon the composition of the bond system. Emissions from dryers and kilns also include products of combustion, such as CO, carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulfur oxides (SO_x), in addition to filterable and condensable PM. Vitrified products produce some emissions as filler materials included to provide voids in the wheel structure are vaporized. Curing resins or rubber that is used in some types of bond systems also produce emissions of VOC. Another small source of emissions may be vaporization during curing of portions of the chloride- and sulfur-based materials that are included within the bonding structure as grinding aids.

Emissions that may result from the production of coated abrasive products consist primarily of VOC from the curing of the resin bonds and adhesives used to coat and attach the abrasive grains to the fabric or paper backing. Emissions from dryers and curing ovens also may include products of combustion, such as CO, CO_2, NO_x, and SO_x, in addition to filterable and condensable PM. Emissions that come from conversion of large rolls of coated abrasives into smaller products such as sanding belts consist of PM and PM-10. In addition, some VOC may be emitted as a result of the volatilization of adhesives used to form joints in those products.

Fabric filters preceded by cyclones are used at some facilities to control PM emissions from abrasive grain production. This configuration of control devices can attain controlled emission concentrations of 37 micrograms per dry standard cubic meter (0.02 grains per dry standard cubic foot) and control efficiencies in excess of 99.9 percent. Little other information is available on the types of controls used by the abrasives industry to control PM emissions. However, it is assumed that other conventional devices such as scrubbers and electrostatic precipitators can be used to control PM emissions from abrasives grain and products manufacturing.

Scrubbers are used at some facilities to control NO_x emissions from aluminum oxide production. In addition, thermal oxidizers are often used in the coated abrasives industry to control emissions of VOC.

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12. METALLURGICAL INDUSTRY

The metallurgical industry can be broadly divided into primary and secondary metal production operations. Primary refers to the production of metal from ore. Secondary refers to production of alloys from ingots and to recovery of metal from scrap and salvage.

The primary metals industry includes both ferrous and nonferrous operations. These processes are characterized by emission of large quantities of sulfur oxides and particulate. Secondary metallurgical processes are also discussed, and the major air contaminant from such activity is particulate in the forms of metallic fumes, smoke, and dust.

12.1 Primary Aluminum Production

12.1.1 General[1]

Primary aluminum refers to aluminum produced directly from mined ore. The ore is refined and electrolytically reduced to elemental aluminum. There are 13 companies operating 23 primary aluminum reduction facilities in the U. S. In 1991, these facilities produced 4.1 million megagrams (Mg) (4.5 million tons) of primary aluminum.

12.1.2 Process Description[2-3]

Primary aluminum production begins with the mining of bauxite ore, a hydrated oxide of aluminum consisting of 30 to 56 percent alumina (Al_2O_3) and lesser amounts of iron, silicon, and titanium. The ore is refined into alumina by the Bayer process. The alumina is then shipped to a primary aluminum plant for electrolytic reduction to aluminum. The refining and reducing processes are seldom accomplished at the same facility. A schematic diagram of primary aluminum production is shown in Figure 12.1-1.

12.1.2.1 Bayer Process Description -

In the Bayer process, crude bauxite ore is dried, ground in ball mills, and mixed with a preheated spent leaching solution of sodium hydroxide (NaOH). Lime (CaO) is added to control phosphorus content and to improve the solubility of alumina. The resulting slurry is combined with sodium hydroxide and pumped into a pressurized digester operated at 105 to 290°C (221 to 554°F). After approximately 5 hours, the slurry of sodium aluminate ($NaAl_2OH$) solution and insoluble red mud is cooled to 100°C (212°F) and sent through either a gravity separator or a wet cyclone to remove coarse sand particles. A flocculent, such as starch, is added to increase the settling rate of the red mud. The overflow from the settling tank contains the alumina in solution, which is further clarified by filtration and then cooled. As the solution cools, it becomes supersaturated with sodium aluminate. Fine crystals of alumina trihydrate ($Al_2O_3 \bullet 3H_2O$) are seeded in the solution, causing the alumina to precipitate out as alumina trihydrate. After being washed and filtered, the alumina trihydrate is calcined to produce a crystalline form of alumina, which is advantageous for electrolysis.

12.1.2.2 Hall-Heroult Process -

Crystalline Al_2O_3 is used in the Hall-Heroult process to produce aluminum metal. Electrolytic reduction of alumina occurs in shallow rectangular cells, or "pots", which are steel shells lined with carbon. Carbon electrodes extending into the pot serve as the anodes, and the carbon lining as the cathode. Molten cryolite (Na_3AlF_6) functions as both the electrolyte and the solvent for the alumina. The electrolytic reduction of Al_2O_3 by the carbon from the electrode occurs as follows:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \tag{1}$$

Aluminum is deposited at the cathode, where it remains as molten metal below the surface of the cryolite bath. The carbon anodes are continuously depleted by the reaction. The aluminum product is tapped every 24 to 48 hours beneath the cryolite cover, using a vacuum siphon. The aluminum is then transferred to a reverberatory holding furnace where it is alloyed, fluxed, and degassed to remove trace impurities. (Aluminum reverberatory furnace operations are discussed in detail in Section 12.8, "Secondary Aluminum Operations".) From the holding furnace, the aluminum is cast or transported to fabricating plants.

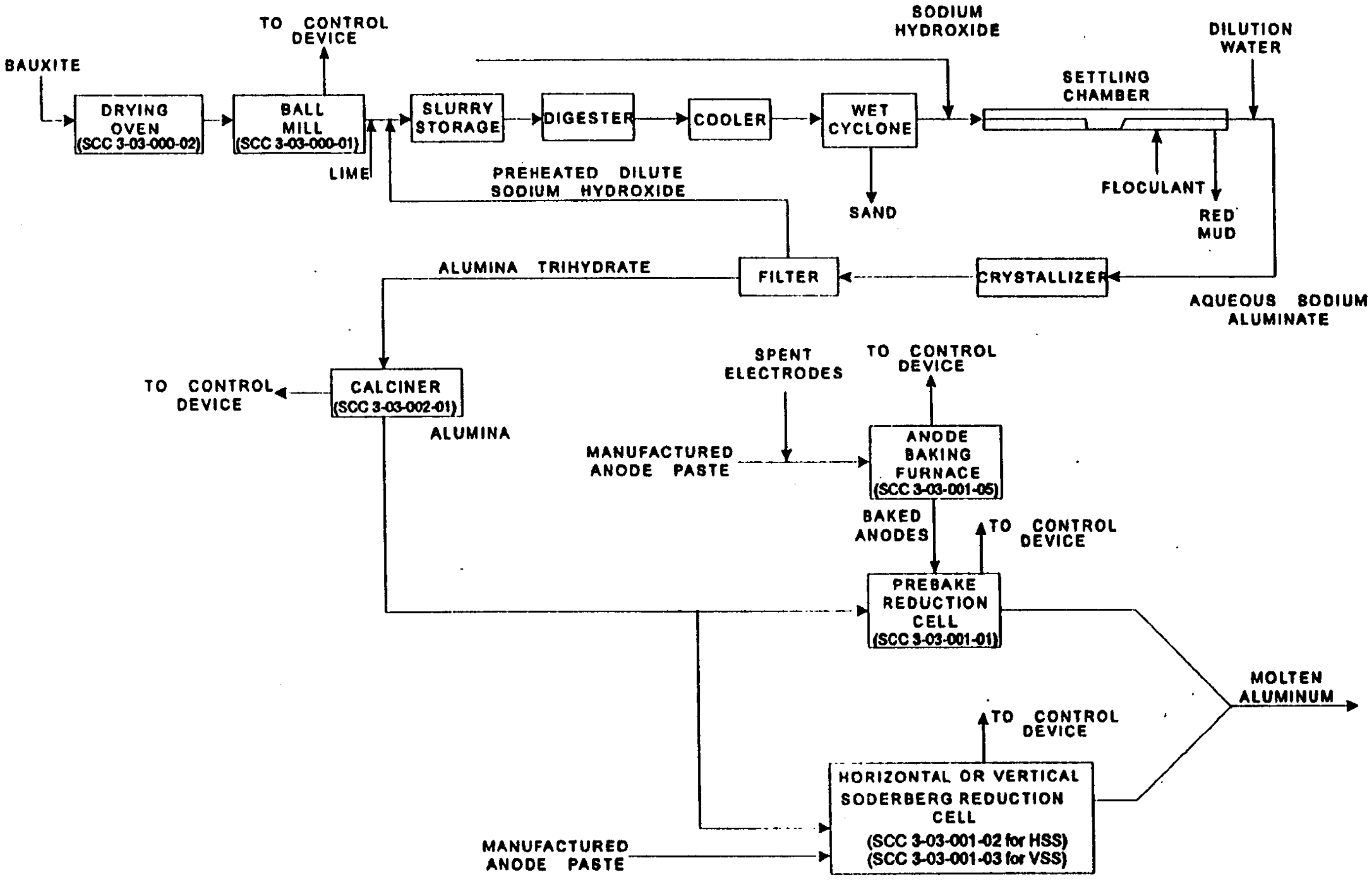

Figure 12.1-1. Schematic diagram of aluminum production process. (Source Classification Codes in parentheses.)

Three types of aluminum reduction cells are now in use: prebaked anode cell (PB), horizontal stud Soderberg anode cell (HSS), and vertical stud Soderberg anode cell (VSS). Most of the aluminum produced in the U. S. is processed using the prebaked cells.

All three aluminum cell configurations require a "paste" (petroleum coke mixed with a pitch binder). Paste preparation includes crushing, grinding, and screening of coke and blending with a pitch binder in a steam jacketed mixer. For Soderberg anodes, the thick paste mixture is added directly to the anode casings. In contrast, the prebaked ("green") anodes are produced as an ancillary operation at a reduction plant.

In prebake anode preparation, the paste mixture is molded into green anode blocks ("butts") that are baked in either a direct-fired ring furnace or a Reid Hammer furnace, which is indirectly heated. After baking, steel rods are inserted and sealed with molten iron. These rods become the electrical connections to the prebaked carbon anode. Prebaked cells are preferred over Soderberg cells because they are electrically more efficient and emit fewer organic compounds.

12.1.3 Emissions And Controls[2-9,12]

Controlled and uncontrolled emission factors for total particulate matter, gaseous fluoride, and particulate fluoride are given in Tables 12.1-1 and 12.1-2. Tables 12.1-3 and 12.1-4 give available data for size-specific particulate matter emissions for primary aluminum industry processes.

In bauxite grinding, hydrated aluminum oxide calcining, and materials handling operations, various dry dust collection devices (centrifugal collectors, multiple cyclones, or ESPs and/or wet scrubbers) have been used. Large amounts of particulate are generated during the calcining of hydrated aluminum oxide, but the economic value of this dust leads to the use of extensive controls which reduce emissions to relatively small quantities.

Emissions from aluminum reduction processes are primarily gaseous hydrogen fluoride and particulate fluorides, alumina, carbon monoxide, volatile organics, and sulfur dioxide (SO_2) from the reduction cells. The source of fluoride emissions from reduction cells is the fluoride electrolyte, which contains cryolite, aluminum fluoride (AlF_3), and fluorospar (CaF_2).

Particulate emissions from reduction cells include alumina and carbon from anode dusting, and cryolite, aluminum fluoride, calcium fluoride, chiolite ($Na_5Al_3F_{14}$), and ferric oxide. Representative size distributions for fugitive emissions from PB and HSS plants, and for particulate emissions from HSS cells, are presented in Tables 12.1-3 and 12.1-4.

Emissions from reduction cells also include hydrocarbons or organics, carbon monoxide, and sulfur oxides. These emission factors are not presented here because of a lack of data. Small amounts of hydrocarbons are released by PB pots, and larger amounts are emitted from HSS and VSS pots. In vertical cells, these organics are incinerated in integral gas burners. Sulfur oxides originate from sulfur in the anode coke and pitch, and concentrations of sulfur oxides in VSS cell emissions range from 200 to 300 parts per million. Emissions from PB plants usually have SO_2 concentrations ranging from 20 to 30 parts per million.

Emissions from anode bake ovens include the products of fuel combustion; high boiling organics from the cracking, distillation, and oxidation of paste binder pitch; sulfur dioxide from the sulfur in carbon paste, primarily from the petroleum coke; fluorides from recycled anode butts; and

Table 12.1-1 (Metric Units). EMISSION FACTORS FOR PRIMARY ALUMINUM PRODUCTION PROCESSES[a,b]

EMISSION FACTOR RATING: A

Operation	Total Particulate[c]	Gaseous Fluoride	Particulate Fluoride	References
Bauxite grinding[d] (SCC 3-03-000-01)				
Uncontrolled	3.0	Neg	Neg	1,3
Spray tower	0.9	Neg	Neg	1,3
Floating bed scrubber	0.85	Neg	Neg	1,3
Quench tower and spray screen	0.5	Neg	Neg	1,3
Aluminum hydroxide calcining[e] (SCC 3-03-002-01)				
Uncontrolled[f]	100.0	Neg	Neg	1,3
Spray tower	30.0	Neg	Neg	1,3
Floating bed scrubber	28.0	Neg	Neg	1,3
Quench tower	17.0	Neg	Neg	1,3
ESP	2.0	Neg	Neg	1,3
Anode baking furnace (SCC 3-03-001-05)				
Uncontrolled	1.5	0.45	0.05	2,10-11
Fugitive (SCC 3-03-001-11)	ND	ND	ND	ND
Spray tower	0.375	0.02	0.015	10
ESP	0.375	0.02	0.015	2
Dry alumina scrubber	0.03	0.004	0.001	2,10
Prebake cell (SCC 3-03-001-01)				
Uncontrolled	47.0	12.0	10.0	1-2,10-11
Fugitive (SCC 3-03-001-08)	2.5	0.6	0.5	2,10
Emissions to collector	44.5	11.4	9.5	2
Crossflow packed bed	13.15	3.25	2.8	10
Multiple cyclones	9.8	11.4	2.1	2
Spray tower	8.9	0.7	1.9	2
Dry ESP plus spray tower	2.25	0.7	1.7	2,10
Floating bed scrubber	8.9	0.25	1.9	2
Dry alumina scrubber	0.9	0.1	0.2	2,10
Coated bag filter dry scrubber	0.9	1.7	0.2	2
Dry plus secondary scrubber	0.35	0.2	0.15	10

Table 12.1-1 (cont.).

Operation	Total Particulate[c]	Gaseous Fluoride	Particulate Fluoride	References
Vertical Soderberg stud cell (SCC 3-03-001-03)				
Uncontrolled	39.0	16.5	5.5	2,10
Fugitive (SCC 3-03-001-10)	6.0	2.45	0.85	10
Emissions to collector	33.0	14.05	4.65	10
Multiple cyclones	16.5	14.05	2.35	2
Spray tower	8.25	0.15	1.15	2
Venturi scrubber	1.3	0.15	0.2	2
Dry alumina scrubber	0.65	0.15	0.1	2
Scrubber plus ESP plus spray screen and scrubber	3.85	0.75	0.65	2
Horizontal Soderberg stud cell (SCC 3-03-001-02)				
Uncontrolled	49.0	11.0	6.0	2,10
Fugitive (SCC 30300109)	5.0	1.1	0.6	2,10
Emissions to collector	44.0	9.9	5.4	2,10
Spray tower	11.0	3.75	1.35	2,10
Floating bed scrubber	9.7	0.2	1.2	2
Scrubber plus wet ESP	0.9	0.1	0.1	2,10
Wet ESP	0.9	0.5	0.1	10
Dry alumina scrubber	0.9	0.2	0.1	10

[a] Units are kilograms (kg) of pollutant/Mg of molten aluminum produced. SCC = Source Classification Code.

[b] Sulfur oxides may be estimated, with an EMISSION FACTOR RATING of C, by the following calculations.

Anode baking furnace, uncontrolled SO_2 emissions (excluding furnace fuel combustion emissions):

20(C)(S)(1-0.01 K) kg/Mg (Metric units)

40(C)(S)(1-0.01 K) pounds/ton (lb/ton) (English units)

Prebake (reduction) cell, uncontrolled SO_2 emissions:

0.2(C)(S)(K) kg/Mg (Metric units)

0.4(C)(S)(K) lb/ton (English units)

where:

C = Anode consumption* during electrolysis, lb anode consumed/lb Al produced (English units)
S = % sulfur in anode before baking
K = % of total SO_2 emitted by prebake (reduction) cells.

*Anode consumption weight is weight of anode paste (coke + pitch) before baking.

[c] Includes particulate fluorides, but does not include condensable organic particulate.

[d] For bauxite grinding, units are kg of pollutant/Mg of bauxite processed.

[e] For aluminum hydroxide calcining, units are kg of pollutant/Mg of alumina produced.

[f] After multicyclones.

Table 12.1-2 (English Units). EMISSION FACTORS FOR PRIMARY ALUMINUM PRODUCTION PROCESSES[a,b]

EMISSION FACTOR RATING: A

Operation	Total Particulate[c]	Gaseous Fluoride	Particulate Fluoride	Reference
Bauxite grinding[d] (SCC 3-03-000-01)				
Uncontrolled	6.0	Neg	Neg	1,3
Spray tower	1.8	Neg	Neg	1,3
Floating bed scrubber	1.7	Neg	Neg	1,3
Quench tower and spray screen	1.0	Neg	Neg	1,3
Aluminum hydroxide calcining[e] (SCC 3-03-002-01)				
Uncontrolled[f]	200.0	Neg	Neg	1,3
Spray tower	60.0	Neg	Neg	1,3
Floating bed scrubber	56.0	Neg	Neg	1,3
Quench tower	34.0	Neg	Neg	1,3
ESP	4.0	Neg	Neg	1,3
Anode baking furnace (SCC 3-03-001-05)				
Uncontrolled	3.0	0.9	0.1	2,10-11
Fugitive (SCC 3-03-001-11)	ND	ND	ND	ND
Spray tower	0.75	0.04	0.03	10
ESP	0.75	0.04	0.03	2
Dry alumina scrubber	0.06	0.009	0.002	2,10
Prebake cell (SCC 3-03-001-01)				
Uncontrolled	94.0	24.0	20.0	1-2,10-11
Fugitive (SCC 3-03-001-08)	5.0	1.2	1.0	2,10
Emissions to collector	89.0	22.8	19.0	2
Multiple cyclones	19.6	22.8	4.2	2
Dry alumina scrubber	1.8	0.2	0.4	2,10
Dry ESP plus spray tower	4.5	1.4	3.4	2,10
Spray tower	112.8	1.4	3.8	2
Floating bed scrubber	112.8	0.5	3.8	2
Coated bag filter dry scrubber	1.8	3.4	0.4	2
Crossflow packed bed	26.3	6.7	5.6	10
Dry plus secondary scrubber	0.7	0.4	0.3	10

Table 12.1-2 (cont.).

Operation	Total Particulate[c]	Gaseous Fluoride	Particulate Fluoride	Reference
Vertical Soderberg stud cell (SCC 3-03-001-03)				
Uncontrolled	78.0	33.0	11.0	2,10
Fugitive (SCC 3-03-001-10)	12.0	4.9	1.7	10
Emissions to collector	66.0	28.1	9.3	10
Spray tower	16.5	0.3	2.3	2
Venturi scrubber	2.6	0.3	0.4	2
Multiple cyclones	33.0	28.1	4.7	2
Dry alumina scrubber	1.3	0.3	0.2	2
Scrubber plus ESP plus spray screen and scrubber	7.7	1.5	1.3	2
Horizontal Soderberg stud cell (SCC 3-03-001-02)				
Uncontrolled	98.0	22.0	12.0	2,10
Fugitive (SCC 3-03-001-09)	10.0	2.2	1.2	2,10
Emissions to collector	88.0	19.8	10.8	2,10
Spray tower	22.0	7.5	2.7	2,10
Floating bed scrubber	19.4	0.4	2.4	2
Scrubber plus wet ESP	1.8	0.2	0.2	2,10
Wet ESP	1.8	1.0	0.2	10
Dry alumina scrubber	1.8	0.4	0.2	10

[a] Units are lb of pollutant/ton of molten aluminum produced. SCC = Source Classification Code.

[b] Sulfur oxides may be estimated, with an EMISSION FACTOR RATING of C, by the following calculations.

Anode baking furnace, uncontrolled SO_2 emissions (excluding furnace fuel combustion emissions):

20(C)(S)(1-0.01 K) kg/Mg (Metric units)

40(C)(S)(1-0.01 K) lb/ton (English units)

Prebake (reduction) cell, uncontrolled SO_2 emissions:

0.2(C)(S)(K) kg/Mg (Metric units)

0.4(C)(S)(K) lb/ton (English units)

where:

C = Anode consumption* during electrolysis, lb anode consumed/lb Al produced

S = % sulfur in anode before baking

K = % of total SO_2 emitted by prebake (reduction) cells.

*Anode consumption weight is weight of anode paste (coke + pitch) before baking.

[c] Includes particulate fluorides, but does not include condensable organic particulate.

[d] For bauxite grinding, units are lb of pollutant/ton of bauxite processed.

[e] For aluminum hydroxide calcining, units are lb of pollutant/ton of alumina produced.

[f] After multicyclones.

Table 12.1-3 (Metric Units). UNCONTROLLED EMISSION FACTORS AND PARTICLE SIZE DISTRIBUTION IN ALUMINUM PRODUCTION[a]

EMISSION FACTOR RATING: D (except as noted)

Particle Size[b] (μm)	Prebake Aluminum Cells[c]		HSS Aluminum Cells		HSS Reduction Cells	
	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor
0.625	13	0.33	8	0.40	26	12.7
1.25	18	0.46	13	0.65	32	15.7
2.5	28	0.70	17	0.85	40	19.6
5	43	1.08	23	1.15	50	25.5
10	58	1.45	31	1.55	58	28.4
15	65	1.62	39	1.95	63	30.9
Total	100	2.5	100	5.0	100	49

[a] Reference 5. Units are kg of pollutant/Mg of aluminum produced.

[b] Expressed as equivalent aerodynamic particle diameter.

[c] EMISSION FACTOR RATING: C

Table 12.1-4 (English Units). UNCONTROLLED EMISSION FACTORS AND PARTICLE SIZE DISTRIBUTION IN ALUMINUM PRODUCTION[a]

EMISSION FACTOR RATING: D (except as noted)

Particle Size[b] (μm)	Prebake Aluminum Cells[c]		HSS Aluminum Cells		HSS Reduction Cells	
	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factor
0.625	13	0.67	8	0.8	26	25.5
1.25	18	0.92	13	1.3	32	31.4
2.5	28	1.40	17	1.7	40	39.2
5	43	2.15	23	2.3	50	49.0
10	58	2.90	31	3.1	58	56.8
15	65	3.23	39	3.9	63	61.7
Total	100	2.5	100	10.0	100	98

[a] Reference 5. Units are lb of pollutant/ton of aluminum produced.

[b] Expressed as equivalent aerodynamic particle diameter.

[c] EMISSION FACTOR RATING: C

other particulate matter. Emission factors for these components are not included in this document due to insufficient data. Concentrations of uncontrolled SO_2 emissions from anode baking furnaces range from 5 to 47 parts per million (based on 3 percent sulfur in coke).

High molecular weight organics and other emissions from the anode paste are released from HSS and VSS cells. These emissions can be ducted to gas burners to be oxidized, or they can be collected and recycled or sold. If the heavy tars are not properly collected, they can cause plugging of exhaust ducts, fans, and emission control equipment.

A variety of control devices has been used to abate emissions from reduction cells and anode baking furnaces. To control gaseous and particulate fluorides and particulate emissions, 1 or more types of wet scrubbers (spray tower and chambers, quench towers, floating beds, packed beds, venturis) have been applied to all 3 types of reduction cells and to anode baking furnaces. In addition, particulate control methods such as wet and dry electrostatic precipitators (ESPs), multiple cyclones, and dry alumina scrubbers (fluid bed, injected, and coated filter types) are used on all 3 cell types and with anode baking furnaces.

The fluoride adsorption system is becoming more prevalent and is used on all 3 cell types. This system uses a fluidized bed of alumina, which has a high affinity for fluoride, to capture gaseous and particulate fluorides. The pot offgases are passed through the crystalline form of alumina, which was generated using the Bayer process. A fabric filter is operated downstream from the fluidized bed to capture the alumina dust entrained in the exhaust gases passing through the fluidized bed. Both the alumina used in the fluidized bed and that captured by the fabric filter are used as feedstock for the reduction cells, thus effectively recycling the fluorides. This system has an overall control efficiency of 99 percent for both gaseous and particulate fluorides. Wet ESPs approach adsorption in particulate removal efficiency, but they must be coupled to a wet scrubber or coated baghouse to catch hydrogen fluoride.

Scrubber systems also remove a portion of the SO_2 emissions. These emissions could be reduced by wet scrubbing or by reducing the quantity of sulfur in the anode coke and pitch, i. e., calcining the coke.

The molten aluminum may be batch treated in furnaces to remove oxide, gaseous impurities, and active metals such as sodium and magnesium. One process consists of adding a flux of chloride and fluoride salts and then bubbling chlorine gas, usually mixed with an inert gas, through the molten mixture. Chlorine reacts with the impurities to form HCl, Al_2O_3, and metal chloride emissions. A dross forms on the molten aluminum and is removed before casting.

Potential sources of fugitive particulate emissions in the primary aluminum industry are bauxite grinding, materials handling, anode baking, and the 3 types of reduction cells (see Tables 12.1-1 and 12.1-2). These fugitive emissions probably have particulate size distributions similar to those presented in Tables 12.1-3 and 12.1-4.

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12.2 Coke Production

12.2.1 General

Metallurgical coke is produced by destructive distillation of coal in coke ovens. Prepared coal is "coked", or heated in an oxygen-free atmosphere until all volatile components in the coal evaporate. The material remaining is called coke.

Most metallurgical coke is used in iron and steel industry processes such as blast furnaces, sinter plants, and foundries to reduce iron ore to iron. Over 90 percent of the total metallurgical coke production is dedicated to blast furnace operations.

Most coke plants are co-located with iron and steel production facilities. Coke demand is dependent on the iron and steel industry. This represents a continuing decline from the about 40 plants that were operating in 1987.

12.2.2 Process Description[1,2]

All metallurgical coke is produced using the "byproduct" method. Destructive distillation ("coking") of coal occurs in coke ovens without contact with air. Most U. S. coke plants use the Kopper-Becker byproduct oven. These ovens must remain airtight under the cyclic stress of expansion and contraction. Each oven has 3 main parts: coking chambers, heating chambers, and regenerative chambers. All of the chambers are lined with refractory (silica) brick. The coking chamber has ports in the top for charging of the coal.

A coke oven battery is a series of 10 to 100 coke ovens operated together. Figure 12.2-1 illustrates a byproduct coke oven battery. Each oven holds between 9 to 32 megagrams (Mg) (10 to 35 tons) of coal. Offtake flues on either end remove gases produced. Process heat comes from the combustion of gases between the coke chambers. Individual coke ovens operate intermittently, with run times of each oven coordinated to ensure a consistent flow of collectible gas. Approximately 40 percent of cleaned oven gas (after the removal of its byproducts) is used to heat the coke ovens. The rest is either used in other production processes related to steel production or sold. Coke oven gas is the most common fuel for underfiring coke ovens.

A typical coke manufacturing process is shown schematically in Figure 12.2-2. Coke manufacturing includes preparing, charging, and heating the coal; removing and cooling the coke product; and cooling, cleaning, and recycling the oven gas.

Coal is prepared for coking by pulverizing so that 80 to 90 percent passes through a 3.2 millimeter (1/8 inch) screen. Several types of coal may be blended to produce the desired properties, or to control the expansion of the coal mixture in the oven. Water or oil may be added to adjust the density of the coal to control expansion and prevent damage to the oven.

Coal may be added to the ovens in either a dry or wet state. Prepared wet coal is finely crushed before charging to the oven. Flash-dried coal may be transported directly to the ovens by the hot gases used for moisture removal. Wall temperatures should stay above 1100°C (2000°F) during loading operations and actual coking. The ports are closed after charging and sealed with luting ("mud") material.

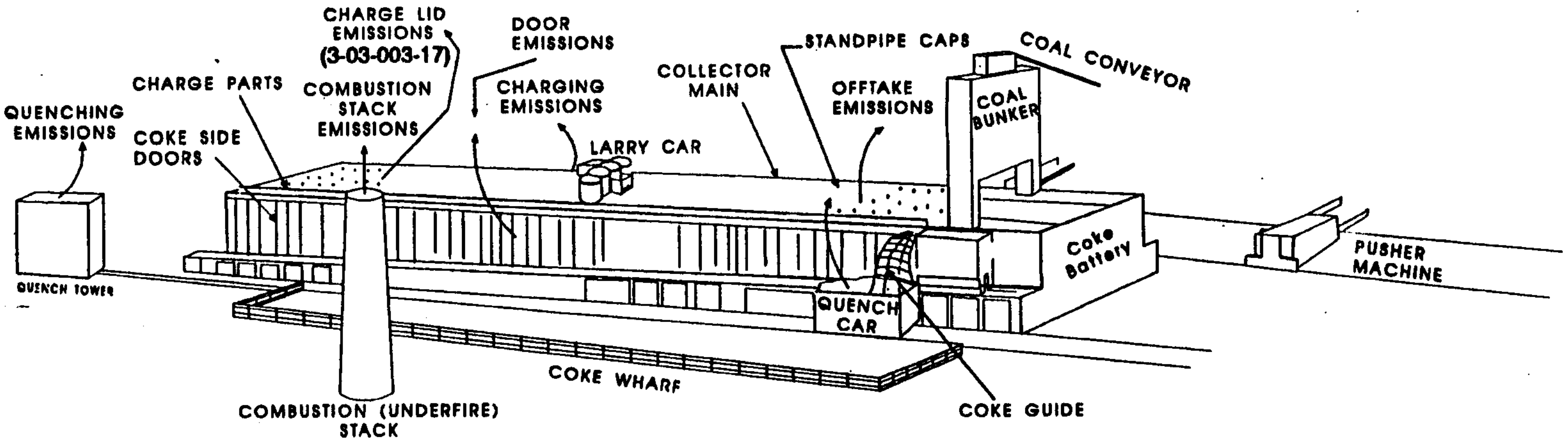

Figure 12.2-1. Byproduct coke oven battery showing major emission points. (Source Classification Codes in parentheses.)

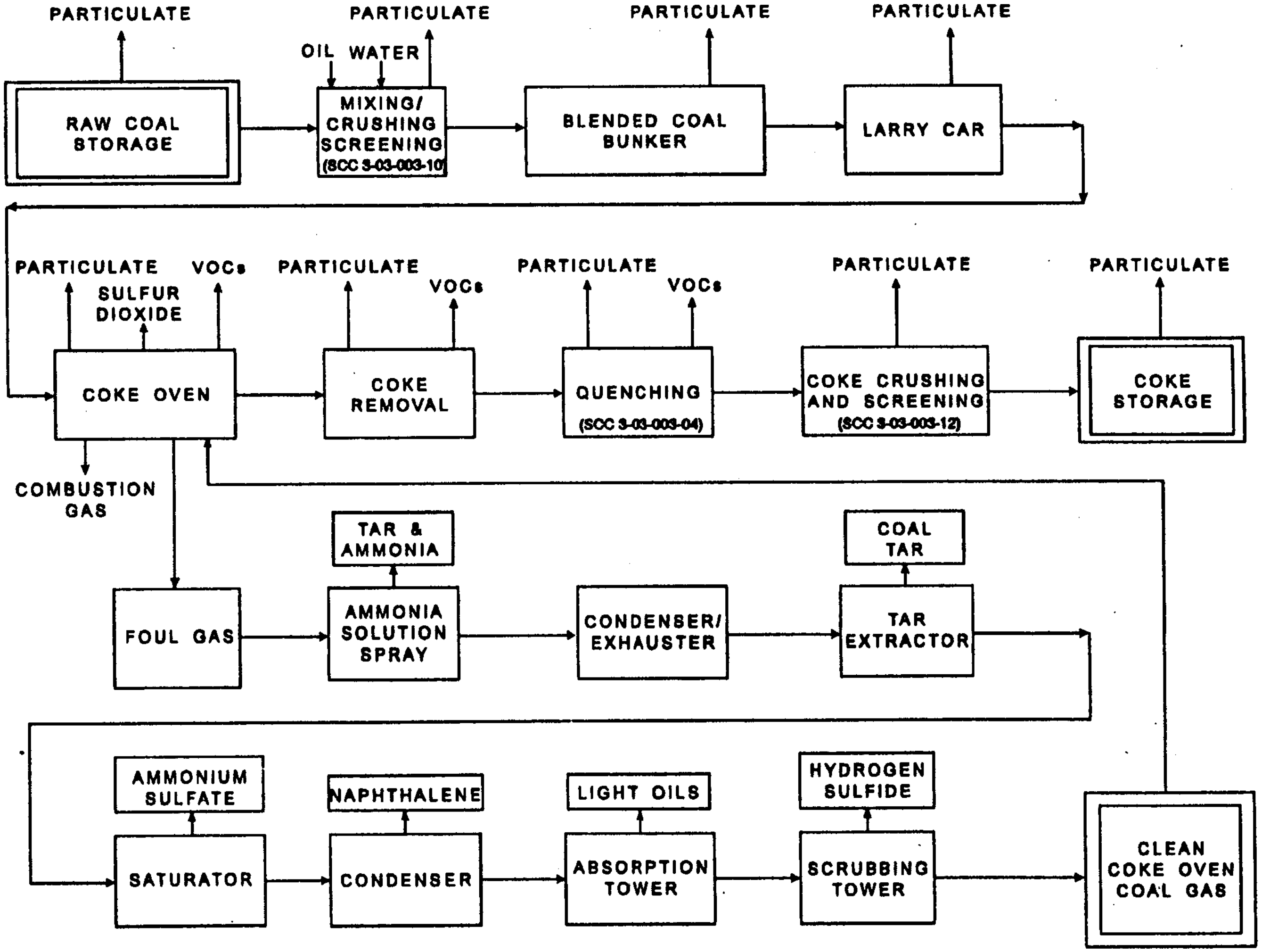

Figure 12.2-2. Flow diagram of coke manufacturing. VOC = volatile organic compound. (Source Classification Codes in parentheses.)

The blended coal mass is heated for 12 to 20 hours for metallurgical coke. Thermal energy from the walls of the coke chamber heats the coal mass by conduction from the sides to the middle of the coke chamber. During the coking process, the charge is in direct contact with the heated wall surfaces and develops into an aggregate "plastic zone". As additional thermal energy is absorbed, the plastic zone thickens and merges toward the middle of the charge. Volatile gases escape in front of the developing zone due to heat progression from the side walls. The maximum temperature attained at the center of the coke mass is usually 1100 to 1150°C (2000 to 2100°F). This distills all volatile matter from the coal mass and forms a high-quality metallurgical coke.

After coking is completed (no volatiles remain), the coke in the chamber is ready to be removed. Doors on both sides of the chamber are opened and a ram is inserted into the chamber. The coke is pushed out of the oven in less than 1 minute, through the coke guide and into a quench car. After the coke is pushed from the oven, the doors are cleaned and repositioned. The oven is then ready to receive another charge of coal.

The quench car carrying the hot coke moves along the battery tracks to a quench tower where approximately 1130 liters (L) of water per Mg of coke (270 gallons of water per ton) are sprayed onto the coke mass to cool it from about 1100 to 80°C (2000 to 180°F) and to prevent it from igniting. The quench car may rely on a movable hood to collect particulate emissions, or it may have a scrubber car attached. The car then discharges the coke onto a wharf to drain and continue cooling. Gates on the wharf are opened to allow the coke to fall onto a conveyor that carries it to the crushing and screening station. After sizing, coke is sent to the blast furnace or to storage.

The primary purpose of modern coke ovens is the production of quality coke for the iron and steel industry. The recovery of coal chemicals is an economical necessity, as they equal approximately 35 percent of the value of the coal.

To produce quality metallurgical coke, a high-temperature carbonization process is used. High-temperature carbonization, which takes place above 900°C (1650°F), involves chemical conversion of coal into a mostly gaseous product. Gaseous products from high-temperature carbonization consist of hydrogen, methane, ethylene, carbon monoxide, carbon dioxide, hydrogen sulfide, ammonia, and nitrogen. Liquid products include water, tar, and crude light oil. The coking process produces approximately 338,000 L of coke oven gas (COG) per megagram of coal charged (10,800 standard cubic feet of COG per ton).

During the coking cycle, volatile matter driven from the coal mass passes upward through cast iron "goosenecks" into a common horizontal steel pipe (called the collecting main), which connects all the ovens in series. This unpurified "foul" gas contains water vapor, tar, light oils, solid particulate of coal dust, heavy hydrocarbons, and complex carbon compounds. The condensable materials are removed from the exhaust gas to obtain purified coke oven gas.

As it leaves the coke chamber, coke oven coal gas is initially cleaned with a weak ammonia spray, which condenses some tar and ammonia from the gas. This liquid condensate flows down the collecting main until it reaches a settling tank. Collected ammonia is used in the weak ammonia spray, while the rest is pumped to an ammonia still. Collected coal tar is pumped to a storage tank and sold to tar distillers, or used as fuel.

The remaining gas is cooled as it passes through a condenser and then compressed by an exhauster. Any remaining coal tar is removed by a tar extractor, either by impingement against a metal surface or collection by an electrostatic precipitator (ESP). The gas still contains 75 percent of original ammonia and 95 percent of the original light oils. Ammonia is removed by passing the gas through a saturator containing a 5 to 10 percent solution of sulfuric acid. In the saturator, ammonia reacts with sulfuric acid to form ammonium sulfate. Ammonium sulfate is then crystallized and removed. The gas is further cooled, resulting in the condensation of naphthalene. The light oils are removed in an absorption tower containing water mixed with "straw oil" (a heavy fraction of petroleum). Straw oil acts as an absorbent for the light oils, and is later heated to release the light oils for recovery and refinement. The last cleaning step is the removal of hydrogen sulfide from the gas. This is normally done in a scrubbing tower containing a solution of ethanolamine (Girbotol), although several other methods have been used in the past. The clean coke oven coal gas is used as fuel for the coke ovens, other plant combustion processes, or sold.

12.2.3 Emissions And Controls

Particulate, VOCs, carbon monoxide and other emissions originate from several byproduct coking operations: (1) coal preparation, (2) coal preheating (if used), (3) coal charging, (4) oven leakage during the coking period, (5) coke removal, (6) hot coke quenching and (7) underfire combustion stacks. Gaseous emissions collected from the ovens during the coking process are subjected to various operations for separating ammonia, coke oven gas, tar, phenol, light oils (benzene, toluene, xylene), and pyridine. These unit operations are potential sources of VOC emissions. Small emissions may occur when transferring coal between conveyors or from conveyors to bunkers. Figure 12.2-2 portrays major emission points from a typical coke oven battery.

The emission factors available for coking operations for total particulate, sulfur dioxide, carbon monoxide, VOCs, nitrogen oxides, and ammonia are given in Tables 12.2-1 and 12.2-2. Tables 12.2-3 and 12.2-4 give size-specific emission factors for coking operations.

A few domestic plants preheat the coal to about 260°C (500°F) before charging, using a flash drying column heated by the combustion of coke oven gas or by natural gas. The air stream that conveys coal through the drying column usually passes through conventional wet scrubbers for particulate removal before discharging to the atmosphere. Leaks occasionally occur from charge lids and oven doors during pipeline charging due to the positive pressure. Emissions from the other methods are similar to conventional wet charging.

Oven charging can produce significant emissions of particulate matter and VOCs from coal decomposition if not properly controlled. Charging techniques can draw most charging emissions into the battery collecting main. Effective control requires that goosenecks and the collecting main passages be cleaned frequently to prevent obstructions.

During the coking cycle, VOC emissions from the thermal distillation process can occur through poorly sealed doors, charge lids, offtake caps, collecting main, and cracks that may develop in oven brickwork. Door leaks may be controlled by diligent door cleaning and maintenance, rebuilding doors, and, in some plants, by manual application of lute (seal) material. Charge lid and offtake leaks may be controlled by an effective patching and luting program. Pushing coke into the quench car is another major source of particulate emissions. If the coke mass is not fully coked, VOCs and combustion products will be emitted. Most facilities control pushing emissions by using mobile scrubber cars with hoods, shed enclosures evacuated to a gas cleaning device, or traveling hoods with a fixed duct leading to a stationary gas cleaner.

Coke quenching entrains particulate from the coke mass. In addition, dissolved solids from the quench water may become entrained in the steam plume rising from the tower. Trace organic compounds may also be present.

Table 12.2-1 (Metric Units). EMISSION FACTORS FOR COKE MANUFACTURING[a]

Type Of Operation	Particulate[b]	EMISSION FACTOR RATING	SO_2	EMISSION FACTOR RATING	CO[c]	EMISSION FACTOR RATING	VOC[c,d]	EMISSION FACTOR RATING	NO_x[c]	EMISSION FACTOR RATING	Ammonia[c]	EMISSION FACTOR RATING
Coal crushing (SCC 3-03-003-10)												
With cyclone	0.055	D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Coal preheating (SCC 3-03-003-13)												
Uncontrolled[e]	1.75	C	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With scrubber	0.125	C	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With wet ESP	0.006	C	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
Oven charging[f] (larry car) (SCC 3-03-003-02)												
Uncontrolled	0.24	E	0.01	D	0.3	D	1.25	D	0.015	D	0.01	D
With sequential charging	0.008	E	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With scrubber	0.007	E	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
Oven door leaks (SCC 3-03-003-08)												
Uncontrolled	0.27	D		D	0.3	D	0.75	D	0.005	D	0.03	D
Oven pushing (SCC 3-03-003-03)												
Uncontrolled	0.58	B	ND	NA	0.035	D	0.1	D	ND	NA	0.05	D
With ESP[g]	0.225	C	ND	NA	0.035	D	0.1	D	ND	NA	ND	NA
With venturi scrubber[h]	0.09	D	ND	NA	0.035	D	0.1	D	ND	NA	ND	NA
With baghouse[h]	0.045	D	ND	NA	0.035	D	0.1	D	ND	NA	ND	NA
With mobile scrubber car[j]	0.036	C	ND	NA	0.035	D	0.1	D	ND	NA	ND	NA
Quenching (SCC 3-03-003-04)												
Uncontrolled												
Dirty water[k]	2.62	D	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA
Clean water[m]	0.57	D	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA
With baffles												
Dirty water[k]	0.65	B	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA
Clean water[m]	0.27	B	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA

Table 12.2-1 (cont.).

Type Of Operation	Particulate[b]	EMISSION FACTOR RATING	SO_2	EMISSION FACTOR RATING	CO[c]	EMISSION FACTOR RATING	VOC[c,d]	EMISSION FACTOR RATING	NO_x[c]	EMISSION FACTOR RATING	Ammonia[c]	EMISSION FACTOR RATING
Combustion stack												
(SCC 3-03-003-17, for COG)												
(SCC 3-03-003-16, for BFG)												
Uncontrolled (raw COG)	0.234	A	2.0[n]	D	ND	NA	ND	NA	ND	NA	ND	NA
Uncontrolled (desulfurized COG)	0.234	A	0.14[p]	C	ND	NA	ND	NA	ND	NA	ND	NA
Uncontrolled (BFG)	0.085	A	0.54[q]	D	ND	NA	ND	NA	ND	NA	ND	NA
With ESP (BFG)	0.046	B	0.32[r]	C	ND	NA	ND	NA	ND	NA	ND	NA
With ESP (COG)	0.055	D	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With baghouse (COG)	0.055	D	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
Coke handling (SCC 3-03-003-12)												
With cyclone[s]	0.003	D	ND	NA	ND	NA	NA	NA	NA	NA	NA	NA

[a] Emission Factors are expressed in kg of pollutant/Mg of coke produced. SCC = Source Classification Code. NA = not applicable. ND = no data. BFG = blast furnace gas.

[b] Reference 1.

[c] Reference 23.

[d] Expressed as methane.

[e] Exhaust gas discharged from series of primary and secondary cyclones used to separate flash-dried coal from hot gas.

[f] Charged coal has not been dried.

[g] Emissions captured by coke side shed.

[h] Emissions captured by travelling hood.

[j] Emissions captured by quench car enclosure.

[k] Dirty water ≥5000 Mg/L total dissolved solids.

[m] Clean water ≤1500 Mg/L total dissolved solids.

[n] Reference 4. Factor for SO_2 is based on these representative conditions: (1) sulfur content of coal charged to oven is 0.8 weight %; (2) about 33 weight % of total sulfur in coal charged to oven is transferred to coke oven gas; (3) about 40% of coke oven gas is burned during underfiring operation, and about 60% is used in other operations where the rest of the SO_2 (3 kilograms/megagrams [6 lb/ton] of coal charged) is discharged; (4) gas used in underfiring has not been desulfurized.

[p] Reference 21, desulfurized COG.

[q] Reference 22.

[r] Reference 23.

[s] Defined as crushing and screening.

Table 12.2-2 (English Units). EMISSION FACTORS FOR COKE MANUFACTURING[a]

Type Of Operation	Particulate[b]	EMISSION FACTOR RATING	SO_2	EMISSION FACTOR RATING	CO[c]	EMISSION FACTOR RATING	VOC[c,d]	EMISSION FACTOR RATING	NO_x[c]	EMISSION FACTOR RATING	Ammonia[c]	EMISSION FACTOR RATING
Coal crushing (SCC 3-03-003-10)												
With cyclone	0.11	D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Coal preheating (SCC 3-03-003-13)												
Uncontrolled[e]	3.50	C	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With scrubber	0.25	C	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With wet ESP	0.012	C	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
Oven charging[f] (larry car) (SCC 3-03-003-02)												
Uncontrolled	0.48	E	0.02	D	0.6	D	2.5	D	0.03	D	0.02	D
With sequential charging	0.016	E	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With scrubber	0.014	E	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
Oven door leaks (SCC 3-03-003-08)												
Uncontrolled	0.54	D	ND	D	0.6	D	1.50	D	0.01	D	0.06	D
Oven pushing (SCC 3-03-003-03)												
Uncontrolled	1.15	B	ND	NA	0.07	D	0.2	D	ND	NA	0.1	D
With ESP[g]	0.45	C	ND	NA	0.07	D	0.2	D	ND	NA	ND	NA
With venturi scrubber[h]	0.18	D	ND	NA	0.07	D	0.2	D	ND	NA	ND	NA
With baghouse[h]	0.09	D	ND	NA	0.07	D	0.2	D	ND	NA	ND	NA
With mobile scrubber car	0.072	C	ND	NA	0.07	D	0.2	D	ND	NA	ND	NA
Quenching[j] (SCC 3-03-003-04)												
Uncontrolled												
Dirty water[k]	5.24	D	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA
Clean water[m]	1.13	D	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA
With baffles												
Dirty water[k]	1.30	B	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA
Clean water[m]	0.54	B	NA	NA	ND	NA	ND	NA	NA	NA	ND	NA

Table 12.2-2 (cont.).

Type Of Operation	Particulate[b]	EMISSION FACTOR RATING	SO_2	EMISSION FACTOR RATING	CO[c]	EMISSION FACTOR RATING	VOC[c,d]	EMISSION FACTOR RATING	NO_x[c]	EMISSION FACTOR RATING	Ammonia[c]	EMISSION FACTOR RATING
Combustion stack												
(SCC 3-03-003-17, for COG)												
(SCC 3-03-003-18, for BFG)												
Uncontrolled (raw COG)	0.47	A	4.0[n]	D	ND	NA	ND	NA	ND	NA	ND	NA
Uncontrolled (desulfurized COG)	0.47	A	0.28[p]	C	ND	NA	ND	NA	ND	NA	ND	NA
Uncontrolled (BFG)	0.17	A	1.08[q]	C	ND	NA	ND	NA	ND	NA	ND	NA
With ESP (BFG)	ND	B	0.64[r]	C	ND	NA	ND	NA	ND	NA	ND	NA
With ESP (COG)	0.091	D	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
With baghouse (COG)	0.11	D	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
Coke handling (SCC 3-03-003-12)												
With cyclone[s]	0.006	D	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

[a] Emission Factors are expressed in lb/ton of coke produced. SCC = Source Classification Code. NA = not applicable. ND = no data. BFG = blast furnace gas.

[b] Reference 1.

[c] References 23.

[d] Expressed as methane.

[e] Exhaust gas discharged from series of primary and secondary cyclones used to separate flash dried coal from hot gas.

[f] Charged coal has not been dried.

[g] Emissions captured by coke side shed.

[h] Emissions captured by travelling hood.

[j] Emissions captured by quench car enclosure.

[k] Dirty water ≥5000 mg/L total dissolved solids.

[m] Clean water ≤1500 mg/L total dissolved solids.

[n] Reference 4. Factor for SO_2 is based on these representative conditions: (1) sulfur content of coal charged to oven is 0.8 weight %; (2) about 33 weight % of total sulfur in coal charged to oven is transferred to coke oven gas; (3) about 40% of coke oven gas is burned during underfiring operation, and about 60% is used in other operations where the rest of the SO_2 (3 kilogram/megagram [6 pounds/ton] of coal charged) is discharged; (4) gas used in underfiring has not been desulfurized.

[p] Reference 21, desulfurized COG.

[q] Reference 22.

[r] Reference 23.

[s] Defined as crushing and screening.

Table 12.2-3. (Metric Units). SIZE-SPECIFIC EMISSION FACTORS FOR COKE MANUFACTURING[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Particle Size (μm)[b]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factors	Reference Source Number
Coal preheating (SCC 3-03-003-13) Uncontrolled	0.5	44	0.8	8
	1.0	48.5	0.8	
	2.0	55	1.0	
	2.5	59.5	1.0	
	5.0	79.5	1.4	
	10.0	97.5	1.7	
	15.0	99.9	1.7	
		100	1.7	
Controlled with venturi scrubber	0.5	78	0.10	8
	1.0	80	0.10	
	2.0	83	0.10	
	2.5	84	0.11	
	5.0	88	0.11	
	10.0	94	0.12	
	15.0	96.5	0.12	
		100	0.12	
Oven charging sequential or stage[c]	0.5	13.5	0.001	9
	1.0	25.2	0.002	
	2.0	33.6	0.003	
	2.5	39.1	0.003	
	5.0	45.8	0.004	
	10.0	48.9	0.004	
	15.0	49.0	0.004	
		100	0.008	
Coke pushing (SCC 3-03-003-03) Uncontrolled	0.5	3.1	0.02	10 - 15
	1.0	7.7	0.04	
	2.0	14.8	0.09	
	2.5	16.7	0.10	
	5.0	26.6	0.15	
	10.0	43.3	0.25	
	15.0	50.0	0.29	
		100	0.58	

Table 12.2-3 (cont.).

Process	Particle Size (μm)[b]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factors	Reference Source Number
Controlled with venturi scrubber	0.5	24	0.02	10, 12
	1.0	47	0.04	
	2.0	66.5	0.06	
	2.5	73.5	0.07	
	5.0	75	0.07	
	10.0	87	0.08	
	15.0	92	0.08	
		100	0.09	
Mobile scrubber car	1.0	28.0	0.010	16
	2.0	29.5	0.011	
	2.5	30.0	0.011	
	5.0	30.0	0.011	
	10.0	32.0	0.012	
	15.0	35.0	0.013	
		100	0.036	
Quenching (SCC 3-03-003-04)				17
Uncontrolled (dirty water)	1.0	13.8	0.36	
	2.5	19.3	0.51	
	5.0	21.4	0.56	
	10.0	22.8	0.60	
	15.0	26.4	0.69	
		100	2.62	
Uncontrolled (clean water)	1.0	4.0	0.02	17
	2.5	11.1	0.06	
	5.0	19.1	0.11	
	10.0	30.1	0.17	
	15.0	37.4	0.21	
		100	0.57	
With baffles (dirty water)	1.0	8.5	0.06	17
	2.5	20.4	0.13	
	5.0	24.8	0.16	
	10.0	32.3	0.21	
	15.0	49.8	0.32	
		100	0.65	

Table 12.2-3 (cont.).

Process	Particle Size (μm)[b]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factors	Reference Source Number
With baffles (clean water)	1.0	1.2	0.003	17
	2.5	6.0	0.02	
	5.0	7.0	0.02	
	10.0	9.8	0.03	
	15.0	15.1	0.04	
		100	0.27	
Combustion stack[d]				
Uncontrolled	1.0	77.4	0.18	18 - 20
	2.0	85.7	0.20	
	2.5	93.5	0.22	
	5.0	95.8	0.22	
	10.0	95.9	0.22	
	15.0	96	0.22	
		100	0.23	

[a] Emission factors are expressed in kg of pollutant/Mg of material processed.

[b] μm = micrometers

[c] EMISSION FACTOR RATING: E

[d] Material processed is coke.

Table 12.2-4. (English Units). SIZE-SPECIFIC EMISSION FACTORS FOR COKE MANUFACTURING[a]

EMISSION FACTOR RATING: D (except as noted)

Process	Particle Size (μm)[b]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factors	Reference Source Number
Coal preheating (SCC 3-03-003-13) Uncontrolled	0.5	44	0.8	8
	1.0	48.5	0.8	
	2.0	55	1.0	
	2.5	59.5	1.0	
	5.0	79.5	1.4	
	10.0	97.5	1.7	
	15.0	99.9	1.7	
		100	1.7	
Controlled with venturi scrubber	0.5	78	0.10	8
	1.0	80	0.10	
	2.0	83	0.10	
	2.5	84	0.11	
	5.0	88	0.11	
	10.0	94	0.12	
	15.0	96.5	0.12	
		100	0.12	
Oven charging sequential or stage[c]	0.5	13.5	0.001	9
	1.0	25.2	0.002	
	2.0	33.6	0.003	
	2.5	39.1	0.003	
	5.0	45.8	0.004	
	10.0	48.9	0.004	
	15.0	49.0	0.004	
		100	0.008	
Coke pushing (SCC 3-03-003-03) Uncontrolled	0.5	3.1	0.02	10 - 15
	1.0	7.7	0.04	
	2.0	14.8	0.09	
	2.5	16.7	0.10	
	5.0	26.6	0.15	
	10.0	43.3	0.25	
	15.0	50.0	0.29	
		100	0.58	

Table 12.2-4 (cont.).

Process	Particle Size (μm)[b]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factors	Reference Source Number
Controlled with venturi scrubber	0.5	24	0.02	10, 12
	1.0	47	0.04	
	2.0	66.5	0.06	
	2.5	73.5	0.07	
	5.0	75	0.07	
	10.0	87	0.08	
	15.0	92	0.08	
		100	0.09	
Mobile scrubber car	1.0	28.0	0.010	16
	2.0	29.5	0.011	
	2.5	30.0	0.011	
	5.0	30.0	0.011	
	10.0	32.0	0.012	
	15.0	35.0	0.013	
		100	0.036	
Quenching (SCC 3-03-003-04)				17
Uncontrolled (dirty water)	1.0	13.8	0.36	
	2.5	19.3	0.51	
	5.0	21.4	0.56	
	10.0	22.8	0.60	
	15.0	26.4	0.69	
		100	2.62	
Uncontrolled (clean water)	1.0	4.0	0.02	17
	2.5	11.1	0.06	
	5.0	19.1	0.11	
	10.0	30.1	0.17	
	15.0	37.4	0.21	
		100	0.57	
With baffles (dirty water)	1.0	8.5	0.06	17
	2.5	20.4	0.13	
	5.0	24.8	0.16	
	10.0	32.3	0.21	
	15.0	49.8	0.32	
		100	0.65	

Table 12.2-4 (cont.).

Process	Particle Size (μm)[b]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factors	Reference Source Number
With baffles (clean water)	1.0	1.2	0.003	17
	2.5	6.0	0.02	
	5.0	7.0	0.02	
	10.0	9.8	0.03	
	15.0	15.1	0.04	
		100	0.27	
Combustion stack[d]				
Uncontrolled	1.0	77.4	0.18	18 - 20
	2.0	85.7	0.20	
	2.5	93.5	0.22	
	5.0	95.8	0.22	
	10.0	95.9	0.22	
	15.0	96	0.22	
		100	0.23	

[a] Emission factors are expressed in lb of pollutant/ton of material processed.
[b] μm = micrometers.
[c] EMISSION FACTOR RATING: E
[d] Material processed is coke.

Combustion of gas in the battery flues produces emissions from the underfire or combustion stack. Sulfur dioxide emissions may also occur if the coke oven gas is not desulfurized. Coal fines may leak into the waste combustion gases if the oven wall brickwork is damaged. Conventional gas cleaning equipment, including electrostatic precipitators and fabric filters, have been installed on battery combustion stacks.

Fugitive particulate emissions are associated with material handling operations. These operations consist of unloading, storing, grinding and sizing of coal, screening, crushing, storing, and unloading of coke.

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12.3 Primary Copper Smelting

12.3.1 General[1]

Copper ore is produced in 13 states. In 1989, Arizona produced 60 percent of the total U. S. ore. Fourteen domestic mines accounted for more than 95 percent of the 1.45 megagrams (Mg) (1.6 millon tons) of ore produced in 1991.

Copper is produced in the U. S. primarily by pyrometallurgical smelting methods. Pyrometallurgical techniques use heat to separate copper from copper sulfide ore concentrates. Process steps include mining, concentration, roasting, smelting, converting, and finally fire and electrolytic refining.

12.3.2 Process Description[2-4]

Mining produces ores with less than 1 percent copper. Concentration is accomplished at the mine sites by crushing, grinding, and flotation purification, resulting in ore with 15 to 35 percent copper. A continuous process called floatation, which uses water, various flotation chemicals, and compressed air, separates the ore into fractions. Depending upon the chemicals used, some minerals float to the surface and are removed in a foam of air bubbles, while others sink and are reprocessed. Pine oils, cresylic acid, and long-chain alcohols are used for the flotation of copper ores. The flotation concentrates are then dewatered by clarification and filtration, resulting in 10 to 15 percent water, 25 percent sulfur, 25 percent iron, and varying quantities of arsenic, antimony, bismuth, cadmium, lead, selenium, magnesium, aluminum, cobalt, tin, nickel, tellurium, silver, gold, and palladium.

A typical pyrometallurgical copper smelting process, as illustrated in Figure 12.3-1, includes 4 steps: roasting, smelting, concentrating, and fire refining. Ore concentration is roasted to reduce impurities, including sulfur, antimony, arsenic, and lead. The roasted product, calcine, serves as a dried and heated charge for the smelting furnace. Smelting of roasted (calcine feed) or unroasted (green feed) ore concentrate produces matte, a molten mixture of copper sulfide (Cu_2S), iron sulfide (FeS), and some heavy metals. Converting the matte yields a high-grade "blister" copper, with 98.5 to 99.5 percent copper. Typically, blister copper is then fire-refined in an anode furnace, cast into "anodes", and sent to an electrolytic refinery for further impurity elimination.

Roasting is performed in copper smelters prior to charging reverberatory furnaces. In roasting, charge material of copper concentrate mixed with a siliceous flux (often a low-grade copper ore) is heated in air to about 650°C (1200°F), eliminating 20 to 50 percent of the sulfur as sulfur dioxide (SO_2). Portions of impurities such as antimony, arsenic, and lead are driven off, and some iron is converted to iron oxide. Roasters are either multiple hearth or fluidized bed; multiple hearth roasters accept moist concentrate, whereas fluidized bed roasters are fed finely ground material. Both roaster types have self-generating energy by the exothermic oxidation of hydrogen sulfide, shown in the reaction below.

$$H_2S + O_2 \rightarrow SO_2 + H_2O + \text{Thermal energy} \qquad (1)$$

In the smelting process, either hot calcine from the roaster or raw unroasted concentrate is melted with siliceous flux in a smelting furnace to produce copper matte. The required heat comes from partial oxidation of the sulfide charge and from burning external fuel. Most of the iron and

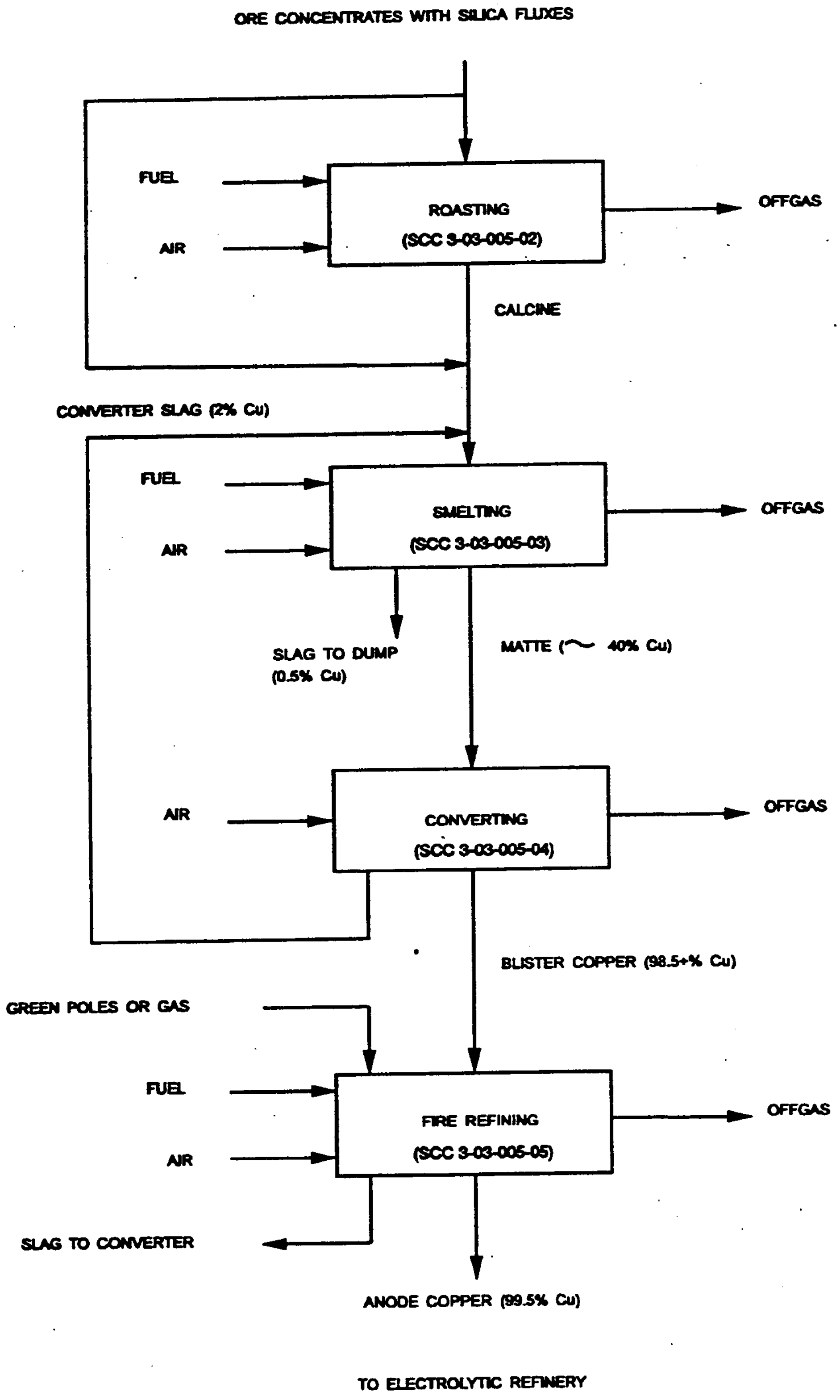

Figure 12.3-1. Typical primary copper smelter process.
(Source Classification Codes in parentheses.)

some of the impurities in the charge oxidize with the fluxes to form a slag on top of the molten bath, which is periodically removed and discarded. Copper matte remains in the furnace until tapped. Matte ranges from 35 to 65 percent copper, with 45 percent the most common. The copper content percentage is referred to as the matte grade. The 4 smelting furnace technologies used in the U. S. are reverberatory, electric, Noranda, and flash.

The reverberatory furnace smelting operation is a continuous process, with frequent charging and periodic tapping of matte, as well as skimming slag. Heat is supplied by natural gas, with conversion to oil during gas restrictions. Furnace temperature may exceed 1500°C (2730°F), with the heat being transmitted by radiation from the burner flame, furnace walls, and roof into the charge of roasted and unroasted materials mixed with flux. Stable copper sulfide (Cu_2S) and stable FeS form the matte with excess sulfur leaving as sulfur dioxide.

Electric arc furnace smelters generate heat with carbon electrodes that are lowered through the furnace roof and submerged in the slag layer of the molten bath. The feed consists of dried concentrates or calcine. The chemical and physical changes occurring in the molten bath are similar to those occurring in the molten bath of a reverberatory furnace. The matte and slag tapping practices are also similar.

The Noranda process, as originally designed, allowed the continuous production of blister copper in a single vessel by effectively combining roasting, smelting, and converting into 1 operation. Metallurgical problems, however, led to the operation of these reactors for the production of copper matte. The Noranda process uses heat generated by the exothermic oxidation of hydrogen sulfide. Additional heat is supplied by oil burners or by coal mixed with the ore concentrates. Figure 12.3-2 illustrates the Noranda process reactor.

Flash furnace smelting combines the operations of roasting and smelting to produce a high-grade copper matte from concentrates and flux. In flash smelting, dried ore concentrates and finely ground fluxes are injected together with oxygen and preheated air (or a mixture of both), into a furnace maintained at approximately 1000°C (1830°F). As with the Noranda process reactor, and in contrast to reverberatory and electric furnaces, flash furnaces use the heat generated from partial oxidation of their sulfide charge to provide much or all of the required heat.

Slag produced by flash furnace operations contains significantly higher amounts of copper than reverberatory or electric furnaces. Flash furnace slag is treated in a slag cleaning furnace with coke or iron sulfide. Because copper has a higher affinity for sulfur than oxygen, the copper in the slag (as copper oxide) is converted to copper sulfide. The copper sulfide is removed and the remaining slag is discarded.

Converting produces blister copper by eliminating the remaining iron and sulfur present in the matte. All but one U. S. smelter uses Pierce-Smith converters, which are refractory-lined cylindrical steel shells mounted on trunnions at either end, and rotated about the major axis for charging and pouring. An opening in the center of the converter functions as a mouth through which molten matte, siliceous flux, and scrap copper are charged and gaseous products are vented. Air, or oxygen-rich air, is blown through the molten matte. Iron sulfide is oxidized to form iron oxide (FeO) and SO_2. Blowing and slag skimming continue until an adequate amount of relatively pure Cu_2S, called "white metal", accumulates in the bottom of the converter. A final air blast ("final blow") oxidizes the copper sulfide to SO_2, and blister copper forms, containing 98 to 99 percent coppers. The blister copper is removed from the converter for subsequent refining. The SO_2 produced throughout the operation is vented to pollution control devices.

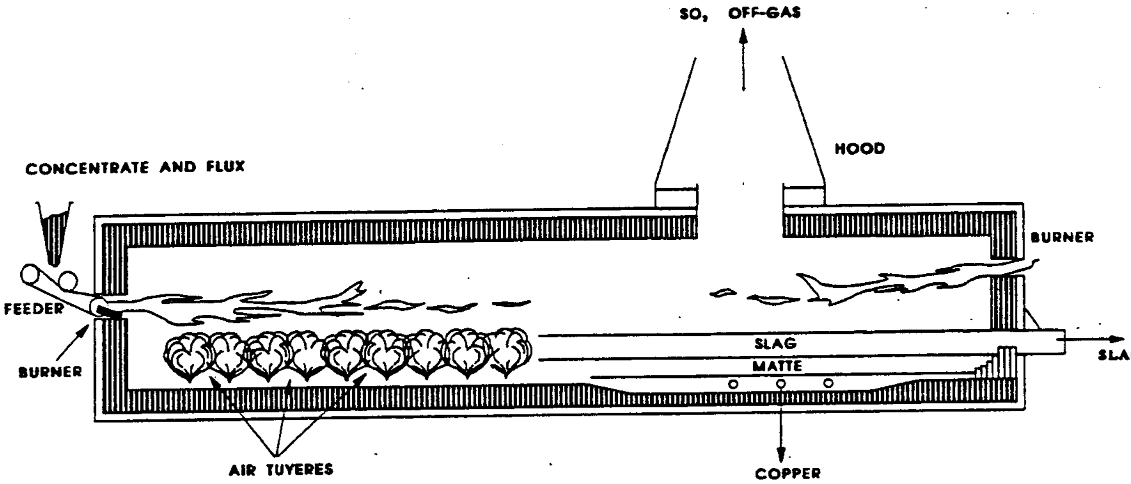

Figure 12.3-2. Schematic of the Noranda process reactor.

One domestic smelter uses Hoboken converters. The Hoboken converter, unlike the Pierce-Smith converter, is fitted with an inverted u-shaped side flue at one end to siphon gases from the interior of the converter directly to an offgas collection system. The siphon results in a slight vacuum at the converter mouth.

Impurities in blister copper may include gold, silver, antimony, arsenic, bismuth, iron, lead, nickel, selenium, sulfur, tellurium, and zinc. Fire refining and electrolytic refining are used to purify blister copper even further. In fire refining, blister copper is usually mixed with flux and charged into the furnace, which is maintained at 1100°C (2010°F). Air is blown through the molten mixture to oxidize the copper and any remaining impurities. The impurities are removed as slag. The remaining copper oxide is then subjected to a reducing atmosphere to form purer copper. The fire-refined copper is then cast into anodes for even further purification by electrolytic refining.

Electrolytic refining separates copper from impurities by electrolysis in a solution containing copper sulfate (Cu_2SO_4) and sulfuric acid (H_2SO_4). The copper anode is dissolved and deposited at the cathode. As the copper anode dissolves, metallic impurities precipitate and form a sludge. Cathode copper, 99.95 to 99.96 percent pure, is then cast into bars, ingots, or slabs.

12.3.3 Emissions And Controls

Emissions from primary copper smelters are principally particulate matter and sulfur oxides (SO_x). Emissions are generated from the roasters, smelting furnaces, and converters. Fugitive emissions are generated during material handling operations.

Roasters, smelting furnaces, and converters are sources of both particulate matter and SO_x. Copper and iron oxides are the primary constituents of the particulate matter, but other oxides, such as arsenic, antimony, cadmium, lead, mercury, and zinc, may also be present, along with metallic sulfates and sulfuric acid mist. Fuel combustion products also contribute to the particulate emissions from multiple hearth roasters and reverberatory furnaces.

Gas effluent from roasters usually are sent to an electrostatic precipitator (ESP) or spray chamber/ESP system or are combined with smelter furnace gas effluent before particulate collection. Overall, the hot ESPs remove only 20 to 80 percent of the total particulate (condensed and vapor) present in the gas. Cold ESPs may remove more than 95 percent of the total particulate present in the gas. Particulate collection systems for smelting furnaces are similar to those for roasters. Reverberatory furnace off-gases are usually routed through waste heat boilers and low-velocity balloon flues to recover large particles and heat, then are routed through an ESP or spray chamber/ESP system.

In the standard Pierce-Smith converter, flue gases are captured during the blowing phase by the primary hood over the converter mouth. To prevent the hood from binding to the converter with splashing molten metal, a gap exists between the hood and the vessel. During charging and pouring operations, significant fugitives may be emitted when the hood is removed to allow crane access. Converter off-gases are treated in ESPs to remove particulate matter, and in sulfuric acid plants to remove SO_2.

Remaining smelter operations process material containing very little sulfur, resulting in insignificant SO_2 emissions. Particulate may be emitted from fire refining operations. Electrolytic refining does not produce emissions unless the associated sulfuric acid tanks are open to the atmosphere. Crushing and grinding systems used in ore, flux, and slag processing also contribute to fugitive dust problems.

Control of SO_2 from smelters is commonly performed in a sulfuric acid plant. Use of a sulfuric acid plant to treat copper smelter effluent gas streams requires that particulate-free gas containing minimum SO_2 concentrations, usually of at least 3 percent SO_2, be maintained. Table 12.3-1 shows typical average SO_2 concentrations from the various smelter units. Additional information on the operation of sulfuric acid plants is discussed in Section 8.10 of this document. Sulfuric acid plants also treat converter gas effluent. Some multiple hearth and all fluidized bed roasters use sulfuric acid plants. Reverberatory furnace effluent contains minimal SO_2 and is usually released directly to the atmosphere with no SO_2 reduction. Effluent from the other types of smelter furnaces contain higher concentrations of SO_2 and are treated in sulfuric acid plants before being vented. Single-contact sulfuric acid plants achieve 92.5 to 98 percent conversion of plant effluent gas. Double-contact acid plants collect from 98 to more than 99 percent of the SO_2, emitting about 500 parts per million (ppm) SO_2. Absorption of the SO_2 in dimethylaniline (DMA) solution has also been used in domestic smelters to produce liquid SO_2.

Particular emissions vary depending upon configuration of the smelting equipment. Tables 12.3-2 and 12.3-3 give the emission factors for various smelter configurations, and Tables 12.3-4, 12.3-5, 12.3-6, 12.3-7, 12.3-8, and 12.3-9 give size-specific emission factors for those copper production processes where information is available.

Roasting, smelting, converting, fire refining, and slag cleaning are potential fugitive emission sources. Tables 12.3-10 and 12.3-11 present fugitive emission factors for these sources. Tables 12.3-12, 12.3-13, 12.3-14, 12.3-15, 12.3-16, and 12.3-17 present cumulative size-specific particulate emission factors for fugitive emissions from reverberatory furnace matte tapping, slag tapping, and converter slag and copper blow operations. The actual quantities of emissions from these sources depend on the type and condition of the equipment and on the smelter operating techniques.

Fugitive emissions are generated during the discharge and transfer of hot calcine from multiple hearth roasters. Fluid bed roasting is a closed loop operation, and has negligible fugitive emissions. Matte tapping and slag skimming operations are sources of fugitive emissions from smelting furnaces. Fugitive emissions can also result from charging of a smelting furnace or from leaks, depending upon the furnace type and condition.

Table 12.3-1. TYPICAL SULFUR DIOXIDE CONCENTRATIONS IN OFFGAS FROM PRIMARY COPPER SMELTING SOURCES[a]

Unit	SO_2 Concentration (Volume %)
Multiple hearth roaster (SCC 3-03-005-02)	1.5 - 3
Fluidized bed roaster (SCC 3-03-005-09)	10 - 12
Reverberatory furnace (SCC 3-03-005-03)	0.5 - 1.5
Electric arc furnace (SCC 3-03-005-10)	4 - 8
Flash smelting furnace (SCC 3-03-005-12)	10 - 70
Continuous smelting furnace (SCC 3-03-005-36)	5 - 15
Pierce-Smith converter (SCC 3-03-005-37)	4 - 7
Hoboken converter (SCC 3-03-005-38)	8
Single contact H_2SO_4 plant (SCC 3-03-005-39)	0.2 - 0.26
Double contact H_2SO_4 plant (SCC 3-03-005-40)	0.05

[a] SCC = Source Classification Code.

Each of the various converter stages (charging, blowing, slag skimming, blister pouring, and holding) is a potential source of fugitive emissions. During blowing, the converter mouth is in the stack (a close-fitting primary hood is over the mouth to capture offgases). Fugitive emissions escape from the hood. During charging, skimming, and pouring, the converter mouth is out of the stack (the converter mouth is rolled out of its vertical position, and the primary hood is isolated). Fugitive emissions are discharged during roll out.

Table 12.3-2. (Metric Units). EMISSION FACTORS FOR PRIMARY COPPER SMELTERS[a,b]

Configuration[c]	Process	Particulate	EMISSION FACTOR RATING	Sulfur Dioxide[d]	EMISSION FACTOR RATING	References
Reverberatory furnace (RF) followed by converter (C) (SCC 3-03-005-23)	RF	25	B	160	B	4-10
	C	18	B	370	B	9,11-15
Multiple hearth roaster (MHR) followed by reverberatory furnace (RF) and converter (C) (SCC 3-03-005-29)	MHR	22	B	140	B	4-5,16-17
	RF	25	B	90	B	4-9,18-19
	C	18	B	300	B	8,11-13
Fluid bed roaster (FBR) followed by reverberatory furnace (RF) and converter (C) (SCC 3-03-005-25)	FBR	ND	ND	180	B	20
	RF	25	B	90	B	—[e]
	C	18	B	270	B	—[e]
Concentrate dryer (CD) followed by electric furnace (EF) and converter (C) (SCC 3-03-005-27)	CD	5	B	0.5	B	21-22
	EF	50	B	120	B	15
	C	18	B	410	B	8,11-13,15

Table 12.3-2 (cont.).

Configuration[c]	Process	Particulate	EMISSION FACTOR RATING	Sulfur Dioxide[d]	EMISSION FACTOR RATING	References
Fluid bed roaster (FBR) followed by electric furnace (EF) and converter (C) (SCC 3-03-005-30)	FBR	ND	ND	180	B	20
	EF	50	B	45	B	15,23
	C	18	B	300	B	3
Concentrate dryer (CD) followed by flash furnace (FF), cleaning furnace (SS) and converter (C) (SCC 3-03-005-26)	CD	5	B	0.5	B	21-22
	FF	70	B	410	B	24
	SS[f]	5	B	0.5	B	22
	C[e]	ND[g]	ND[g]	120	B	22
Concentrate dryer (CD) followed by Noranda reactors (NR) and converter (C) (SCC 3-03-005-41)	CD	5	B	0.5	B	21-22
	NR	ND	ND	ND	ND	—
	C	ND	ND	ND	ND	—

[a] Expressed as kg of pollutant/Mg of concentrated ore processed by the smelter. Approximately 4 unit weights of concentrate are required to produce 1 unit weight of blister copper. SCC = Source Classification Code. ND = no data.

[b] For particulate matter removal, gaseous effluents from roasters, smelting furnaces, and converters usually are treated in hot ESPs at 200 to 340°C (400 to 650°F) or in cold ESPs with gases cooled to about 120°C (250°F before) ESP. Particulate emissions from copper smelters contain volatile metallic oxides that remain in vapor form at higher temperatures, around 120°C (250°F). Therefore, overall particulate removal in hot ESPs may range 20 to 80% and in cold ESPs may be 99%. Converter gas effluents and, at some smelters, roaster gas effluents are treated in single contact acid plants (SCAP) or double contact acid plants (DCAP) for SO_2 removal. Typical SCAPs are about 96% efficient, and DCAPs are up to 99.8% efficient in SO_2 removal. They also remove over 99% of particulate matter. Noranda and flash furnace offgases are also processed through acid plants and are subject to the same collection efficiencies as cited for converters and some roasters.

[c] In addition to sources indicated, each smelter configuration contains fire refining anode furnaces after the converters. Anode furnaces emit negligible SO_2. No particulate emission data are available for anode furnaces.

[d] Factors for all configurations except reverberatory furnaces followed by converters have been developed by normalizing test data for several smelters to represent 30% sulfur content in concentrated ore.

[e] Based on the test data for the configuration multiple hearth roaster followed by reverberatory furnaces and converters.

[f] Used to recover copper from furnace slag and converter slag.

[g] Since converters at flash furnace and Noranda furnace smelters treat high copper content matte, converter particulate emissions from flash furnace smelters are expected to be lower than those from conventional smelters with multiple hearth roasters, reverberatory furnaces, and converters.

Table 12.3-3 (English Units). EMISSION FACTORS FOR PRIMARY COPPER SMELTERS[a,b]

Configuration[c]	Process	Particulate	EMISSION FACTOR RATING	Sulfur dioxide[d]	EMISSION FACTOR RATING	References
Reverberatory furnace (RF) followed by converter (C) (SCC 3-03-005-23)	RF	50	B	320	B	4-10
	C	36	B	740	B	9,11-15
Multiple hearth roaster (MHR) followed by reverberatory furnace (RF) and converter (C) (SCC 3-03-005-29)	MHR	45	B	280	B	4-5,16-17
	RF	50	B	180	B	4-9,18-19
	C	36	B	600	B	8,11-13
Fluid bed roaster (FBR) followed by reverberatory furnace (RF) and converter (C) (SCC 3-03-005-25)	FBR	ND	ND	360	B	20
	RF	50	B	180	B	—[e]
	C	36	B	540	B	—[e]
Concentrate dryer (CD) followed by electric furnace (EF) and converter (C) (SCC 3-03-005-27)	CD	10	B	1	B	21-22
	EF	100	B	240	B	15
	C	36	B	820	B	8,11-13,15
Fluid bed roaster (FBR) followed by electric furnace (EF) and converter (C) (SCC 3-03-005-30)	FBR	ND	ND	360	B	20
	EF	100	B	90	B	15,23
	C	36	B	600	B	3
Concentrate dryer (CD) followed by flash furnace (FF), cleaning furnace (SS) and converter (C) (SCC 3-03-005-26)	CD	10	B	1	B	21-22
	FF	140	B	820	B	24
	SS[f]	10	B	1	B	22
	C[e]	ND[g]	ND[g]	240	B	22
Concentrate dryer (CD) followed by Noranda reactors (NR) and converter (C) (SCC 3-03-005-41)	CD	10	B	1	B	21-22
	NR	ND	ND	ND	ND	—
	C	ND	ND	ND	ND	—

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[a] Expressed as lb of pollutant/ton of concentrated ore processed by the smelter. Approximately 4 unit weights of concentrate are required to produce 1 unit weight of blister copper. SCC = Source Classification Code. ND = no data.

[b] For particulate matter removal, gaseous effluents from roasters, smelting furnaces and converters usually are treated in hot ESPs at 200 to 340°C (400 to 650°F) or in cold ESPs with gases cooled to about 120°C (250°F before) ESP. Particulate emissions from copper smelters contain volatile metallic oxides which remain in vapor form at higher temperatures, around 120°C (250°F). Therefore, overall particulate removal in hot ESPs may range 20 to 80% and in cold ESPs may be 99%. Converter gas effluents and, at some smelters, roaster gas effluents are treated in single contact acid plants (SCAPs) or double contact acid plants (DCAPs) for SO_2 removal. Typical SCAPs are about 96% efficient, and DCAPs are up to 99.8% efficient in SO_2 removal. They also remove over 99% of particulate matter. Noranda and flash furnace offgases are also processed through acid plants and are subject to the same collection efficiencies as cited for converters and some roasters.

[c] In addition to sources indicated, each smelter configuration contains fire refining anode furnaces after the converters. Anode furnaces emit negligible SO_2. No particulate emission data are available for anode furnaces.

Table 12.3-3 (cont.).

[d] Factors for all configurations except reverberatory furnaces followed by converters have been developed by normalizing test data for several smelters to represent 30% sulfur content in concentrated ore.

[e] Based on the test data for the configuration multiple hearth roaster followed by reverberatory furnaces and converters.

[f] Used to recover copper from furnaces slag and converter slag.

[g] Since converters at flash furnaces and Noranda furnace smelters treat high copper content matte, converter particulate emissions from flash furnace smelters are expected to be lower than those from conventional smelters with multiple hearth roasters, reverberatory furnaces, and converters.

Table 12.3-4 (Metric Units). PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR MULTIPLE HEARTH ROASTER AND REVERBERATORY SMELTER OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Emission Factors	
	Uncontrolled	ESP Controlled[c]
15	47	0.47
10	47	0.47
5	47	0.46
2.5	46	0.40
1.25	31	0.36
0.625	12	0.29

[a] Reference 26. Expressed as kg of pollutant/Mg of concentrated ore processed by the smelter.
[b] Expressed as aerodynamic equivalent diameter.
[c] Nominal particulate removal efficiency is 99%.

Table 12.3-5 (English Units). PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR MULTIPLE HEARTH ROASTER AND REVERBERATORY SMELTER OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Emission Factors	
	Uncontrolled	ESP Controlled[c]
15	95	0.95
10	94	0.94
5	93	0.93
2.5	80	0.80
1.25	72	0.72
0.625	59	0.59

[a] Reference 26. Expressed as lb of pollutant/ton of concentrated ore processed by the smelter.
[b] Expressed as aerodynamic equivalent diameter.
[c] Nominal particulate removal efficiency is 99%.

Table 12.3-6 (Metric Units). SIZE-SPECIFIC EMISSION FACTORS FOR REVERBERATORY SMELTER OPERATIONS[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Emission Factors	
	Uncontrolled	ESP Controlled[c]
15	NR	0.21
10	6.8	0.20
5	5.8	0.18
2.5	5.3	0.14
1.25	4.0	0.10
0.625	2.3	0.08

[a] Reference 26. Expressed as kg of pollutant/Mg of concentrated ore processed by the smelter. NR = not reported because of excessive extrapolation.

[b] Expressed as aerodynamic equivalent diameter.

[c] Nominal particulate removal efficiency is 99%.

Table 12.3-7 (English Units). SIZE-SPECIFIC EMISSION FACTORS FOR REVERBERATORY SMELTER OPERATIONS[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Emission Factors	
	Uncontrolled	ESP Controlled[c]
15	NR	0.42
10	13.6	0.40
5	11.6	0.36
2.5	10.6	0.28
1.25	8.0	0.20
0.625	4.6	0.16

[a] Reference 26. Expressed as lb of pollutant/ton of concentrated ore processed by the smelter. NR = not reported because of excessive extrapolation.

[b] Expressed as aerodynamic equivalent diameter.

[c] Nominal particulate removal efficiency is 99%.

Table 12.3-8 (Metric Units). SIZE-SPECIFIC EMISSION FACTORS FOR COPPER CONVERTER OPERATIONS[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Emission Factors	
	Uncontrolled	ESP Controlled[c]
15	NR	0.18
10	10.6	0.17
5	5.8	0.13
2.5	2.2	0.10
1.25	0.5	0.08
0.625	0.2	0.05

[a] Reference 26. Expressed as kg of pollutant/Mg of concentrated ore processed by the smelter. NR = not reported because of excessive extrapolation.

[b] Expressed as aerodynamic equivalent diameter.

[c] Nominal particulate removal efficiency is 99%.

Table 12.3-9 (English Units). SIZE-SPECIFIC EMISSION FACTORS FOR REVERBERATORY SMELTER OPERATIONS[a]

EMISSION FACTOR RATING: E

Particle Size[b] (μm)	Cumulative Emission Factors	
	Uncontrolled	ESP Controlled[c]
15	NR	0.36
10	21.2	0.36
5	11.5	0.26
2.5	4.3	0.20
1.25	1.1	0.15
0.625	0.4	0.11

[a] Reference 26. Expressed as lb of pollutant/ton of concentrated ore processed by the smelter. NR = not reported because of excessive extrapolation.

[b] Expressed as aerodynamic equivalent diameter.

[c] Nominal particulate removal efficiency is 99%.

Table 12.3-10 (Metric Units). FUGITIVE EMISSION FACTORS FOR PRIMARY COPPER SMELTERS[a]

EMISSION FACTOR RATING: B

Source Of Emission	Particulate	SO_2
Roaster calcine discharge (SCC 3-03-005-13)	1.3	0.5
Smelting furnace[b] (SCC 3-03-005-14)	0.2	2
Converter (SCC 3-03-005-15)	2.2	65
Converter slag return (SCC 3-03-005-18)	ND	0.05
Anode refining furnace (SCC 3-03-005-16)	0.25	0.05
Slag cleaning furnace[c] (SCC 3-03-005-17)	4	3

[a] References 17,23,26-33. Expressed as mass kg of pollutant/Mg of concentrated ore processed by the smelter. Approximately 4 unit weights of concentrate are required to produce 1 unit weight of copper metal. Factors for flash furnace smelters and Noranda furnace smelters may be lower than reported values. SCC = Source Classification Code. ND = no data.

[b] Includes fugitive emissions from matte tapping and slag skimming operations. About 50% of fugitive particulate emissions and about 90% of total SO_2 emissions are from matte tapping operations, with remainder from slag skimming.

[c] Used to treat slags from smelting furnaces and converters at the flash furnace smelter.

Table 12.3-11 (English Units). FUGITIVE EMISSION FACTORS FOR PRIMARY COPPER SMELTERS[a]

EMISSION FACTOR RATING: B

Source Of Emission	Particulate	SO_2
Roaster calcine discharge (SCC 3-03-005-13)	2.6	1
Smelting furnace[b] (SCC 3-03-005-14)	0.4	4
Converter (SCC 3-03-005-15)	4.4	130
Converter slag return (SCC 3-03-005-18)	ND	0.1
Anode refining furnace (SCC 3-03-005-16)	0.5	0.1
Slag cleaning furnace[c] (SCC 3-03-005-17)	8	6

[a] References 17, 23, 26-33. Expressed as mass lb of pollutant/ton of concentrated ore processed by the smelter. Approximately 4 unit weights of concentrate are required to produce 1 unit weight of copper metal. Factors for flash furnace smelters and Noranda furnace smelters may be lower than reported values. SCC = Source Classification Code. ND = no data.

[b] Includes fugitive emissions from matte tapping and slag skimming operations. About 50% of fugitive particulate emissions and about 90% of total SO_2 emissions are from matte tapping operations, with remainder from slag skimming.

[c] Used to treat slags from smelting furnaces and converters at the flash furnace smelter.

Table 12.3-12 (Metric Units). UNCONTROLLED PARTICLE SIZE AND SIZE-SPECIFIC EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM REVERBERATORY FURNACE MATTE TAPPING OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factors
15	76	0.076
10	74	0.074
5	72	0.072
2.5	69	0.069
1.25	67	0.067
0.625	65	0.065

[a] Reference 26. Expressed as kg of pollutant/Mg of concentrated ore processed by the smelter.
[b] Expressed as aerodynamic equivalent diameter.

Table 12.3-13 (English Units). UNCONTROLLED PARTICLE SIZE AND SIZE SPECIFIC EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM REVERBERATORY FURNACE MATTE TAPPING OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factors
15	76	0.152
10	74	0.148
5	72	0.144
2.5	69	0.138
1.25	67	0.134
0.625	65	0.130

[a] Reference 26. Expressed as lb of pollutant/ton of concentrated ore processed by the smelter.
[b] Expressed as aerodynamic equivalent diameter.

Table 12.3-14 (Metric Units). PARTICLE SIZE AND SIZE-SPECIFIC EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM REVERBERATORY FURNACE SLAG TAPPING OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factors
15	33	0.033
10	28	0.028
5	25	0.025
2.5	22	0.022
1.25	20	0.020
0.625	17	0.017

[a] Reference 26. Expressed as kg of pollutant/Mg of concentrated ore processed by the smelter.
[b] Expressed as aerodynamic equivalent diameter.

Table 12.3-15 (English Units). PARTICLE SIZE AND SIZE-SPECIFIC EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM REVERBERATORY FURNACE SLAG TAPPING OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factors
15	33	0.066
10	28	0.056
5	25	0.050
2.5	22	0.044
1.25	20	0.040
0.625	17	0.034

[a] Reference 26. Expressed as lb of pollutant/ton of concentrated ore processed by the smelter.
[b] Expressed as aerodynamic equivalent diameter.

Table 12.3-16 (Metric Units). PARTICLE SIZE AND SIZE-SPECIFIC EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM CONVERTER SLAG AND COPPER BLOW OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factors
15	98	2.2
10	96	2.1
5	87	1.9
2.5	60	1.3
1.25	47	1.0
0.625	38	0.8

[a] Reference 26. Expressed as kg of pollutant/Mg weight of concentrated ore processed by the smelter.

[b] Expressed as aerodynamic equivalent diameter.

Table 12.3-17 (English Units). PARTICLE SIZE AND SIZE-SPECIFIC EMISSION FACTORS FOR FUGITIVE EMISSIONS FROM CONVERTER SLAG AND COPPER BLOW OPERATIONS[a]

EMISSION FACTOR RATING: D

Particle Size[b] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Emission Factors
15	98	4.3
10	96	4.2
5	87	3.8
2.5	60	2.6
1.25	47	2.1
0.625	38	1.7

[a] Reference 26. Expressed as lb of pollutant/ton weight of concentrated ore processed by the smelter.

[b] Expressed as aerodynamic equivalent diameter.

Table 12.3-18 (Metric Units). LEAD EMISSION FACTORS FOR PRIMARY COPPER SMELTERS[a]

Operation	EMISSION FACTOR[b]	EMISSION FACTOR RATING
Roasting[c] (SCC 3-03-005-02)	0.075	C
Smelting[d] (SCC 3-03-005-03)	0.036	C
Converting[e] (SCC 3-03-005-04)	0.13	C
Refining (SCC 3-03-005-05)	ND	ND

[a] Reference 34. Expressed as kg of pollutant/Mg of concentrated ore processed by smelter. Approximately 4 unit weights of concentrate are required to produce 1 unit weights of copper metal. Based on test data for several smelters with 0.1 to 0.4% lead in feed throughput. SCC = Source Classification Code. ND = no data.

[b] For process and fugitive emissions totals.

[c] Based on test data on multihearth roasters. Includes total of process emissions and calcine transfer fugitive emissions. The latter are about 10% of total process and fugitive emissions.

[d] Based on test data on reverberatory furnaces. Includes total process emissions and fugitive emissions from matte tapping and slag skimming operations. Fugitive emissions from matte tapping and slag skimming operations amount to about 35% and 2%, respectively.

[e] Includes total of process and fugitive emissions. Fugitives constitute about 50% of total.

Table 12.3-19 (English Units). LEAD EMISSION FACTORS FOR PRIMARY COPPER SMELTERS[a]

Operation	EMISSION FACTOR[b]	EMISSION FACTOR RATING
Roasting[c] (SCC 3-03-005-02)	0.15	C
Smelting[d] (SCC 3-03-005-03)	0.072	C
Converting[e] (SCC 3-03-005-04)	0.27	C
Refining (SCC 3-03-005-05)	ND	ND

[a] Reference 34. Expressed as lb of pollutant/ton of concentrated ore processed by smelter. Approximately 4 unit weights of concentrate are required to produce 1 unit weights of copper metal. Based on test data for several smelters with 0.1 to 0.4% lead in feed throughput. SCC = Source Classification Code. ND = no data.

[b] For process and fugitive emissions totals.

[c] Based on test data on multihearth roasters. Includes total of process emissions and calcine transfer Fugitive emissions. The latter are about 10% of total process and fugitive emissions.

[d] Based on test data on reverberatory furnaces. Includes total process emissions and fugitive emissions from matte tapping and slag skimming operations. Fugitive emissions from matte tapping and slag skimming operations amount to about 35% and 2%, respectively.

[e] Includes total of process and fugitive emissions. Fugitives constitute about 50% of total.

Occasionally slag or blister copper may not be transferred immediately to the converters from the smelting furnace. This holding stage may occur for several reasons, including insufficient matte in the smelting furnace, unavailability of a crane, and others. Under these conditions, the converter is rolled out of its vertical position and remains in a holding position and fugitive emissions may result.

At primary copper smelters, both process emissions and fugitive particulate from various pieces of equipment contain oxides of many inorganic elements, including lead. The lead content of particulate emissions depends upon both the lead content of the smelter feed and the process offgas temperature. Lead emissions are effectively removed in particulate control systems operating at low temperatures, about 120°C (250°F).

Tables 12.3-18 and 12.3-19 present process and fugitive lead emission factors for various operations of primary copper smelters.

Fugitive emissions from primary copper smelters are captured by applying either local ventilation or general ventilation techniques. Once captured, fugitive emissions may be vented directly to a collection device or can be combined with process off-gases before collection. Close-fitting exhaust hood capture systems are used for multiple hearth roasters and hood ventilation systems for smelt matte tapping and slag skimming operations. For converters, secondary hood systems or building evacuation systems are used.

A number of hazardous air pollutants (HAPs) are identified as being present in some copper concentrates being delivered to primary copper smelters for processing. They include arsenic, antimony, cadmium, lead, selenium, and cobalt. Specific emission factors are not presented due to lack of data. A part of the reason for roasting the concentrate is to remove certain volatile impurities including arsenic and antimony. There are HAPs still contained in blister copper, including arsenic, antimony, lead, and selenium. After electrolytic refining, copper is 99.95 percent to 99.97 percent pure.

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12.4 Ferroalloy Production

12.4.1 General

Ferroalloy is an alloy of iron with some element other than carbon. Ferroalloy is used to physically introduce or "carry" that element into molten metal, usually during steel manufacture. In practice, the term ferroalloy is used to include any alloys that introduce reactive elements or alloy systems, such as nickel and cobalt-based aluminum systems. Silicon metal is consumed in the aluminum industry as an alloying agent and in the chemical industry as a raw material in silicon-based chemical manufacturing.

The ferroalloy industry is associated with the iron and steel industries, its largest customers. Ferroalloys impart distinctive qualities to steel and cast iron and serve important functions during iron and steel production cycles. The principal ferroalloys are those of chromium, manganese, and silicon. Chromium provides corrosion resistance to stainless steels. Manganese is essential to counteract the harmful effects of sulfur in the production of virtually all steels and cast iron. Silicon is used primarily for deoxidation in steel and as an alloying agent in cast iron. Boron, cobalt, columbium, copper, molybdenum, nickel, phosphorus, titanium, tungsten, vanadium, zirconium, and the rare earths impart specific characteristics and are usually added as ferroalloys.

United States ferroalloy production in 1989 was approximately 894,000 megagrams (Mg) (985,000 tons), substantially less than shipments in 1975 of approximately 1,603,000 megagrams (1,770,000 tons). In 1989, ferroalloys were produced in the U. S. by 28 companies, although 5 of those produced only ferrophosphorous as a byproduct of elemental phosphorous production.

12.4.2 Process Description

A typical ferroalloy plant is illustrated in Figure 12.4-1. A variety of furnace types, including submerged electric arc furnaces, exothermic (metallothermic) reaction furnaces, and electrolytic cells can be used to produce ferroalloys. Furnace descriptions and their ferroalloy products are given in Table 12.4-1.

12.4.2.1 Submerged Electric Arc Process -

In most cases, the submerged electric arc furnace produces the desired product directly. It may produce an intermediate product that is subsequently used in additional processing methods. The submerged arc process is a reduction smelting operation. The reactants consist of metallic ores (ferrous oxides, silicon oxides, manganese oxides, chrome oxides, etc.) and a carbon-source reducing agent, usually in the form of coke, charcoal, high- and low-volatility coal, or wood chips. Limestone may also be added as a flux material. Raw materials are crushed, sized, and, in some cases, dried, and then conveyed to a mix house for weighing and blending. Conveyors, buckets, skip hoists, or cars transport the processed material to hoppers above the furnace. The mix is then gravity-fed through a feed chute either continuously or intermittently, as needed. At high temperatures in the reaction zone, the carbon source reacts with metal oxides to form carbon monoxide and to reduce the ores to base metal. A typical reaction producing ferrosilicon is shown below:

$$Fe_2O_3 + 2SiO_2 + 7C \rightarrow 2FeSi + 7\,CO \qquad (1)$$

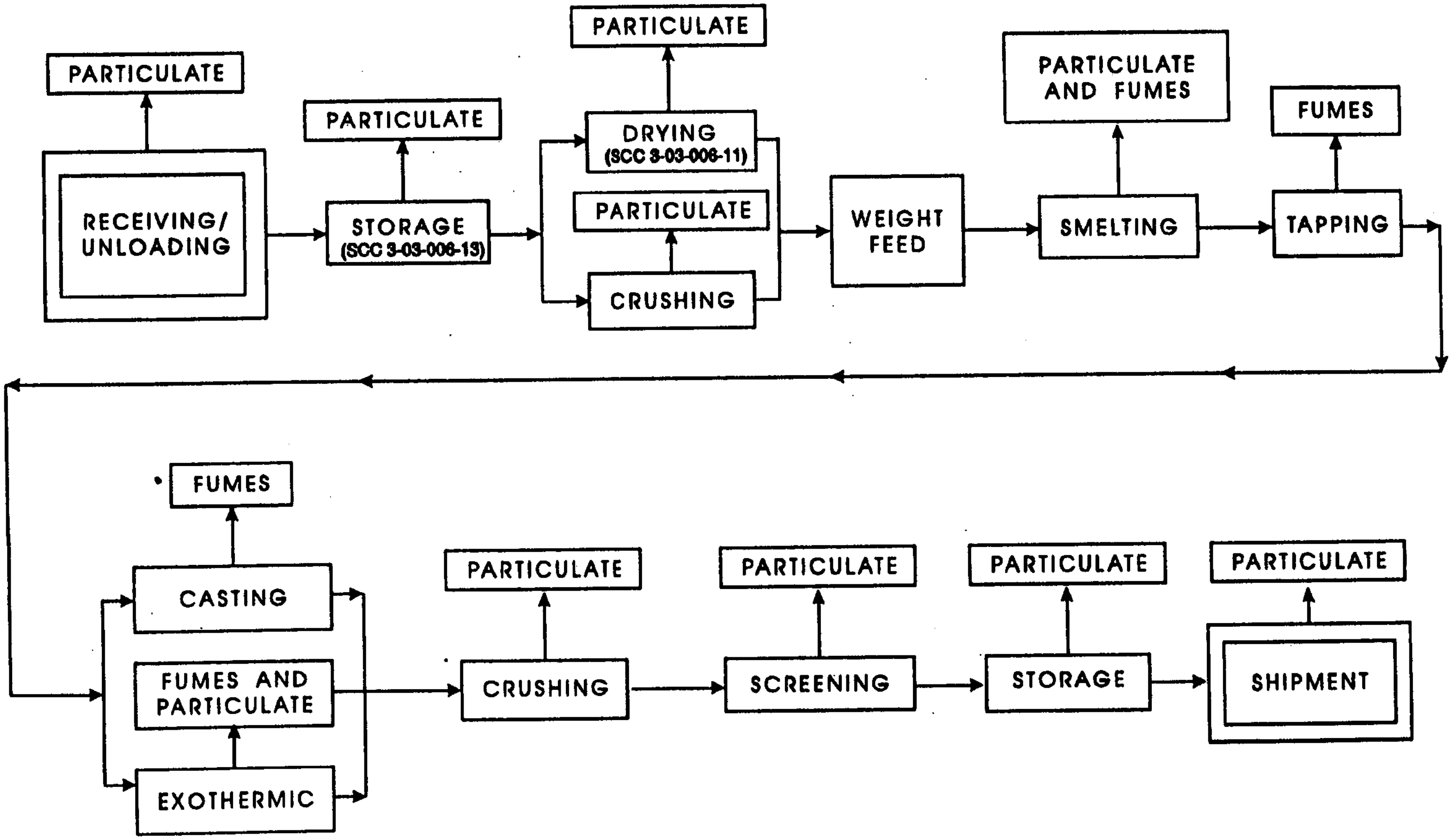

Figure 12.4-1. Typical ferroalloy production process. (Source Classification Code in parentheses.)

Table 12.4-1. FERROALLOY PROCESSES AND RESPECTIVE PRODUCT GROUPS

Process	Product
Submerged arc furnace[a]	Silvery iron (15-22% Si) Ferrosilicon (50% Si) Ferrosilicon (65-75% Si) Silicon metal Silicon/manganese/zirconium (SMZ) High carbon (HC) ferromanganese Siliconmanganese HC ferrochrome Ferrochrome/silicon FeSi (90% Si)
Exothermic[b]	
Silicon reduction	Low carbon (LC) ferrochrome, LC ferromanganese, medium carbon (MC) ferromanganese
Aluminum Reduction	Chromium metal, ferrotitanium, ferrocolumbium, ferovanadium
Mixed aluminothermal/silicothermal	Ferromolybdenum, ferrotungsten
Electrolytic[c]	Chromium metal, manganese metal
Vacuum furnace[d]	LC ferrochrome
Induction furnace[e]	Ferrotitanium

[a] Process by which metal is smelted in a refractory-lined cup-shaped steel shell by submerged graphite electrodes.

[b] Process by which molten charge material is reduced, in exothermic reaction, by addition of silicon, aluminum, or a combination of the 2.

[c] Process by which simple ions of a metal, usually chromium or manganese in an electrolyte, are plated on cathodes by direct low-voltage current.

[d] Process by which carbon is removed from solid-state high-carbon ferrochrome within vacuum furnaces maintained at temperatures near melting point of alloy.

[e] Process that converts electrical energy into heat, without electrodes, to melt metal charges in a cup or drum-shaped vessel.

Smelting in an electric arc furnace is accomplished by conversion of electrical energy to heat. An alternating current applied to the electrodes causes current to flow through the charge between the electrode tips. This provides a reaction zone at temperatures up to 2000°C (3632°F). The tip of each electrode changes polarity continuously as the alternating current flows between the tips. To maintain a uniform electric load, electrode depth is continuously varied automatically by mechanical or hydraulic means.

A typical submerged electric arc furnace design is depicted in Figure 12.4-2. The lower part of the submerged electric arc furnace is composed of a cylindrical steel shell with a flat bottom or hearth. The interior of the shell is lined with 2 or more layers of carbon blocks. The furnace shell may be water-cooled to protect it from the heat of the process. A water-cooled cover and fume collection hood are mounted over the furnace shell. Normally, 3 carbon electrodes arranged in a triangular formation extend through the cover and into the furnace shell opening. Prebaked or self-baking (Soderberg) electrodes ranging from 76 to over 100 cm (30 to over 40 inches) in diameter are typically used. Raw materials are sometimes charged to the furnace through feed chutes from above the furnace. The surface of the furnace charge, which contains both molten material and unconverted charge during operation, is typically maintained near the top of the furnace shell. The lower ends of the electrodes are maintained at about 0.9 to 1.5 meters (3 to 5 feet) below the charge surface. Three-phase electric current arcs from electrode to electrode, passing through the charge material. The charge material melts and reacts to form the desired product as the electric energy is converted into heat. The carbonaceous material in the furnace charge reacts with oxygen in the metal oxides of the charge and reduces them to base metals. The reactions produce large quantities of carbon monoxide (CO) that passes upward through the furnace charge. The molten metal and slag are removed (tapped) through 1 or more tap holes extending through the furnace shell at the hearth level. Feed materials may be charged continuously or intermittently. Power is applied continuously. Tapping can be intermittent or continuous based on production rate of the furnace.

Submerged electric arc furnaces are of 2 basic types, open and covered. Most of the submerged electric arc furnaces in the U. S. are open furnaces. Open furnaces have a fume collection hood at least 1 meter (3.3 feet) above the top of the furnace shell. Moveable panels or screens are sometimes used to reduce the open area between the furnace and hood, and to improve emissions capture efficiency. Carbon monoxide rising through the furnace charge burns in the area between the charge surface and the capture hood. This substantially increases the volume of gas the containment system must handle. Additionally, the vigorous open combustion process entrains finer material in the charge. Fabric filters are typically used to control emissions from open furnaces.

Covered furnaces may have a water-cooled steel cover that fits closely to the furnace shell. The objective of covered furnaces is to reduce air infiltration into the furnace gases, which reduces combustion of that gas. This reduces the volume of gas requiring collection and treatment. The cover has holes for the charge and electrodes to pass through. Covered furnaces that partially close these hood openings with charge material are referred to as "mix-sealed" or "semi-enclosed furnaces". Although these covered furnaces significantly reduce air infiltration, some combustion still occurs under the furnace cover. Covered furnaces that have mechanical seals around the electrodes and sealing compounds around the outer edges are referred to as "sealed" or "totally closed". These furnaces have little, if any, air infiltration and undercover combustion. Water leaks from the cover into the furnace must be minimized as this leads to excessive gas production and unstable furnace operation. Products prone to highly variable releases of process gases are typically not made in covered furnaces for safety reasons. As the degree of enclosure increases, less gas is produced for capture by the hood system and the concentration of carbon monoxide in the furnace gas increases. Wet scrubbers are used to control emissions from covered furnaces. The scrubbed, high carbon monoxide content gas may be used within the plant or flared.

The molten alloy and slag that accumulate on the furnace hearth are removed at 1 to 5-hour intervals through the tap hole. Tapping typically lasts 10 to 15 minutes. Tap holes are opened with pellet shot from a gun, by drilling, or by oxygen lancing. The molten metal and slag flow from the tap hole into a carbon-lined trough, then into a carbon-lined runner that directs the metal and slag into a reaction ladle, ingot molds, or chills. (Chills are low, flat iron or steel pans that provide rapid

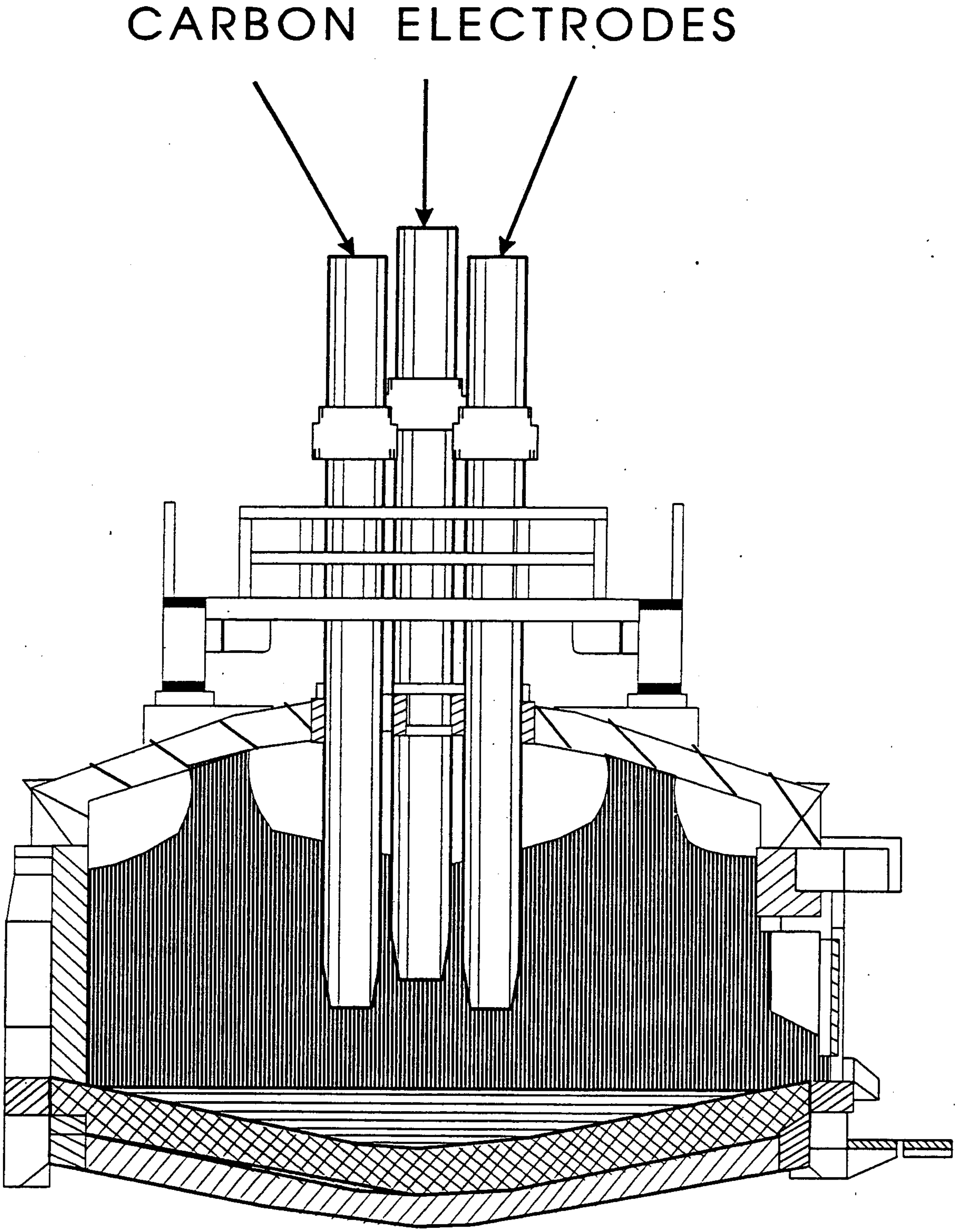

Figure 12.4-2. Typical submerged arc furnace design.

cooling of the molten metal.) After tapping is completed, the furnace is resealed by inserting a carbon paste plug into the tap hole.

Chemistry adjustments may be necessary after furnace smelting to achieve a specified product. Ladle treatment reactions are batch processes and may include metal and alloy additions.

During tapping, and/or in the reaction ladle, slag is skimmed from the surface of the molten metal. It can be disposed of in landfills, sold as road ballast, or used as a raw material in a furnace or reaction ladle to produce a chemically related ferroalloy product.

After cooling and solidifying, the large ferroalloy castings may be broken with drop weights or hammers. The broken ferroalloy pieces are then crushed, screened (sized), and stored in bins until shipment. In some instances, the alloys are stored in lump form in inventories prior to sizing for shipping.

12.4.2.2 Exothermic (Metallothermic) Process -

The exothermic process is generally used to produce high-grade alloys with low-carbon content. The intermediate molten alloy used in the process may come directly from a submerged electric arc furnace or from another type of heating device. Silicon or aluminum combines with oxygen in the molten alloy, resulting in a sharp temperature rise and strong agitation of the molten bath. Low- and medium-carbon content ferrochromium (FeCr) and ferromanganese (FeMn) are produced by silicon reduction. Aluminum reduction is used to produce chromium metal, ferrotitanium, ferrovanadium, and ferrocolumbium. Mixed alumino/silico thermal processing is used for producing ferromolybdenum and ferrotungsten. Although aluminum is more expensive than carbon or silicon, the products are purer. Low-carbon (LC) ferrochromium is typically produced by fusing chromium ore and lime in a furnace. A specified amount is then placed in a ladle (ladle No. 1). A known amount of an intermediate grade ferrochromesilicon is then added to the ladle. The reaction is extremely exothermic and liberates chromium from its ore, producing LC ferrochromium and a calcium silicate slag. This slag, which still contains recoverable chromium oxide, is reacted in a second ladle (ladle No. 2) with molten high-carbon ferrochromesilicon to produce the intermediate-grade ferrochromesilicon. Exothermic processes are generally carried out in open vessels and may have emissions similar to the submerged arc process for short periods while the reduction is occurring.

12.4.2.3 Electrolytic Processes -

Electrolytic processes are used to produce high-purity manganese and chromium. As of 1989, there were 2 ferroalloy facilities using electrolytic processes.

Manganese may be produced by the electrolysis of an electrolyte extracted from manganese ore or manganese-bearing ferroalloy slag. Manganese ores contain close to 50 percent manganese; furnace slag normally contains about 10 percent manganese. The process has 5 steps: (1) roasting the ore to convert it to manganese oxide (MnO), (2) leaching the roasted ore with sulfuric acid (H_2SO_4) to solubilize manganese, (3) neutralization and filtration to remove iron and aluminum hydroxides, (4) purifying the leach liquor by treatment with sulfide and filtration to remove a wide variety of metals, and (5) electrolysis.

Electrolytic chromium is generally produced from high-carbon ferrochromium. A large volume of hydrogen gas is produced by dissolving the alloy in sulfuric acid. The leachate is treated with ammonium sulfate and conditioned to remove ferrous ammonium sulfate and produce a chrome-alum for feed to the electrolysis cells. The electrolysis cells are well ventilated to reduce ambient hydrogen and hexavalent chromium concentrations in the cell rooms.

12.4.3 Emissions And Controls

Particulate is generated from several activities during ferroalloy production, including raw material handling, smelting, tapping, and product handling. Organic materials are generated almost exclusively from the smelting operation. The furnaces are the largest potential sources of particulate and organic emissions. The emission factors are given in Tables 12.4-2 and 12.4-3. Size-specific emission factors for submerged arc ferroalloy furnaces are given in Tables 12.4-4 and 12.4-5.

Particulate emissions from electric arc furnaces in the form of fumes account for an estimated 94 percent of the total particulate emissions in the ferroalloy industry. Large amounts of carbon monoxide and organic materials also are emitted by submerged electric arc furnaces. Carbon monoxide is formed as a byproduct of the chemical reaction between oxygen in the metal oxides of the charge and carbon contained in the reducing agent (coke, coal, etc.). Reduction gases containing organic compounds and carbon monoxide continuously rise from the high-temperature reaction zone, entraining fine particles and fume precursors. The mass weight of carbon monoxide produced sometimes exceeds that of the metallic product. The heat-induced fume consists of oxides of the products being produced and carbon from the reducing agent. The fume is enriched by silicon dioxide, calcium oxide, and magnesium oxide, if present in the charge.

In an open electric arc furnace, virtually all carbon monoxide and much of the organic matter burns with induced air at the furnace top. The remaining fume, captured by hooding about 1 meter above the furnace, is directed to a gas cleaning device. Fabric filters are used to control emissions from 85 percent of the open furnaces in the U. S. Scrubbers are used on 13 percent of the furnaces, and electrostatic precipitators on 2 percent.

Two emission capture systems, not usually connected to the same gas cleaning device, are necessary for covered furnaces. A primary capture system withdraws gases from beneath the furnace cover. A secondary system captures fumes released around the electrode seals and during tapping. Scrubbers are used almost exclusively to control exhaust gases from sealed furnaces. The scrubbers capture a substantial percentage of the organic emissions, which are much greater for covered furnaces than open furnaces. The gas from sealed and mix-sealed furnaces is usually flared at the exhaust of the scrubber. The carbon monoxide-rich gas is sometimes used as a fuel in kilns and sintering machines. The efficiency of flares for the control of carbon monoxide and the reduction of VOCs has been estimated to be greater than 98 percent. A gas heating reduction of organic and carbon monoxide emissions is 98 percent efficient.

Tapping operations also generate fumes. Tapping is intermittent and is usually conducted during 10 to 20 percent of the furnace operating time. Some fumes originate from the carbon lip liner, but most are a result of induced heat transfer from the molten metal or slag as it contacts the runners, ladles, casting beds, and ambient air. Some plants capture these emissions to varying degrees with a main canopy hood. Other plants employ separate tapping hoods ducted to either the furnace emission control device or a separate control device. Emission factors for tapping emissions are unavailable due to lack of data.

After furnace tapping is completed, a reaction ladle may be used to adjust the metallurgy by chlorination, oxidation, gas mixing, and slag metal reactions. Ladle reactions are an intermittent process, and emissions have not been quantified. Reaction ladle emissions are often captured by the tapping emissions control system.

Table 12.4-2 (Metric Units). EMISSION FACTORS FOR PARTICULATE FROM SUBMERGED ARC FERROALLOY FURNACES[a]

Product[b]	Furnace Type	Particulate Emission Factors Uncontrolled[c]	EMISSION FACTOR RATING	Control Device[d]	Particulate Emission Factors Controlled[c]	EMISSION FACTOR RATING
FeSi (50%) (SCC 3-03-006-01)	Open[e,f,g]	35	B	Baghouse[e,f]	0.9	B
	Covered[h]	46	E	Scrubber[h,j]		
				High energy	0.24	E
				Low energy	4.5	E
FeSi (75%) (SCC 3-03-006-02)	Open[k]	158	E	Scrubber[h,j]		
				Low energy	4.0	E
	Covered[h,j]	103	E	ND	ND	NA
FeSi (90%) (SCC 3-03-006-03)	Open[m]	282	E	ND	ND	NA
Si metal (98%) (SCC 3-03-006-04)	Open[n,p]	436	B	Baghouse[n,p]	16	B
FeMn (80%) (SCC 3-03-006-06)	Open[q,r]	14	B	Baghouse[q,r]	0.24	B
				Scrubber[h,s]		
				High energy	0.8	E
FeMn (1% Si) (SCC 3-03-007-01)	Covered[h,t]	6	E	Scrubber High energy[h,s,w]	0.25	C
	Sealed[u,v]	37	E	ND	ND	NA
FeCr (high carbon) (SCC 3-03-006-07)	Open[x,y]	78	C	ESP[x,y]	1.2	C
SiMn (SCC 3-03-006-05)	Open[z,aa]	96	C	Scrubber[aa,bb]	2.1	C
	Sealed	—	—	Scrubber[v,w]		
				High energy	0.15	C

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[a] Emission factors are expressed as kg of pollutant/Mg alloy produced. Factors are for main furnace dust collection system before and after control device. Where other emissions, such as leaks or tapping, are included or quantified separately, such is noted. Particulate sources not included: raw material handling, storage, and preparation; and product crushing, screening, handling, and packaging. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Percentages are of the main alloying agent in product.

Table 12.4-2 (cont.).

[c] In most source testing, fugitive emissions are not measured or collected. Where tapping emissions are controlled by primary system, their contribution to total emissions could not be determined. Fugitive emissions may vary greatly among sources, with furnace and collection system design and operating practices.

[d] Low-energy scrubbers are those with $\Delta P < 20$ inches of H_2O; high-energy with $\Delta P > 20$ inches of H_2O.

[e] Includes fumes captured by tapping hood (efficiency estimated at near 100%).

[f] References 4,10,21.

[g] Factor is average of 3 sources, fugitive emissions not included. Fugitive emissions at 1 source measured an additional 10.5 kg/Mg alloy, or 2.7 kg/MW-hr.

[h] References 4,10.

[j] Does not include emissions from tapping or mix seal leaks.

[k] References 25-26.

[m] Reference 23.

[n] Estimated 60% of tapping emissions captured by control system (escaped fugitive emissions not included in factor).

[p] References 10,13.

[q] Estimated 50% of tapping emissions captured by control system (escaped fugitive emissions not included in factor).

[r] References 4,10,12.

[s] Includes fumes only from primary control system.

[t] Includes tapping fumes and mix seal leak fugitive emissions. Fugitive emissions measured at 33% of total uncontrollable emissions.

[u] Assumes tapping fumes not included in emission factor.

[v] Reference 14.

[w] Does not include tapping or fugitive emissions.

[x] Tapping emissions included.

[y] References 2,15-17.

[z] Factor is average of 2 test series. Tests at 1 source included fugitive emissions (3.4% of total uncontrolled emissions). Second test insufficient to determine if fugitive emissions were included in total.

[aa] References 2,18-19.

[bb] Factors developed from 2 scrubber controlled sources, 1 operated at $\Delta P = 47\text{-}57$ inches of H_2O, the other at unspecified ΔP. Uncontrolled tapping operations emissions are 2.1 kg/Mg alloy.

Table 12.4-3 (English Units). EMISSION FACTORS FOR PARTICULATE FROM SUBMERGED ARC FERROALLOY FURNACES[a]

Product[b]	Furnace Type	Particulate Emission factors Uncontrolled[c]	EMISSION FACTOR RATING	Control Device[d]	Particulate Emission factors Controlled[c]	EMISSION FACTOR RATING
FeSi (50%) (SCC 3-03-006-01)	Open[e,f,g]	70	B	Baghouse[e,f]	1.8	B
	Covered[h]	92	E	Scrubber[h,j] High energy Low energy	 0.48 9.0	 E E
FeSi (75%) (SCC 3-03-006-02)	Open[k]	316	E	Scrubber[h,j] Low energy	 8.0	 E
	Covered[h,j]	206	E	ND	ND	NA
FeSi (90%) (SCC 3-03-006-03)	Open[m]	564	E	ND	ND	NA
Si metal (98%) (SCC 3-03-006-04)	Open[n,p]	872	B	Baghouse[n,p]	32	B
FeMn (80%) (SCC 3-03-006-06)	Open[q,r]	28	B	Baghouse[q,r] Scrubber[h,s] High energy	0.48 1.6	B E
FeMn (1% Si) (SCC 3-03-007-01)	Covered[h,t]	12	E	Scrubber High energy[h,s,w]	 0.5	 C
	Sealed[u,v]	74	E	ND	ND	NA
FeCr (high carbon) (SCC 3-03-006-07)	Open[x,y]	157	C	ESP[x,y]	2.3	C
SiMn (SCC 3-03-006-05)	Open[z,aa]	192	C	Scrubber[aa,bb]	4.2	C
	Sealed	—	—	Scrubber[v,w] High energy	 0.30	 C

[a] Emission factors expressed as lb of pollutant/ton of Alloy produced. Factors are for main furnace dust collection system before and after control device. Where other emissions, such as leaks or tapping, are included or quantified separately, such is noted. Particulate sources not included: raw material handling, storage, and preparation; and product crushing, screening, handling, and packaging. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Percentages are of the main alloying agent in product.

Table 12.4-3 (cont.).

[c] In most source testing, fugitive emissions are not measured or collected. Where tapping emissions are controlled by primary system, their contribution to total emissions could not be determined. Fugitive emissions may vary greatly among sources, with furnace and collection system design and operating practices.

[d] Low-energy scrubbers are those with $\Delta P < 20$ inches of H_2O; high-energy with $\Delta P > 20$ inches of H_2O.

[e] Includes fumes captured by tapping hood (efficiency estimated at near 100%).

[f] References 4,10,21.

[g] Factor is average of 3 sources, fugitive emissions not included. Fugitive emissions at 1 source measured an additional 21 lb/ton alloy, or 5.9 lb/MW-hr.

[h] References 4,10.

[j] Does not include emissions from tapping or mix seal leaks.

[k] References 25-26.

[m] Reference 23.

[n] Estimated 60% of tapping emissions captured by control system (escaped fugitive emissions not included in factor).

[p] References 10,13.

[q] Estimated 50% of tapping emissions captured by control system (escaped fugitive emissions not included in factor).

[r] References 4,10,12.

[s] Includes fumes only from primary control system.

[t] Includes tapping fumes and mix seal leak fugitive emissions. Fugitive emissions measured at 33% of total uncontrollable emissions.

[u] Assumes tapping fumes not included in emission factor.

[v] Reference 14.

[w] Does not include tapping or fugitive emissions.

[x] Tapping emissions included.

[y] References 2,15-17.

[z] Factor is average of 2 test series. Tests at 1 source included fugitive emissions (3.4% of total uncontrolled emissions). Second test insufficient to determine if fugitive emissions were included in total.

[aa] References 2,18-19.

[bb] Factors developed from 2 scrubber controlled sources, 1 operated at $\Delta P = 47\text{-}57$ inches of H_2O, the other at unspecified ΔP. Uncontrolled tapping operations emissions are 4.2 lb/ton alloy.

Table 12.4-4 (Metric Units). SIZE-SPECIFIC EMISSION FACTORS FOR SUBMERGED ARC FERROALLOY FURNACES

Product	Control Device	Particle Size[a] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor (kg/Mg alloy)	EMISSION FACTOR RATING
50% FeSi Open furnace (SCC 3-03-006-01)	None[b,c]	0.63	45	16	B
		1.00	50	18	
		1.25	53	19	
		2.50	57	20	
		6.00	61	21	
		10.00	63	22	
		15.00	66	23	
		20.00	69	24	
		—[d]	100	35	
	Baghouse	0.63	31	0.28	B
		1.00	39	0.35	
		1.25	44	0.40	
		2.50	54	0.49	
		6.00	63	0.57	
		10.00	72	0.65	
		15.00	80	0.72	
		20.00	85	0.77	
			100	0.90	
80% FeMn Open furnace (SCC 3-03-006-06)	None[e,f]	0.63	30	4	B
		1.00	46	7	
		1.25	52	8	
		2.50	62	9	
		6.00	72	10	
		10.00	86	12	
		15.00	96	13	
		20.00	97	14	
		—[d]	100	14	
	Baghouse[e]	0.63	20	0.048	B
		1.00	30	0.070	
		1.25	35	0.085	
		2.50	49	0.120	
		6.00	67	0.160	
		10.00	83	0.200	
		15.00	92	0.220	
		20.00	97	0.235	
		—[d]	100	0.240	

Table 12.4-4 (cont.).

Product	Control Device	Particle Size[a] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor (kg/Mg alloy)	EMISSION FACTOR RATING
Si Metal[g]					
Open furnace	None[h]	0.63	57	249	B
(SCC 3-03-006-04)		1.00	67	292	
		1.25	70	305	
		2.50	75	327	
		6.00	80	349	
		10.00	86	375	
		15.00	91	397	
		20.00	95	414	
		—[d]	100	436	
	Baghouse	1.00	49	7.8	
		1.25	53	8.5	
		2.50	64	10.2	
		6.00	76	12.2	
		10.00	87	13.9	
		15.00	96	15.4	
		20.00	99	15.8	
			100	16.0	
FeCr (HC)					
Open furnace	None[b,j]	0.5	19	15	C
(SCC 3-03-006-07)		1.0	36	28	
		2.0	60	47	
		2.5	63[k]	49	
		4.0	76	59	
		6.0	88[k]	67	
		10.0	91	71	
		—[d]	100	78	
	ESP	0.5	33	0.40	C
		1.0	47	0.56	
		2.0	67	0.80	
		2.5	80	0.96	
		4.0	86	1.03	
		6.0	90	1.08	
		10.0	100	1.2	
		—[d]			

Table 12.4-4 (cont.).

Product	Control Device	Particle Size[a] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor (kg/Mg alloy)	EMISSION FACTOR RATING
SiMn Open furnace (SCC 3-03-006-05)	None[b,m]	0.5	28	27	C
		1.0	44	42	
		2.0	60	58	
		2.5	65	62	
		4.0	76	73	
		6.0	85	82	
		10.0	96[k]	92[k]	
		—[d]	100	96	
	Scrubber[m,n]	0.5	56	1.18	C
		1.0	80	1.68	
		2.0	96	2.02	
		2.5	99	2.08	
		4.0	99.5	2.09	
		6.0	99.9[k]	2.10[k]	
		10.0	100	2.1	

[a] Aerodynamic diameter, based on Task Group On Lung Dynamics definition. Particle density = 1 g/cm^3.

[b] Includes tapping emissions.

[c] References 4,10,21.

[d] Total particulate, based on Method 5 total catch (see Tables 12.4-2 and 12.4-3).

[e] Includes tapping fumes (estimated capture efficiency 50%).

[f] References 4,10,12.

[g] References 10,13.

[h] Includes tapping fumes (estimated capture efficiency 60%).

[j] References 1,15-17.

[k] Interpolated data.

[m] References 2,18-19.

[n] Primary emission control system only, without tapping emissions.

Table 12.4-5 (English Units). SIZE-SPECIFIC EMISSION FACTORS FOR SUBMERGED ARC FERROALLOY FURNACES

Product	Control Device	Particle Size[a] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor (lb/ton alloy)	EMISSION FACTOR RATING
50% FeSi Open furnace (SCC 3-03-006-01)	None[b,c]	0.63	45	32	B
		1.00	50	35	
		1.25	53	37	
		2.50	57	40	
		6.00	61	43	
		10.00	63	44	
		15.00	66	46	
		20.00	69	48	
		—[d]	100	70	
	Baghouse	0.63	31	0.56	B
		1.00	39	0.70	
		1.25	44	0.80	
		2.50	54	1.0	
		6.00	63	1.1	
		10.00	72	1.3	
		15.00	80	1.4	
		20.00	85	1.5	
			100	1.8	
80% FeMn Open furnace (SCC 3-03-006-06)	None[e,f]	0.63	30	8	B
		1.00	46	13	
		1.25	52	15	
		2.50	62	17	
		6.00	72	20	
		10.00	86	24	
		15.00	96	26	
		20.00	97	27	
		—[d]	100	28	
	Baghouse[e]	0.63	20	0.10	B
		1.00	30	0.14	
		1.25	35	0.17	
		2.50	49	0.24	
		6.00	67	0.32	
		10.00	83	0.40	
		15.00	92	0.44	
		20.00	97	0.47	
		—[d]	100	0.48	

Table 12.4-5 (cont.).

Product	Control Device	Particle Size[a] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor (lb/ton alloy)	EMISSION FACTOR RATING
Si Metal[g] Open Furnace (SCC 3-03-006-04)	None[h]	0.63	57	497	B
		1.00	67	584	
		1.25	70	610	
		2.50	75	654	
		6.00	80	698	
		10.00	86	750	
		15.00	91	794	
		20.00	95	828	
		—[d]	100	872	
	Baghouse	1.00	49	15.7	B
		1.25	53	17.0	
		2.50	64	20.5	
		6.00	76	24.3	
		10.00	87	28.0	
		15.00	96	31.0	
		20.00	99	31.7	
			100	32.0	
FeCr (HC) Open furnace (SCC 3-03-006-07)	None[b,j]	0.5	19	30	C
		1.0	36	57	
		2.0	60	94	
		2.5	63[k]	99	
		4.0	76	119	
		6.0	88[k]	138	
		10.0	91	143	
		—[d]	100	157	
	ESP	0.5	33	0.76	C
		1.0	47	1.08	
		2.0	67	1.54	
		2.5	80	1.84	
		4.0	86	1.98	
		6.0	90	2.07	
		10.0	100	2.3	
		—[d]			

Table 12.4-5 (cont.).

Product	Control Device	Particle Size[a] (μm)	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor (lb/ton alloy)	EMISSION FACTOR RATING
SiMn Open furnace (SCC 3-05-006-05)	None[b,m]	0.5	28	54	C
		1.0	44	84	
		2.0	60	115	
		2.5	65	125	
		4.0	76	146	
		6.0	85	163	
		10.0	96[k]	177[k]	
		—[d]	100	192	
	Scrubber[m,n]	0.5	56	2.36	C
		1.0	80	3.34	
		2.0	96	4.03	
		2.5	99	4.16	
		4.0	99.5	4.18	
		6.0	99.9[k]	4.20[k]	
		10.0	100	4.3	

[a] Aerodynamic diameter, based on Task Group On Lung Dynamics definition. Particle density = 1 g/cm^3.

[b] Includes tapping emissions.

[c] References 4,10,21.

[d] Total particulate, based on Method 5 total catch (see Tables 12.4-2 and 12.4-3).

[e] Includes tapping fumes (estimated capture efficiency 50%).

[f] References 4,10,12.

[g] References 10,13.

[h] Includes tapping fumes (estimated capture efficiency 60%).

[j] References 1,15-17.

[k] Interpolated data.

[m] References 2,18-19.

[n] Primary emission control system only, without tapping emissions.

Available data are insufficient to provide emission factors for raw material handling, pretreatment, and product handling. Dust particulate is emitted from raw material handling, storage, and preparation activities (see Figure 12.4-1). These activities include unloading raw materials from delivery vehicles (ship, railway car, or truck), storing raw materials in piles, loading raw materials from storage piles into trucks or gondola cars, and crushing and screening raw materials. Raw materials may be dried before charging in rotary or other types of dryers, and these dryers can generate significant particulate emissions. Dust may also be generated by heavy vehicles used for loading, unloading, and transferring material. Crushing, screening, and storage of the ferroalloy product emit particulate matter in the form of dust. The properties of particulate matter emitted as dust are similar to the natural properties of the ores or alloys from which they originated, ranging in size from 3 to 100 micrometers (μm).

Approximately half of all ferroalloy facilities have some type of control for dust emissions. Dust generated from raw material storage may be controlled in several ways, including sheltering storage piles from the wind with block walls, snow fences, or plastic covers. Occasionally, piles are sprayed with water to prevent airborne dust. Emissions generated by heavy vehicle traffic may be reduced by using a wetting agent or paving the plant yard. Moisture in the raw materials, which may be as high as 20 percent, helps to limit dust emissions from raw material unloading and loading. Dust generated by crushing, sizing, drying, or other pretreatment activities may be controlled by dust collection equipment such as scrubbers, cyclones, or fabric filters. Ferroalloy product crushing and sizing usually require a fabric filter. The raw material emission collection equipment may be connected to the furnace emission control system. For fugitive emissions from open sources, see Section 13.2 of this document.

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12.5 Iron And Steel Production

12.5.1 Process Description[1-3]

The production of steel at an integrated iron and steel plant is accomplished using several interrelated processes. The major operations are: (1) coke production, (2) sinter production, (3) iron production, (4) iron preparation, (5) steel production, (6) semifinished product preparation, (7) finished product preparation, (8) heat and electricity supply, and (9) handling and transport of raw, intermediate, and waste materials. The interrelation of these operations is depicted in a general flow diagram of the iron and steel industry in Figure 12.5-1. Coke production is discussed in detail in Section 12.2 of this publication, and more information on the handling and transport of materials is found in Chapter 13.

12.5.1.1 Sinter Production -

The sintering process converts fine-sized raw materials, including iron ore, coke breeze, limestone, mill scale, and flue dust, into an agglomerated product, sinter, of suitable size for charging into the blast furnace. The raw materials are sometimes mixed with water to provide a cohesive matrix, and then placed on a continuous, travelling grate called the sinter strand. A burner hood, at the beginning of the sinter strand ignites the coke in the mixture, after which the combustion is self supporting and it provides sufficient heat, 1300 to 1480°C (2400 to 2700°F), to cause surface melting and agglomeration of the mix. On the underside of the sinter strand is a series of windboxes that draw combusted air down through the material bed into a common duct, leading to a gas cleaning device. The fused sinter is discharged at the end of the sinter strand, where it is crushed and screened. Undersize sinter is recycled to the mixing mill and back to the strand. The remaining sinter product is cooled in open air or in a circular cooler with water sprays or mechanical fans. The cooled sinter is crushed and screened for a final time, then the fines are recycled, and the product is sent to be charged to the blast furnaces. Generally, 2.3 Mg (2.5 tons) of raw materials, including water and fuel, are required to produce 0.9 Mg (1 ton) of product sinter.

12.5.1.2 Iron Production -

Iron is produced in blast furnaces by the reduction of iron bearing materials with a hot gas. The large, refractory lined furnace is charged through its top with iron as ore, pellets, and/or sinter; flux as limestone, dolomite, and sinter; and coke for fuel. Iron oxides, coke and fluxes react with the blast air to form molten reduced iron, carbon monoxide (CO), and slag. The molten iron and slag collect in the hearth at the base of the furnace. The byproduct gas is collected through offtakes located at the top of the furnace and is recovered for use as fuel.

The production of 1 ton of iron requires 1.4 tons of ore or other iron bearing material; 0.5 to 0.65 tons of coke; 0.25 tons of limestone or dolomite; and 1.8 to 2 tons of air. Byproducts consist of 0.2 to 0.4 tons of slag, and 2.5 to 3.5 tons of blast furnace gas containing up to 100 pounds (lb) of dust.

The molten iron and slag are removed, or cast, from the furnace periodically. The casting process begins with drilling a hole, called the taphole, into the clay-filled iron notch at the base of the hearth. During casting, molten iron flows into runners that lead to transport ladles. Slag also flows into the clay-filled iron notch at the base of the hearth. During casting, molten iron flows into runners that lead to transport ladles. Slag also flows from the furnace, and is directed through separate runners to a slag pit adjacent to the casthouse, or into slag pots for transport to a remote slag

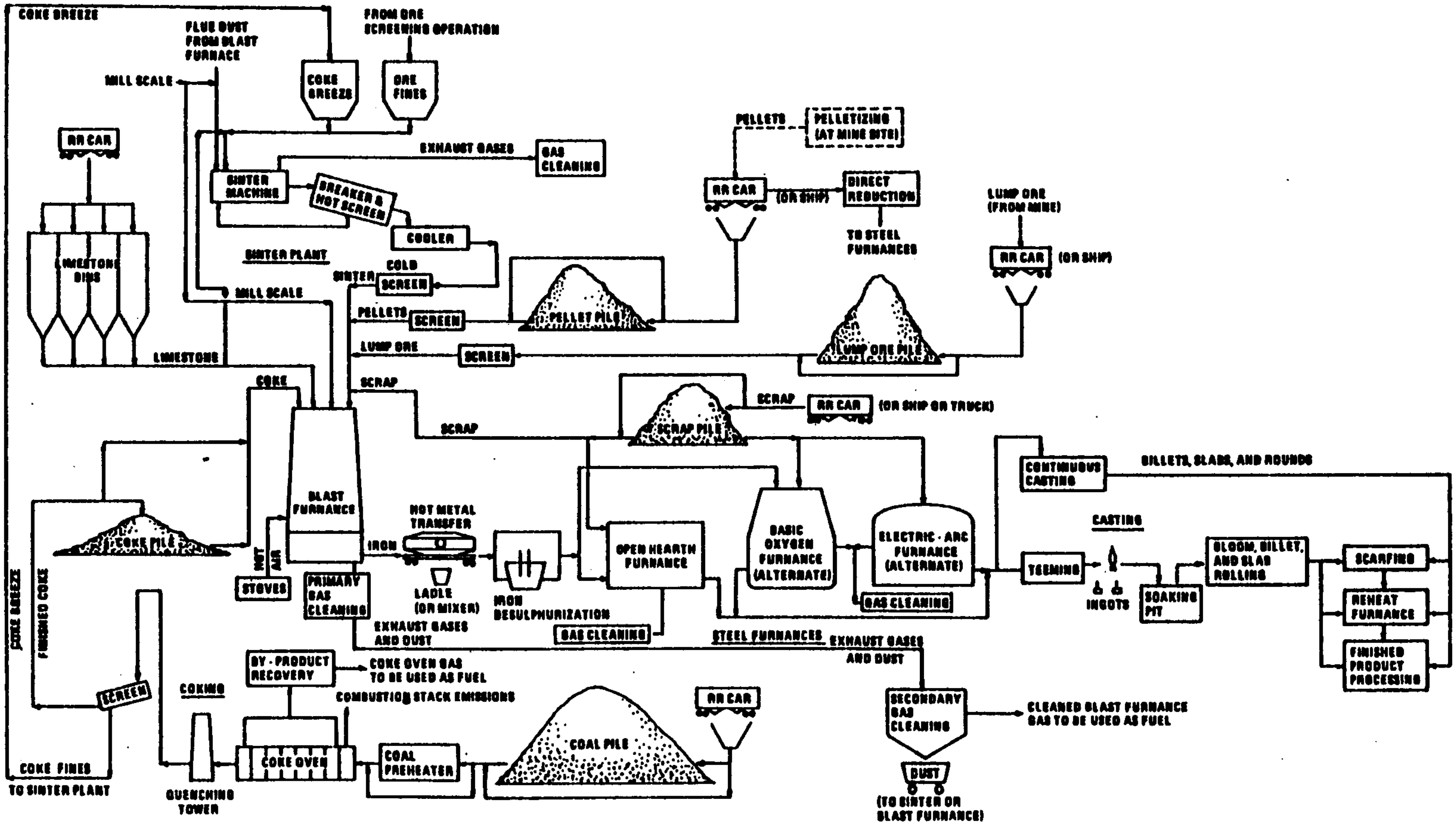

Figure 12.5-1. General flow diagram for the iron and steel industry.

pit. At the conclusion of the cast, the taphole is replugged with clay. The area around the base of the furnace, including all iron and slag runners, is enclosed by a casthouse. The blast furnace byproduct gas, which is collected from the furnace top, contains CO and particulate. Because of its high CO content, this blast furnace gas has a low heating value, about 2790 to 3350 joules per liter (J/L) (75 to 90 British thermal units per cubic foot [Btu/ft^3]) and is used as a fuel within the steel plant. Before it can be efficiently oxidized, however, the gas must be cleaned of particulate. Initially, the gases pass through a settling chamber or dry cyclone to remove about 60 percent of the particulate. Next, the gases undergo a 1- or 2-stage cleaning operation. The primary cleaner is normally a wet scrubber, which removes about 90 percent of the remaining particulate. The secondary cleaner is a high-energy wet scrubber (usually a venturi) or an electrostatic precipitator, either of which can remove up to 90 percent of the particulate that eludes the primary cleaner. Together these control devices provide a clean fuel of less than 0.05 grams per cubic meter (g/m^3) (0.02 grains per cubic foot [g/ft^3]). A portion of this gas is fired in the blast furnace stoves to preheat the blast air, and the rest is used in other plant operations.

12.5.1.3 Iron Preparation Hot Metal Desulfurization -

Sulfur in the molten iron is sometimes reduced before charging into the steelmaking furnace by adding reagents. The reaction forms a floating slag which can be skimmed off. Desulfurization may be performed in the hot metal transfer (torpedo) car at a location between the blast furnace and basic oxygen furnace (BOF), or it may be done in the hot metal transfer (torpedo) ladle at a station inside the BOF shop.

The most common reagents are powdered calcium carbide (CaC_2) and calcium carbonate ($CaCO_3$) or salt-coated magnesium granules. Powdered reagents are injected into the metal through a lance with high-pressure nitrogen. The process duration varies with the injection rate, hot metal chemistry, and desired final sulfur content, and is in the range of 5 to 30 minutes.

12.5.1.4 Steelmaking Process — Basic Oxygen Furnaces -

In the basic oxygen process (BOP), molten iron from a blast furnace and iron scrap are refined in a furnace by lancing (or injecting) high-purity oxygen. The input material is typically 70 percent molten metal and 30 percent scrap metal. The oxygen reacts with carbon and other impurities to remove them from the metal. The reactions are exothermic, i. e., no external heat source is necessary to melt the scrap and to raise the temperature of the metal to the desired range for tapping. The large quantities of CO produced by the reactions in the BOF can be controlled by combustion at the mouth of the furnace and then vented to gas cleaning devices, as with open hoods, or combustion can be suppressed at the furnace mouth, as with closed hoods. BOP steelmaking is conducted in large (up to 363 Mg.[400 ton] capacity) refractory lined pear shaped furnaces. There are 2 major variations of the process. Conventional BOFs have oxygen blown into the top of the furnace through a water-cooled lance. In the newer, Quelle Basic Oxygen process (Q-BOP), oxygen is injected through tuyeres located in the bottom of the furnace. A typical BOF cycle consists of the scrap charge, hot metal charge, oxygen blow (refining) period, testing for temperature and chemical composition of the steel, alloy additions and reblows (if necessary), tapping, and slagging. The full furnace cycle typically ranges from 25 to 45 minutes.

12.5.1.5 Steelmaking Process — Electric Arc Furnace -

Electric arc furnaces (EAF) are used to produce carbon and alloy steels. The input material to an EAF is typically 100 percent scrap. Cylindrical, refractory lined EAFs are equipped with carbon electrodes to be raised or lowered through the furnace roof. With electrodes retracted, the furnace roof can be rotated aside to permit the charge of scrap steel by overhead crane. Alloying agents and fluxing materials usually are added through the doors on the side of the furnace. Electric current of the opposite polarity electrodes generates heat between the electrodes and through the scrap. After melting and refining periods, the slag and steel are poured from the furnace by tilting.

The production of steel in an EAF is a batch process. Cycles, or "heats", range from about 1-1/2 to 5 hours to produce carbon steel and from 5 to 10 hours or more to produce alloy steel. Scrap steel is charged to begin a cycle, and alloying agents and slag materials are added for refining. Stages of each cycle normally are charging and melting operations, refining (which usually includes oxygen blowing), and tapping.

12.5.1.6 Steelmaking Process — Open Hearth Furnaces -

The open hearth furnace (OHF) is a shallow, refractory-lined basin in which scrap and molten iron are melted and refined into steel. Scrap is charged to the furnace through doors in the furnace front. Hot metal from the blast furnace is added by pouring from a ladle through a trough positioned in the door. The mixture of scrap and hot metal can vary from all scrap to all hot metal, but a half-and-half mixture is most common. Melting heat is provided by gas burners above and at the side of the furnace. Refining is accomplished by the oxidation of carbon in the metal and the formation of a limestone slag to remove impurities. Most furnaces are equipped with oxygen lances to speed up melting and refining. The steel product is tapped by opening a hole in the base of the furnace with an explosive charge. The open hearth steelmaking process with oxygen lancing normally requires from 4 to 10 hours for each heat.

12.5.1.7 Semifinished Product Preparation -

After the steel has been tapped, the molten metal is teemed (poured) into ingots which are later heated and formed into other shapes, such as blooms, billets, or slabs. The molten steel may bypass this entire process and go directly to a continuous casting operation. Whatever the production technique, the blooms, billets, or slabs undergo a surface preparation step, scarfing, which removes surface defects before shaping or rolling. Scarfing can be performed by a machine applying jets of oxygen to the surface of hot semifinished steel, or by hand (with torches) on cold or slightly heated semifinished steel.

12.5.2 Emissions And Controls

12.5.2.1 Sinter -

Emissions from sinter plants are generated from raw material handling, windbox exhaust, discharge end (associated sinter crushers and hot screens), cooler, and cold screen. The windbox exhaust is the primary source of particulate emissions, mainly iron oxides, sulfur oxides, carbonaceous compounds, aliphatic hydrocarbons, and chlorides. At the discharge end, emissions are mainly iron and calcium oxides. Sinter strand windbox emissions commonly are controlled by cyclone cleaners followed by a dry or wet ESP, high pressure drop wet scrubber, or baghouse. Crusher and hot screen emissions, usually controlled by hooding and a baghouse or scrubber, are the next largest emissions source. Emissions are also generated from other material handling operations. At some sinter plants, these emissions are captured and vented to a baghouse.

12.5.2.2 Blast Furnace -

The primary source of blast furnace emissions is the casting operation. Particulate emissions are generated when the molten iron and slag contact air above their surface. Casting emissions also are generated by drilling and plugging the taphole. The occasional use of an oxygen lance to open a clogged taphole can cause heavy emissions. During the casting operation, iron oxides, magnesium oxide and carbonaceous compounds are generated as particulate. Casting emissions at existing blast furnaces are controlled by evacuation through retrofitted capture hoods to a gas cleaner, or by suppression techniques. Emissions controlled by hoods and an evacuation system are usually vented to a baghouse. The basic concept of suppression techniques is to prevent the formation of pollutants by excluding ambient air contact with the molten surfaces. New furnaces have been constructed with evacuated runner cover systems and local hooding ducted to a baghouse.

Another potential source of emissions is the blast furnace top. Minor emissions may occur during charging from imperfect bell seals in the double bell system. Occasionally, a cavity may form in the blast furnace charge, causing a collapse of part of the burden (charge) above it. The resulting pressure surge in the furnace opens a relief valve to the atmosphere to prevent damage to the furnace by the high pressure created and is referred to as a "slip".

12.5.2.3 Hot Metal Desulfurization -

Emissions during the hot metal desulfurization process are created by both the reaction of the reagents injected into the metal and the turbulence during injection. The pollutants emitted are mostly iron oxides, calcium oxides, and oxides of the compound injected. The sulfur reacts with the reagents and is skimmed off as slag. The emissions generated from desulfurization may be collected by a hood positioned over the ladle and vented to a baghouse.

12.5.2.4 Steelmaking -

The most significant emissions from the BOF process occur during the oxygen blow period. The predominant compounds emitted are iron oxides, although heavy metals and fluorides are usually present. Charging emissions will vary with the quality and quantity of scrap metal charged to the furnace and with the pour rate. Tapping emissions include iron oxides, sulfur oxides, and other metallic oxides, depending on the grade of scrap used. Hot metal transfer emissions are mostly iron oxides.

BOFs are equipped with a primary hood capture system located directly over the open mouth of the furnaces to control emissions during oxygen blow periods. Two types of capture systems are used to collect exhaust gas as it leaves the furnace mouth: closed hood (also known as an off gas, or O. G., system) or open, combustion-type hood. A closed hood fits snugly against the furnace mouth, ducting all particulate and CO to a wet scrubber gas cleaner. CO is flared at the scrubber outlet stack. The open hood design allows dilution air to be drawn into the hood, thus combusting the CO in the hood system. Charging and tapping emissions are controlled by a variety of evacuation systems and operating practices. Charging hoods, tapside enclosures, and full furnace enclosures are used in the industry to capture these emissions and send them to either the primary hood gas cleaner or a second gas cleaner.

12.5.2.5 Steelmaking — Electric Arc Furnace -

The operations which generate emissions during the electric arc furnace steelmaking process are melting and refining, charging scrap, tapping steel, and dumping slag. Iron oxide is the predominant constituent of the particulate emitted during melting. During refining, the primary particulate compound emitted is calcium oxide from the slag. Emissions from charging scrap are difficult to quantify, because they depend on the grade of scrap utilized. Scrap emissions usually contain iron and other metallic oxides from alloys in the scrap metal. Iron oxides and oxides from the fluxes are the primary constituents of the slag emissions. During tapping, iron oxide is the major particulate compound emitted.

Emission control techniques involve an emission capture system and a gas cleaning system. Five emission capture systems used in the industry are fourth hold (direct shell) evacuation, side draft hood, combination hood, canopy hood, and furnace enclosures. Direct shell evacuation consists of ductwork attached to a separate or fourth hole in the furnace roof which draws emissions to a gas cleaner. The fourth hole system works only when the furnace is up-right with the roof in place. Side draft hoods collect furnace off gases from around the electrode holes and the work doors after the gases leave the furnace. The combination hood incorporates elements from the side draft and fourth hole ventilation systems. Emissions are collected both from the fourth hole and around the electrodes. An air gap in the ducting introduces secondary air for combustion of CO in the exhaust gas. The combination hood requires careful regulation of furnace interval pressure. The canopy hood is the least efficient of the 4 ventilation systems, but it does capture emissions during charging and tapping. Many new electric arc furnaces incorporate the canopy hood with one of the other 3 systems. The full furnace enclosure completely surrounds the furnace and evacuates furnace emissions through hooding in the top of the enclosure.

12.5.2.6 Steelmaking — Open Hearth Furnace -

Particulate emissions from an open hearth furnace vary considerably during the process. The use of oxygen lancing increases emissions of dust and fume. During the melting and refining cycle, exhaust gas drawn from the furnace passes through a slag pocket and a regenerative checker chamber, where some of the particulate settles out. The emissions, mostly iron oxides, are then ducted to either an ESP or a wet scrubber. Other furnace-related process operations which produce fugitive emissions inside the shop include transfer and charging of hot metal, charging of scrap, tapping steel, and slag dumping. These emissions are usually uncontrolled.

12.5.2.7 Semifinished Product Preparation -

During this activity, emissions are produced when molten steel is poured (teamed) into ingot molds, and when semifinished steel is machine or manually scarfed to remove surface defects. Pollutants emitted are iron and other oxides (FeO, Fe_2O_3, SiO_2, CaO, MgO). Teeming emissions are rarely controlled. Machine scarfing operations generally use as ESP or water spray chamber for control. Most hand scarfing operations are uncontrolled.

12.5.2.8 Miscellaneous Combustion -

Every iron and steel plant operation requires energy in the form of heat or electricity. Combustion sources that produce emissions on plant property are blast furnace stoves, boilers, soaking pits, and reheat furnaces. These facilities burn combinations of coal, No. 2 fuel oil, natural gas, coke oven gas, and blast furnace gas. In blast furnace stoves, clean gas from the blast furnace is burned to heat the refractory checker work, and in turn, to heat the blast air. In soaking pits, ingots are heated until the temperature distribution over the cross-section of the ingots is acceptable and the surface temperature is uniform for further rolling into semifinished products (blooms, billets, and slabs). In slab furnaces, a slab is heated before being rolled into finished products (plates, sheets, or strips). Emissions from the combustion of natural gas, fuel oil, or coal in the soaking pits or slab furnaces are estimated to be the same as those for boilers. (See Chapter 1 of this document.) Emission factor data for blast furnace gas and coke oven gas are not available and must be estimated. There are 3 facts available for making the estimation. First, the gas exiting the blast furnace passes through primary and secondary cleaners and can be cleaned to less than 0.05 g/m^3 (0.02 g/ft^3). Second, nearly one-third of the coke oven gas is methane. Third, there are no blast furnace gas constituents that generate particulate when burned. The combustible constituent of blast furnace gas is CO, which burns clean. Based on facts 1 and 3, the emission factor for combustion of blast furnace gas is equal to the particulate loading of that fuel, 0.05 g/m^3 (2.9 $lb/10^6\ ft^3$) having an average heat value of 3092 J/L (83 Btu/ft^3).

Emissions for combustion of coke oven gas can be estimated in the same fashion. Assume that cleaned coke oven gas has as much particulate as cleaned blast furnace gas. Since one-third of the coke oven gas is methane, the main component of natural gas, it is assumed that the combustion of this methane in coke oven gas generates 0.06 g/m^3 (3.3 $lb/10^6\ ft^3$) of particulate. Thus, the emission factor for the combustion of coke oven gas is the sum of the particulate loading and that generated by the methane combustion, or 0.1 g/m^3 (6.2 $lb/10^6 ft^3$) having an average heat value of 19,222 J/L (516 Btu/ft^3).

The particulate emission factors for processes in Table 12.5-1 are the result of an extensive investigation by EPA and the American Iron and Steel Institute.[3] Particle size distributions for controlled and uncontrolled emissions from specific iron and steel industry processes have been calculated and summarized from the best available data.[1] Size distributions have been used with particulate emission factors to calculate size-specific factors for the sources listed in Table 12.5-1 for which data are available. Table 12.5-2 presents these size-specific particulate emission factors. Particle size distributions are presented in Figure 12.5-2, Figure 12.5-3, and Figure 12.5-4.CO emission factors are in Table 12.5-3.[6]

12.5.2.9 Open Dust Sources -

Like process emission sources, open dust sources contribute to the atmospheric particulate burden. Open dust sources include vehicle traffic on paved and unpaved roads, raw material handling outside of buildings, and wind erosion from storage piles and exposed terrain. Vehicle traffic consists of plant personnel and visitor vehicles, plant service vehicles, and trucks handling raw materials, plant deliverables, steel products, and waste materials. Raw materials are handled by clamshell buckets, bucket/ladder conveyors, rotary railroad dumps, bottom railroad dumps, front end loaders, truck dumps, and conveyor transfer stations, all of which disturb the raw material and expose fines to the wind. Even fine materials, resting on flat areas or in storage piles are exposed and are subject to wind erosion. It is not unusual to have several million tons of raw materials stored at a plant and to have in the range of 9.7 to 96.7 hectares (10 to 100 acres) of exposed area there.

Open dust source emission factors for iron and steel production are presented in Table 12.5-4. These factors were determined through source testing at various integrated iron and steel plants.

As an alternative to the single-valued open dust emission factors given in Table 12.5-4, empirically derived emission factor equations are presented in Section 13.2 of this document. Each equation was developed for a source operation defined on the basis of a single dust generating mechanism which crosses industry lines, such as vehicle traffic on unpaved roads. The predictive equation explains much of the observed variance in measured emission factors by relating emissions to parameters which characterize source conditions. These parameters may be grouped into 3 categories: (1) measures of source activity or energy expended (e. g., the speed and weight of a vehicle traveling on an unpaved road), (2) properties of the material being disturbed (e. g., the content of suspendible fines in the surface material on an unpaved road) and (3) climatic parameters (e. g., number of precipitation free days per year, when emissions tend to a maximum).[4]

Because the predictive equations allow for emission factor adjustment to specific source conditions, the equations should be used in place of the factors in Table 12.5-4, if emission estimates for sources in a specific iron and steel facility are needed. However, the generally higher-quality ratings assigned to the equations are applicable only if (1) reliable values of correction parameters have been determined for the specific sources of interest and (2) the correction parameter values lie within the ranges tested in developing the equations. Section 13.2 lists measured properties of aggregate process materials and road surface materials in the iron and steel industry, which can be used to estimate correction parameter values for the predictive emission factor equations, in the event that site-specific values are not available.

Use of mean correction parameter values from Section 13.2 reduces the quality ratings of the emission factor equation by one level.

Table 12.5-1 (Metric And English Units). PARTICULATE EMISSION FACTORS FOR IRON AND STEEL MILLS[a]

Source	Units	Emission Factor		EMISSION FACTOR RATING	Particle Size Data
Sintering					
Windbox	kg/Mg (lb/ton) finished sinter				
Uncontrolled					
Leaving grate		5.56	(11.1)	B	Yes
After coarse particulate removal		4.35	(8.7)	A	
Controlled by dry ESP		0.8	(1.6)	B	
Controlled by wet ESP		0.085	(0.17)	B	Yes
Controlled by venturi scrubber		0.235	(0.47)	B	Yes
Controlled by cyclone		0.5	(1.0)	B	Yes
Sinter discharge (breaker and hot screens)	kg/Mg (lb/ton) finished sinter				
Uncontrolled		3.4	(6.8)	B	
Controlled by baghouse		0.05	(0.1)	B	Yes
Controlled by venturi scrubber		0.295	(0.59)	A	
Windbox and discharge	kg/Mg (lb/ton) finished sinter				
Controlled by baghouse		0.15	(0.3)	A	

Table 12.5-1 (cont.).

Source	Units	Emission Factor		EMISSION FACTOR RATING	Particle Size Data
Blast furnace					
Slip	kg/Mg (lb/ton) slip	39.5	(87.0)	D	
Uncontrolled casthouse	kg/Mg (lb/ton) hot metal				
Roof monitor[b]		0.3	(0.6)	B	Yes
Furnace with local evacuation[c]		0.65	(1.3)	B	Yes
Taphole and trough only (not runners)		0.15	(0.3)	B	
Hot metal desulfurization	kg/Mg (lb/ton) hot metal				
Uncontrolled[d]		0.55	(1.09)	D	Yes
Controlled by baghouse		0.0045	(0.009)	D	Yes
Basic oxygen furnace (BOF)					
Top blown furnace melting and refining	kg/Mg (lb/ton) steel				
Uncontrolled		14.25	(28.5)	B	
Controlled by open hood venter to:					
ESP		0.065	(0.13)	A	
Scrubber		0.045	(0.09)	B	

Table 12.5-1 (cont.).

Source	Units	Emission Factor		EMISSION FACTOR RATING	Particle Size Data
Controlled by closed hood vented to:					
Scrubber		0.0034	(0.0068)	A	Yes
BOF Charging	kg/Mg (lb/ton) hot metal				
At source		0.3	(0.6)	D	Yes
At building monitor		0.071	(0.142)	B	
Controlled by baghouse		0.0003	(0.0006)	B	Yes
BOF Tapping	kg/Mg (lb/ton) steel				
At source		0.46	(0.92)	D	Yes
At building monitor		0.145	(0.29)	B	
Controlled by baghouse		0.0013	(0.0026)	B	Yes
Hot metal transfer	kg/Mg (lb/ton) hot metal				
At source		0.095	(0.19)	A	
At building monitor		0.028	(0.056)	B	
BOF monitor (all sources)	kg/Mg (lb/ton) steel	0.25	(0.5)	B	
Q-BOF melting and refining	kg/Mg (lb/ton) steel				
Controlled by scrubber		0.028	(0.056)	B	Yes

Table 12.5-1 (cont.).

Source	Units	Emission Factor		EMISSION FACTOR RATING	Particle Size Data
Electric arc furnace					
Melting and refining	kg/Mg (lb/ton) steel				
Uncontrolled carbon steel		19.0	(38.0)	C	Yes
Charging, tapping, and slagging	kg/Mg (lb/ton) steel				
Uncontrolled emissions escaping monitor		0.7	(1.4)	C	
Melting, refining, charging, tapping, and slagging	kg/Mg (lb/ton) steel				
Uncontrolled					
Alloy steel		5.65	(11.3)	A	
Carbon steel		25.0	(50.0)	C	
Controlled by:[e]					
Building evacuation to baghouse for alloy steel		0.15	(0.3)	A	
Direct shell evacuation (plus charging hood) vented to common baghouse for carbon steel		0.0215	(0.043)	E	Yes

Table 12.5-1 (cont.).

Source	Units	Emission Factor	EMISSION FACTOR RATING	Particle Size Data
Open hearth furnace				
Melting and refining	kg/Mg (lb/ton) steel			
Uncontrolled		10.55 (21.1)	D	Yes
Controlled by ESP		0.14 (0.28)	D	Yes
Roof monitor		0.084 (0.168)	C	
Teeming				
Leaded steel	kg/Mg (lb/ton) steel			
Uncontrolled (measured at source)		0.405 (0.81)	A	
Controlled by side draft hood vented to baghouse		0.0019 (0.0038)	A	
Unleaded steel				
Uncontrolled (measured at source)		0.035 (0.07)	A	
Controlled by side draft hood vented to baghouse		0.0008 (0.0016)	A	
Machine scarfing	kg/Mg (lb/ton) metal through scarfer			
Uncontrolled		0.05 (0.1)	B	
Controlled by ESP		0.0115 (0.023)	A	

Table 12.5-1 (cont.).

Source	Units	Emission Factor		EMISSION FACTOR RATING	Particle Size Data
Miscellaneous combustion sources[f]		—[f]	—[f]		
Boiler, soaking pit, and slab reheat	kg/10^9 J (lb/10^6 Btu)				
Blast furnace gas[g]		0.015	(0.035)	D	
Coke oven gas[g]		0.0052	(0.012)	D	

[a] Reference 3, except as noted.

[b] Typical of older furnaces with no controls, or for canopy hoods or total casthouse evacuation.

[c] Typical of large, new furnaces with local hoods and covered evacuated runners. Emissions are higher than without capture systems because they are not diluted by outside environment.

[d] Emission factor of 0.55 kg/Mg (1.09 lb/ton) represents 1 torpedo car; 1.26 kg/Mg (2.53 lb/ton) for 2 torpedo cars, and 1.37 kg/Mg (2.74 lb/ton) for 3 torpedo cars.

[e] Building evacuation collects all process emissions, and direct shell evacuation collects only melting and refining emissions.

[f] For various fuels, use the emission factors in Chapter 1 of this document. The EMISSION FACTOR RATING for these fuels in boilers is A, and in soaking pits and slab reheat furnaces is D.

[g] Based on methane content and cleaned particulate loading.

Table 12.5-2 (Metric And English Units). SIZE SPECIFIC EMISSION FACTORS

Source	EMISSION FACTOR RATING	Particle Size (μm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
Sintering					
Windbox					
Uncontrolled leaving grate	D	0.5	4[b]	0.22	0.44
		1.0	4	0.22	0.44
		2.5	65	0.28	0.56
		5.0	9	0.50	1.00
		10	15	0.83	1.67
		15	20[c]	1.11	2.22
		—[d]	100	5.56	11.1
Controlled by wet ESP	C	0.5	18[b]	0.015	0.03
		1.0	25	0.021	0.04
		2.5	33	0.028	0.06
		5.0	48	0.041	0.08
		10	59[b]	0.050	0.10
		15	69	0.059	0.12
		—[d]	100	0.085	0.17
Controlled by venturi scrubber	C	0.5	55	0.129	0.26
		1.0	75	0.176	0.35
		2.5	89	0.209	0.42
		5.0	93	0.219	0.44
		10	96	0.226	0.45
		15	98	0.230	0.46
		—[d]	100	0.235	0.47
Controlled by cyclone[e]	C	0.5	25[c]	0.13	0.25
		1.0	37[b]	0.19	0.37
		2.5	52	0.26	0.52
		5.0	64	0.32	0.64
		10	74	0.37	0.74
		15	80	0.40	0.80
		—[d]	100	0.5	1.0

Table 12.5-2 (cont.).

Source	EMISSION FACTOR RATING	Particle Size (μm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
Controlled by baghouse	C	0.5	3.0	0.005	0.009
		1.0	9.0	0.014	0.027
		2.5	27.0	0.041	0.081
		5.0	47.0	0.071	0.141
		10.0	69.0	0.104	0.207
		15.0	79.0	0.119	0.237
		—[d]	100.0	0.15	0.3
Sinter discharge breaker and hot screens controlled by baghouse	C	0.5	2[b]	0.001	0.002
		1.0	4	0.002	0.004
		2.5	11	0.006	0.011
		5.0	20	0.010	0.020
		10	32[b]	0.016	0.032
		15	42[b]	0.021	0.042
		—[d]	100	0.05	0.1
Blast furnace					
Uncontrolled casthouse emissions					
Roof monitor[f]	C	0.5	4	0.01	0.02
		1.0	15	0.05	0.09
		2.5	23	0.07	0.14
		5.0	35	0.11	0.21
		10	51	0.15	0.31
		15	61	0.18	0.37
		—[d]	100	0.3	0.06

Table 12.5-2 (cont.).

Source	EMISSION FACTOR RATING	Particle Size (μm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
Furnace with local evacuation[g]	C	0.5	7[c]	0.04	0.09
		1.0	9	0.06	0.12
		2.5	15	0.10	0.20
		5.0	20	0.13	0.26
		10	24	0.16	0.31
		15	26	0.17	0.34
		—[d]	100	0.65	1.3
Hot metal desulfurization[h] Uncontrolled	E	0.5	—[j]		
		1.0	2[c]	0.01	0.02
		2.5	11	0.06	0.12
		5.0	19	0.10	0.22
		10	19	0.10	0.22
		15	21	0.12	0.23
		—[d]	100	0.55	1.09
Hot metal desulfurization[h] Controlled baghouse	D	0.5	8	0.0004	0.0007
		1.0	18	0.0009	0.0016
		2.5	42	0.0019	0.0038
		5.0	62	0.0028	0.0056
		10	74	0.0033	0.0067
		15	78	0.0035	0.0070
		—[d]	100	0.0045	0.009

Table 12.5-2 (cont.).

Source	EMISSION FACTOR RATING	Particle Size (μm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
Basic oxygen furnace BOF					
Top blown furnace melting and refining controlled by closed hood and vented to scrubber	C	0.5	34	0.0012	0.0023
		1.0	55	0.0019	0.0037
		2.5	65	0.0022	0.0044
		5.0	66	0.0022	0.0045
		10	67	0.0023	0.0046
		15	72[c]	0.0024	0.0049
		—[d]	100	0.0034	0.0068
BOF charging at source[k]	E	0.5	8[c]	0.02	0.05
		1.0	12	0.04	0.07
		2.5	22	0.07	0.13
		5.0	35	0.10	0.21
		10	46	0.14	0.28
		15	56	0.17	0.34
		—[d]	100	0.3	0.6
Controlled by baghouse	D	0.5	3	$9.0x10^{-6}$	$1.8x10^{-5}$
		1.0	10	$3.0x10^{-5}$	$6.0x10^{-5}$
		2.5	22	$6.6x10^{-5}$	0.0001
		5.0	31	$9.3x10^{-5}$	0.0002
		10	45	0.0001	0.0003
		15	60	0.0002	0.0004
		—[d]	100	0.0003	0.0006

Table 12.5-2 (cont.).

Source	EMISSION FACTOR RATING	Particle Size (μm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
BOF tapping at source[k]	E	0.5	—[j]	—[j]	—[j]
		1.0	11	0.05	0.10
		2.5	37	0.17	0.34
		5.0	43	0.20	0.40
		10	45	0.21	0.41
		15	50	0.23	0.46
		—[d]	100	0.46	0.92
BOF tapping Controlled by baghouse	D	0.5	4	5.2×10^{-5}	0.0001
		1.0	7	0.0001	0.0002
		2.5	16	0.0002	0.0004
		5.0	22	0.0003	0.0006
		10	30	0.0004	0.0008
		15	40	0.0005	0.0010
		—[d]	100	0.0013	0.0026
Q-BOP melting and refining controlled by scrubber	D	0.5	45	0.013	0.025
		1.0	52	0.015	0.029
		2.5	56	0.016	0.031
		5.0	58	0.016	0.032
		10	68	0.019	0.038
		15	85[c]	0.024	0.048
		—[d]	100	0.028	0.056

Table 12.5-2 (cont.).

Source	EMISSION FACTOR RATING	Particle Size (µm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
Electric arc furnace melting and refining carbon steel					
Uncontrolled[m]	D	0.5	8	1.52	3.04
		1.0	23	4.37	8.74
		2.5	43	8.17	16.34
		5.0	53	10.07	20.14
		10	58	11.02	22.04
		15	61	11.59	23.18
		—[d]	100	19.0	38.0
Electric arc furnace					
Melting, refining, charging, tapping, slagging					
Controlled by direct shell evacuation plus charing hood vented to common baghouse for carbon steel[n]	E	0.5	74[b]	0.0159	0.0318
		1.0	74	0.0159	0.0318
		2.5	74	0.0159	0.0318
		5.0	74	0.0159	0.0318
		10	76	0.0163	0.0327
		15	80	0.0172	0.0344
		—[d]	100	0.0215	0.043
Open hearth furnace					
Melting and refining					
Uncontrolled	E	0.5	1[b]	0.11	0.21
		1.0	21	2.22	4.43
		2.5	60	6.33	12.66
		5.0	79	8.33	16.67
		10	83	8.76	17.51
		15	85[c]	8.97	17.94
		—[d]	100	10.55	21.1

Table 12.5-2 (cont.).

Source	EMISSION FACTOR RATING	Particle Size (μm)[a]	Cumulative Mass % ≤ Stated Size	Cumulative Mass Emission Factor	
				kg/Mg	lb/ton
Open hearth furnaces					
Controlled by ESP[p]	E	0.5	10[b]	0.01	0.02
		1.0	21	0.03	0.06
		2.5	39	0.05	0.10
		5.0	47	0.07	0.13
		10	53[b]	0.07	0.15
		15	56[b]	0.08	0.16
		—[d]	100	0.14	0.28

[a] Particle aerodynamic diameter micrometers (μm) as defined by Task Group on Lung Dynamics. (Particle density = 1 g/cm^3).

[b] Interpolated data used to develop size distribution.

[c] Extrapolated, using engineering estimates.

[d] Total particulate based on Method 5 total catch. See Table 12.5-1.

[e] Average of various cyclone efficiencies.

[f] Total casthouse evacuation control system.

[g] Evacuation runner covers and local hood over taphole, typical of new state-of-the-art blast furnace technology.

[h] Torpedo ladel desulfurization with CaC_2 and $CaCO_3$.

[j] Unable to extrapolate because of insufficient data and/or curve exceeding limits.

[k] Doghouse-type furnace enclosure using front and back sliding doors, totally enclosing the furnace, with emissions vented to hoods.

[m] Full cycle emissions captured by canopy and side draft hoods.

[n] Information on control system not available.

[p] May not be representative. Test outlet size distribution was larger than inlet and may indicate reentrainment problem.

Table 12.5-3 (Metric And English Units). UNCONTROLLED CARBON MONOXIDE EMISSION FACTORS FOR IRON AND STEEL MILLS[a]

EMISSION FACTOR RATING: C

Source	kg/Mg	lb/ton
Sintering windbox[b]	22	44
Basic oxygen furnace[c]	69	138
Electric arc furnace[c]	9	18

[a] Reference 6.

[b] kg/Mg (lb/ton) of finished sinter.

[c] kg/Mg (lb/ton) of finished steel.

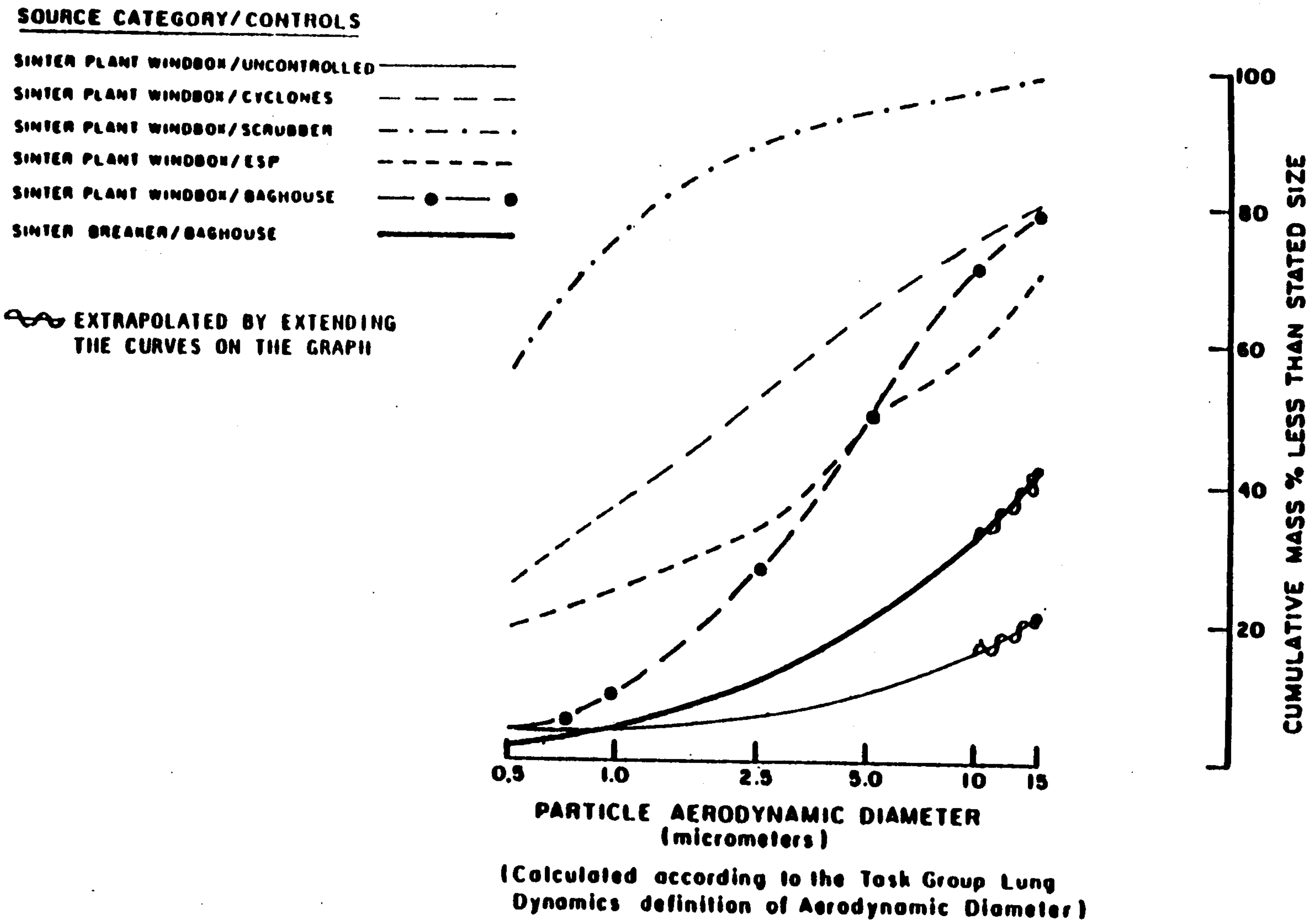

Figure 12.5-2. Particle size distribution of sinter plant emissions.

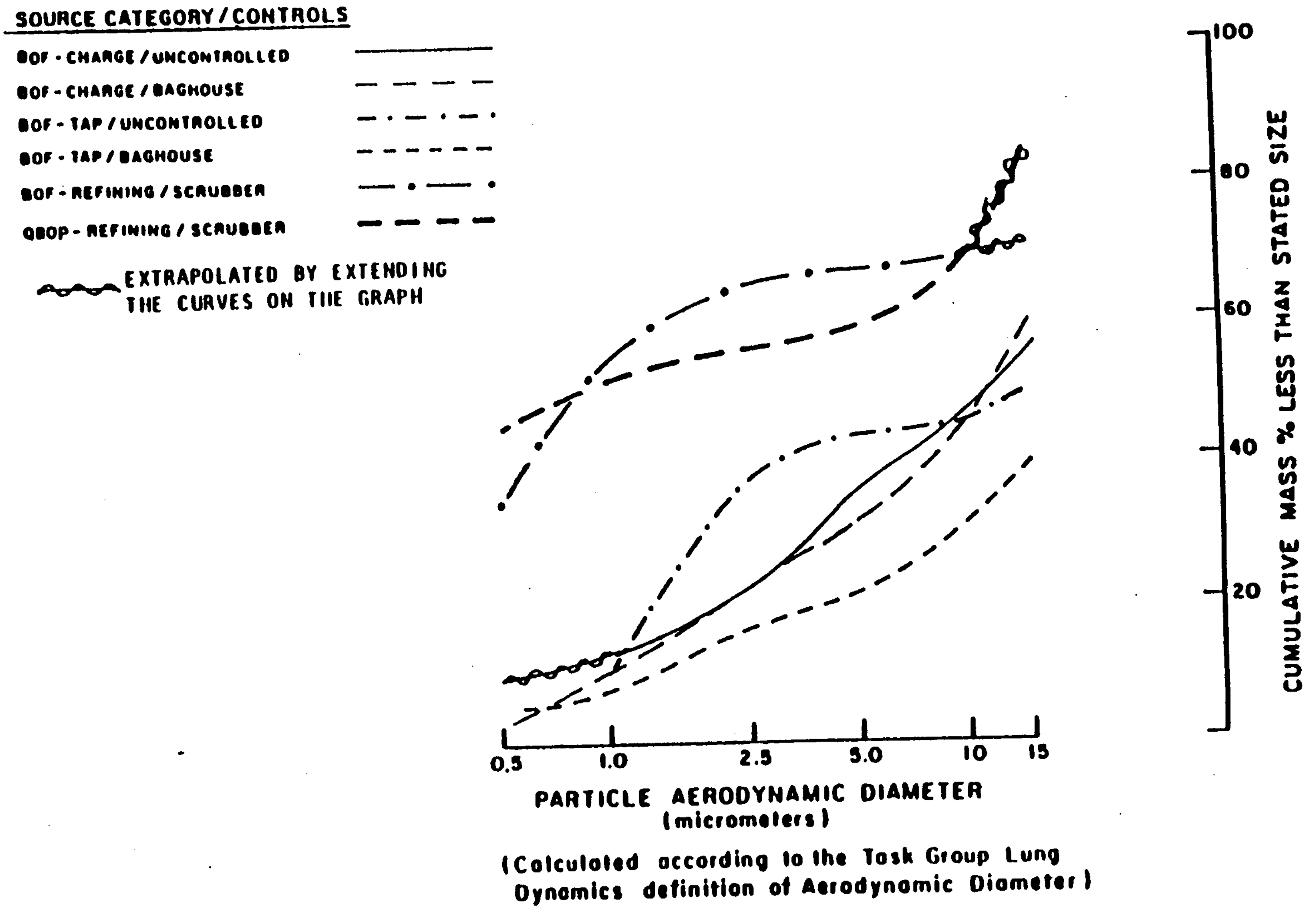

Figure 12.5-3. Particle size distribution of basic oxygen furnace emissions.

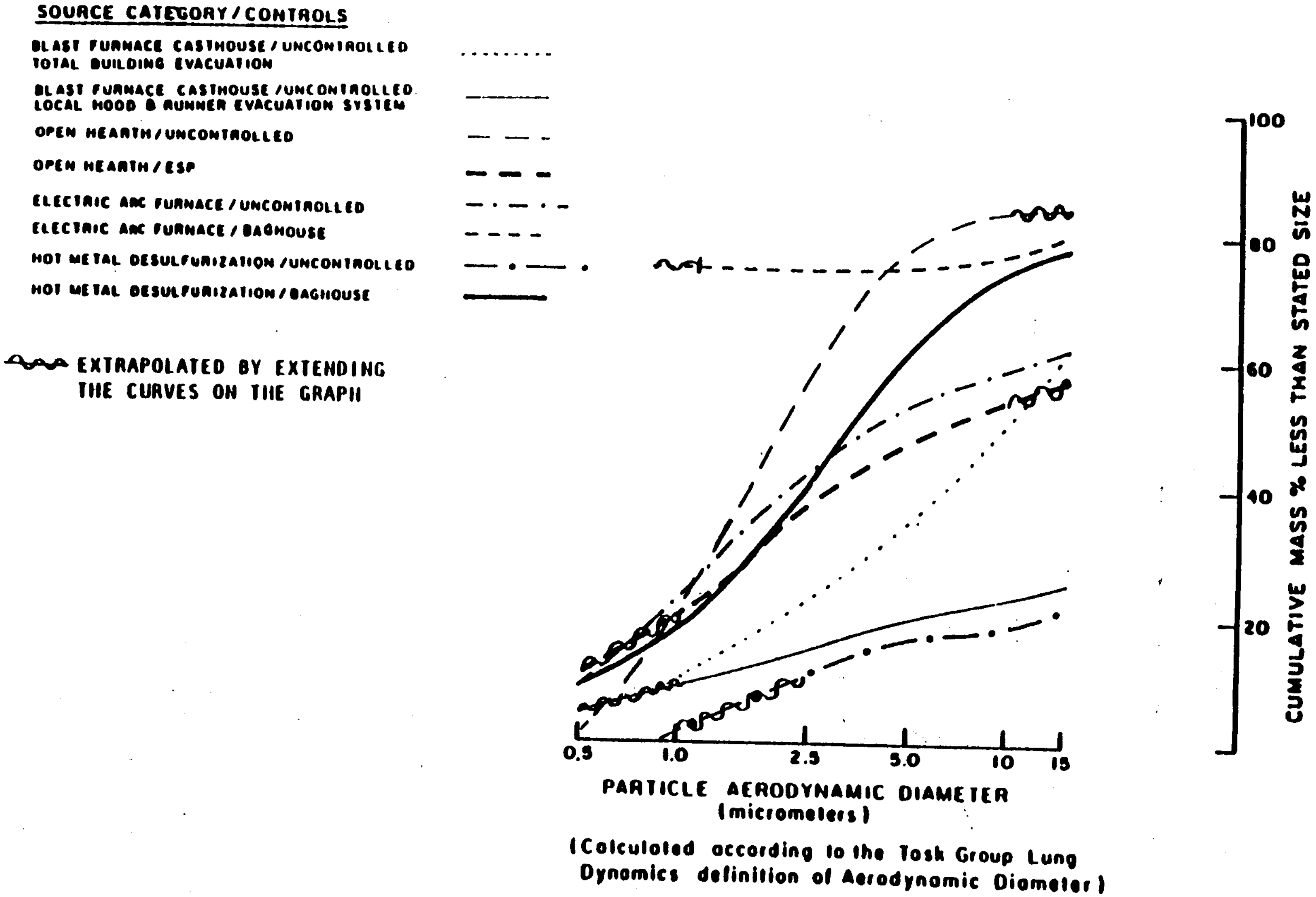

Figure 12.5-4. Particle size distribution of blast furnace, open hearth, electric arc furnace and hot metal desulfurization emissions.

Table 12.5-4 (Metric And English Units). UNCONTROLLED PARTICULATE EMISSION FACTORS FOR OPEN DUST SOURCES AT IRON AND STEEL MILLS[a]

Operation	Emissions By Particle Size Range (Aerodynamic Diameter)					Units[b]	EMISSION FACTOR RATING
	≤ 30 μm	≤ 15 μm	≤ 10 μm	≤ 5 μm	≤ 2.5 μm		
Continuous Drop							
Conveyor transfer station sinter[c]	13 0.026	9.0 0.018	6.5 0.013	4.2 0.0084	2.3 0.0046	g/Mg lb/ton	D D
Pile formation stacker pellet ore[c]	1.2 0.0024	0.75 0.0015	0.55 0.0011	0.32 0.00064	0.17 0.00034	g/Mg lb/ton	B B
Lump ore[c]	0.15 0.00030	0.095 0.00019	0.075 0.00015	0.040 0.000081	0.022 0.000043	g/Mg lb/ton	C C
Coal[d]	0.055 0.00011	0.034 0.000068	0.026 0.000052	0.014 0.000028	0.0075 0.000015	g/Mg lb/ton	E E
Batch drop							
Front end loader/truck[c]							
High silt slag	13 0.026	8.5 0.017	6.5 0.013	4.0 0.0080	2.3 0.0046	g/Mg lb/ton	C C
Low silt slag	4.4 0.0088	2.9 0.0058	2.2 0.0043	1.4 0.0028	0.8 0.0016	g/Mg lb/ton	C C
Vehicle travel on unpaved roads						kg/VKT lb/VMT	C C
Light duty vehicle[d]	0.51 1.8	0.37 1.3	0.28 1.0	0.18 0.64	0.10 0.36		
Medium duty vehicle[d]	2.1 7.3	1.5 5.2	1.2 4.1	0.70 2.5	0.42 1.5	kg/VKT lb/VMT	C C
Heavy duty vehicle[d]	3.9 14	2.7 9.7	2.1 7.6	1.4 4.8	0.76 2.7	kg/VKT lb/VMT	B B
Vehicle travel on paved roads							C C
Light/heavy vehicle mix[c]	0.22 0.78	0.16 0.58	0.12 0.44	0.079 0.28	0.042 0.15	kg/VKT lb/VMT	

[a] Predictive emission factor equations are generally preferred over these single values emission factors. Predictive emission factor estimates are presented in Chapter 13, Section 13.2. VKT = Vehicle kilometers traveled. VMT = Vehicle miles traveled.

[b] Units/unit of material transferred or units/unit of distance traveled.

[c] Reference 4. Interpolation to other particle sizes will be approximate.

[d] Reference 5. Interpolation to other particle sizes will be approximate.

References For Section 12.5

1. J. Jeffery and J. Vay, *Source Category Report For The Iron and Steel Industry*, EPA-600/7-86-036, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1986.

2. H. E. McGannon, ed., *The Making, And Shaping And Treating Of Steel*, U. S. Steel Corporation, Pittsburgh, PA, 1971.

3. T. A. Cuscino, Jr., *Particulate Emission Factors Applicable To The Iron And Steel Industry*, EPA-450/4-79-028, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1979.

4. R. Bohn, *et al.*, *Fugitive Emissions From Integrated Iron And Steel Plants*, EPA-600/2-78-050, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1978.

5. C. Cowherd,. Jr., *et al.*, *Iron And Steel Plant Open Source Fugitive Emission Evaluation*, EPA-600/2-79-103, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1979.

6. *Control Techniques For Carbon Monoxide Emissions from Stationary Sources*, AP-65, 0. S. Department Of Health, Education And Welfare, Washington, DC, March 1970.

12.6 Primary Lead Smelting

12.6.1 General[15]

Lead is found naturally as a sulfide ore containing small amounts of copper, iron, zinc, precious metals, and other trace elements. The lead in this ore, typically after being concentrated at or near the mine (see Section 12.18), is processed into metallurgical lead at 4 facilities in the U. S. (2 smelters/refineries in Missouri, 1 smelter in Montana, and 1 refinery in Nebraska). Demand for lead from these primary sources is expected to remain relatively stable in the early 1990s, due in large part to storage battery recycling programs being implemented by several states. Significant emissions of sulfur dioxide (SO_2), particulate matter, and especially lead have caused much attention to be focused on identifying, and quantifying emissions from, sources within these facilities.

12.6.2 Process Description[15,16]

The processing of lead concentrate into metallurgical lead involves 3 major steps: sintering, reduction, and refining. A diagram of a typical facility, with particle and gaseous emission sources indicated, is shown in Figure 12.6-1.

12.6.2.1 Sintering -

The primary purpose of the sinter machine is the reduction of sulfur content of the feed material. This feed material typically consists of the following:

1. Lead concentrates, including pyrite concentrates that are high in sulfur content, and concentrates that are high in impurities such as arsenic, antimony, and bismuth, as well as relatively pure high-lead-concentrates;
2. Lime rock and silica, incorporated in the feed to maintain a desired sulfur content;
3. High-lead-content sludge byproducts from other facilities; and
4. Undersized sinter recycled from the roast exiting the sinter machine.

The undersized sinter return stream mixes with the other feed components, or green feed, as the 2 streams enter a rotary pelletizing drum. A water spray into the drum enhances the formation of nodules in which the sinter returns form a core rich in lead oxide and the green feed forms a coating rich in lead sulfide. The smaller nodules are separated out and conveyed through an ignition furnace, then covered with the remaining nodules on a moving grate and conveyed through the sinter machine, which is essentially a large oven. Excess air is forced upward through the grate, facilitating combustion, releasing SO_2 and oxidizing the lead sulfide to lead oxide. The "strong gas" from the front end of the sinter machine, containing 2.5 to 4 percent SO_2, is vented to gas cleaning equipment before possibly being piped to a sulfuric plant. Gases from the rear part of the sinter machine are recirculated up through the moving grate and are typically vented to a baghouse. That portion of the product which is undersized, usually due to insufficient desulfurization, is filtered out and recycled through the sinter; the remaining sinter roast is crushed before being transported to the blast furnace.

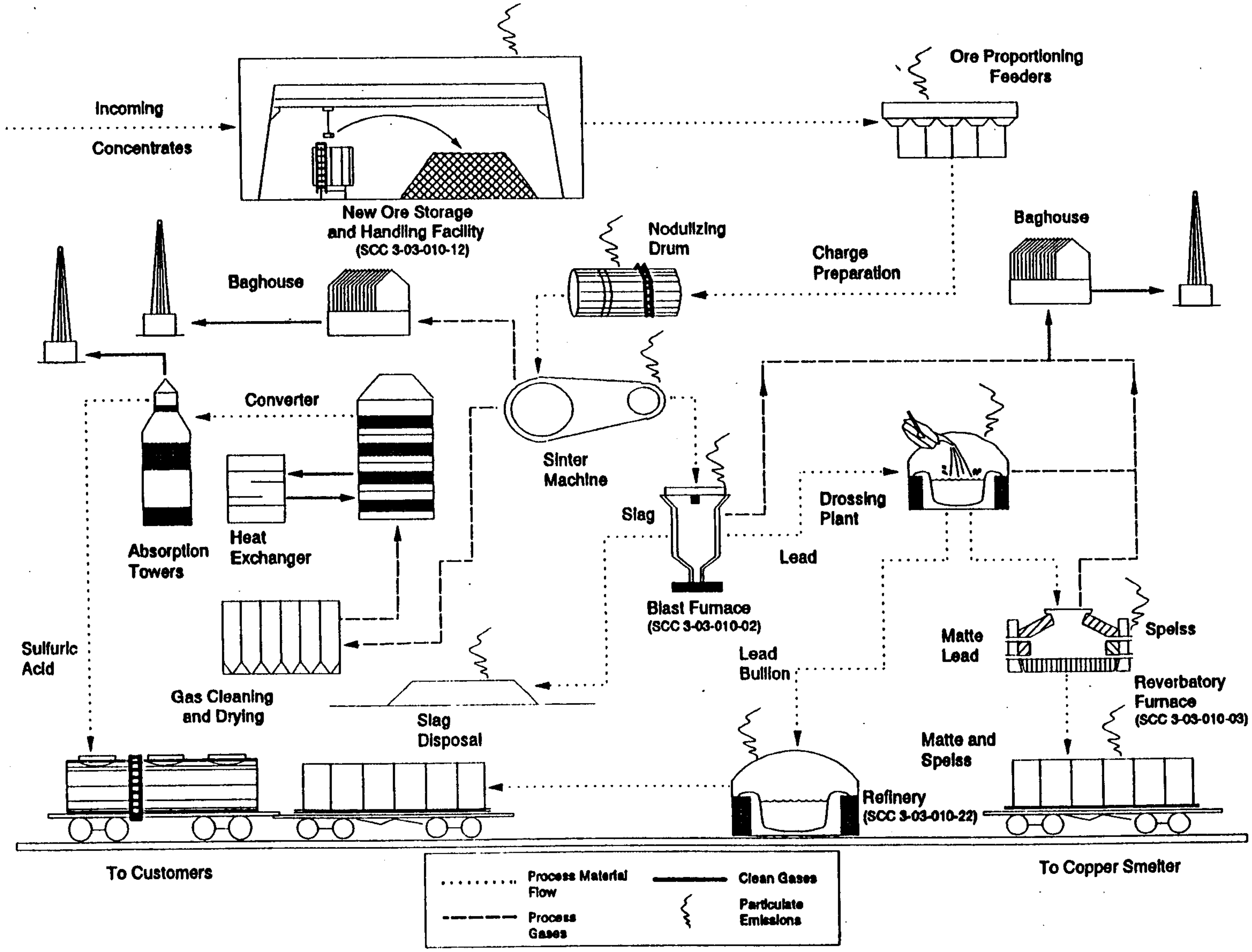

Figure 12.6-1. A typical primary lead smelting and refining. (Source Classification Code in parentheses.)

12.6.2.2 Reduction -

The sinter roast is then conveyed to the blast furnace in charge cars along with coke, ores containing high amounts of precious metals, slags and byproducts dusts from other smelters, and byproduct dusts from baghouses and various other sources within the facility. Iron scrap is often added to the charge to aid heat distribution and to combine with the arsenic in the charge. The blast furnace process rate is controlled by the proportion of coke in the charge and by the air flow through the tuyeres in the floor of the furnace. The charge descends through the furnace shaft into the smelting zone, where it becomes molten, and is tapped into a series of settlers that allow the separation of lead from slag. The slag is allowed to cool before being stored, and the molten lead of roughly 85 percent purity is transported in pots to the dross building.

12.6.2.3 Refining -

The drossing area consists of a variety of interconnected kettles, heated from below by natural gas combustion. The lead pots arriving from the blast furnace are poured into receiving kettles and allowed to cool to the point at which copper dross rises to the top of the top and can be skimmed off and transferred to a reverbatory furnace. The remaining lead dross is transferred to a finishing kettle where such materials as wood chips, coke fines, and sulfur are added and mixed to facilitate further separation, and this sulfur dross is also skimmed off and transferred to the reverbatory furnace. To the drosses in the reverbatory furnace are added tetrahedrite ore, which is high in silver content but low in lead and may have been dried elsewhere within the facility, coke fines, and soda ash. When heated in the same fashion as the kettles, the dross in the reverbatory furnace separates into 3 layers: lead bullion settles to the bottom and is tapped back to the receiving kettles, and matte (copper sulfide and other metal sulfides), which rises to the top, and speiss (high in arsenic and antimony content) are both typically forwarded to copper smelters.

The third and final phase in the processing of lead ore to metallurgical lead, the refining of the bullion in cast iron kettles, occurs in 5 steps: (1) removal of antimony, tin, and arsenic; (2) removal of precious metals by Parke's Process, in which zinc combines with gold and silver to form an insoluble intermetallic at operating temperatures; (3) vacuum removal of zinc; (4) removal of bismuth by the Betterson Process, in which calcium and magnesium are added to form an insoluble compound with the bismuth that is skimmed from the kettle; and (5) removal of remaining traces of metal impurities through the adding of NaOH and $NaNO_3$. The final refined lead, from 99.990 to 99.999 percent pure, is typically cast into 45 kilogram (100 pound) pigs for shipment.

12.6.3 Emissions And Controls[15-17]

Emissions of lead and particulate occur in varying amounts from nearly every process and process component within primary lead smelter/refineries, and SO_2 is also emitted from several sources. The lead and particulate emissions point, volume, and area sources may include:

1. The milling, dividing, and fire assaying of samples of incoming concentrates and high-grade ores;
2. Fugitive emissions within the crushing mill area, including the loading and unloading of ores and concentrates from rail cars onto conveyors;
3. The ore crushers and associated transfer points, which may be controlled by baghouses;

4. Fugitive emissions from the unloading, storage, and transfer of byproduct dusts, high-grade ores, residues, coke, lime, silica, and any other materials stored in outdoor piles;

5. Strong gases from the front end of the sinter machine, which are typically vented to an electrostatic precipitator (ESP), 1 or more scrubbers, and a wet ESP for sulfuric acid mist elimination, but during shutdowns of the acid plant may bypass the ESP;

6. Weak gases from the back end of the sinter machine, which are high in lead dust content but typically pass through cyclones and a baghouse;

7. Fugitive emissions from the sinter building, including leaks in the sinter machine and the sinter cake crusher;

8. Gases exiting the top of the blast furnace, which are typically controlled with a baghouse;

9. Fugitive emissions from the blast furnace, including leaks from the furnace covers and the bottoms of charge cars, dust from the charge car bottom dump during normal operation, and escaping gases when blow holes develop in the shaft and must be "shot" with explosives;

10. Lead fumes from the molten lead and slag leaving the blast furnace area;

11. Fugitive leaks from the tapping of the kettles and settlers;

12. The hauling and dumping of slag, at both the handling and cooling area and the slag storage pile;

13. The combustion of natural gas, as well as the creation of lead-containing fumes at the kettles and reverbatory furnace, all of which are typically vented to a baghouse at the drossing building;

14. Fugitive emissions from the various pouring, pumping, skimming, cooling, and tapping operations within the drossing building;

15. The transporting, breaking, granulating, and storage of speiss and matte;

16. The loading, transferring, and drying of tetrahedrite ore, which is typically controlled with cyclones and a baghouse;

17. The periodic cleanout of the blast and reverbatory furnaces; and

18. Dust caused by wind erosion and plant vehicular traffic, which are normally estimated with factors from Section 13.2 of AP-42, but are addressed herein due to the high lead content of the dust at primary lead smelting and refining facilities.

Tables 12.6.1 and 12.6.2 present particulate, PM-10, lead, and SO_2 emission factors for primary lead smelting.

Table 12.6-1 (Metric Units). EMISSION FACTORS FOR PRIMARY LEAD SMELTING[a]

EMISSION FACTOR RATING: E

Process	Particulate[b]	PM-10[c]	Lead	SO_2
Ore crushing[d] (SCC 3-03-010-04)	0.023	0.018	0.001	NA
Ore screening[e] (SCC 3-03-010-27)	0.004	0.005	0.001	NA
Tetrahedrite drier[f] (SCC 3-03-010-28)	0.012	0.013	0.0003	NA
Sinter machine (weak gas)[g] (SCC 3-03-010-29)	0.051	0.052	0.009	275[h]
Sinter building fugitives[g] (SCC 3-03-010-25)	0.118	0.058	0.016	NA
Sinter storage[j] (SCC 3-03-010-30)	NA	NA	NA	NA
Blast furnace[k] (SCC 3-03-010-02)	0.21	0.43	0.034	23[h]
Speiss pit[m] (SCC 3-03-010-31)	NA	NA	NA	NA

[a] Most of the processes are controlled by baghouses; otherwise it is noted. SCC = Source Classification Code. NA = not applicable.

[b] Filterable particulate only.

[c] Filterable and condensable particulate; ≤ 10 μm mean diameter.

[d] Entire ore crushing building at one facility, including transfer points; kg/Mg of ore, except lead, which is kg/Mg of lead in ore.

[e] Tests at one facility; kg/Mg ore.

[f] kg/Mg dried; tests at one facility.

[g] kg/Mg sinter produced; tests at one facility. The sinter machine is controlled by ESP and scrubbers.

[h] Uncontrolled emission factor from 1971 tests on two facilities (References 5 and 6).

[j] kg/Mg throughput; includes charge car loading; from tests at one facility.

[k] kg/Mg of bullion, includes dross kettles; from tests at one facility.

[m] kg/Mg granulated; from tests at one facility.

Table 12.6-2 (English Units). EMISSION FACTORS FOR PRIMARY LEAD SMELTING[a]

EMISSION FACTOR RATING: E

Process	Particulate[b]	PM-10[c]	Lead	SO_2
Ore crushing[d] (SCC 3-03-010-04)	0.0445	0.036	0.002	NA
Ore screening[e] (SCC 3-03-010-27)	0.007	0.009	0.002	NA
Tetrahedrite drier[f] (SCC 3-03-010-28)	0.023	0.026	0.0006	NA
Sinter machine (weak gas)[g] (SCC 3-03-010-29)	0.10	0.104	0.019	550[h]
Sinter building fugitives[g] (SCC 3-03-010-25)	0.24	0.117	0.032	NA
Sinter storage[j] (SCC 3-03-010-30)	NA	NA	NA	NA
Blast furnace[k] (SCC 3-03-010-02)	0.43	0.863	0.067	45[h]
Speiss pit[m] (SCC 3-03-101-31)	NA	NA	NA	NA

[a] Most of the processes are controlled by baghouses; otherwise it is noted. SCC = Source Classification Code. NA = not applicable.

[b] Filterable particulate only.

[c] Filterable and condensable particulate; ≤ 10 μm mean diameter.

[d] Entire ore crushing building at one facility, including transfer points; lb/ton of ore, except lead, which is lb/ton of lead in ore.

[e] Tests at one facility; lb/ton ore.

[f] lb/ton dried; tests at one facility.

[g] lb/ton sinter produced; tests at one facility. The sinter machine is controlled by ESP and scrubbers.

[h] Uncontrolled emission factor from 1971 tests on two facilities (5,6).

[j] lb/ton throughput; includes charge car loading; from tests at one facility.

[k] lb/ton of bullion, includes dross kettles; from tests at one facility.

[m] lb/ton granulated; from tests at one facility.

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12.7 Zinc Smelting

12.7.1 General[1-2]

Zinc is found in the earth's crust primarily as zinc sulfide (ZnS). Primary uses for zinc include galvanizing of all forms of steel, as a constituent of brass, for electrical conductors, vulcanization of rubber and in primers and paints. Most of these applications are highly dependent upon zinc's resistance to corrosion and its light weight characteristics. In 1991, approximately 260,000 megagrams (287,000 tons) of zinc were refined at the 4 U. S. primary zinc smelters. The annual production volume has remained constant since the 1980s. Three of these 4 plants, located in Illinois, Oklahoma, and Tennessee, utilize electrolytic technology, and the 1 plant in Pennsylvania uses an electrothermic process. This annual production level approximately equals production capacity, despite a mined zinc ore recovery level of 520 megagrams (573 tons), a domestic zinc demand of 1190 megagrams (1311 tons), and a secondary smelting production level of only 110 megagrams (121 tons). As a result, the U. S. is a leading exporter of zinc concentrates as well as the world's largest importer of refined zinc.

Zinc ores typically may contain from 3 to 11 percent zinc, along with cadmium, copper, lead, silver, and iron. Beneficiation, or the concentration of the zinc in the recovered ore, is accomplished at or near the mine by crushing, grinding, and flotation process. Once concentrated, the zinc ore is transferred to smelters for the production of zinc or zinc oxide. The primary product of most zinc companies is slab zinc, which is produced in 5 grades: special high grade, high grade, intermediate, brass special, and prime western. The 4 U. S. primary smelters also produce sulfuric acid as a byproduct.

12.7.2 Process Description

Reduction of zinc sulfide concentrates to metallic zinc is accomplished through either electrolytic deposition from a sulfate solution or by distillation in retorts or furnaces. Both of these methods begin with the elimination of most of the sulfur in the concentrate through a roasting process, which is described below. A generalized process diagram depicting primary zinc smelting is presented in Figure 12.7-1.

Roasting is a high-temperature process that converts zinc sulfide concentrate to an impure zinc oxide called calcine. Roaster types include multiple-hearth, suspension, or fluidized bed. The following reactions occur during roasting:

$$2ZnS + 3O_2 \rightarrow 2ZnO + SO_2 \qquad (1)$$

$$2SO_2 + O_2 \rightarrow 2SO_3 \qquad (2)$$

In a multiple-hearth roaster, the concentrate drops through a series of 9 or more hearths stacked inside a brick-lined cylindrical column. As the feed concentrate drops through the furnace, it is first dried by the hot gases passing through the hearths and then oxidized to produce calcine. The reactions are slow and can be sustained only by the addition of fuel. Multiple hearth roasters are unpressurized and operate at about 690°C (1300°F). Operating time depends upon the composition of concentrate and the amount of the sulfur removal required. Multiple hearth roasters have the capability of producing a high-purity calcine.

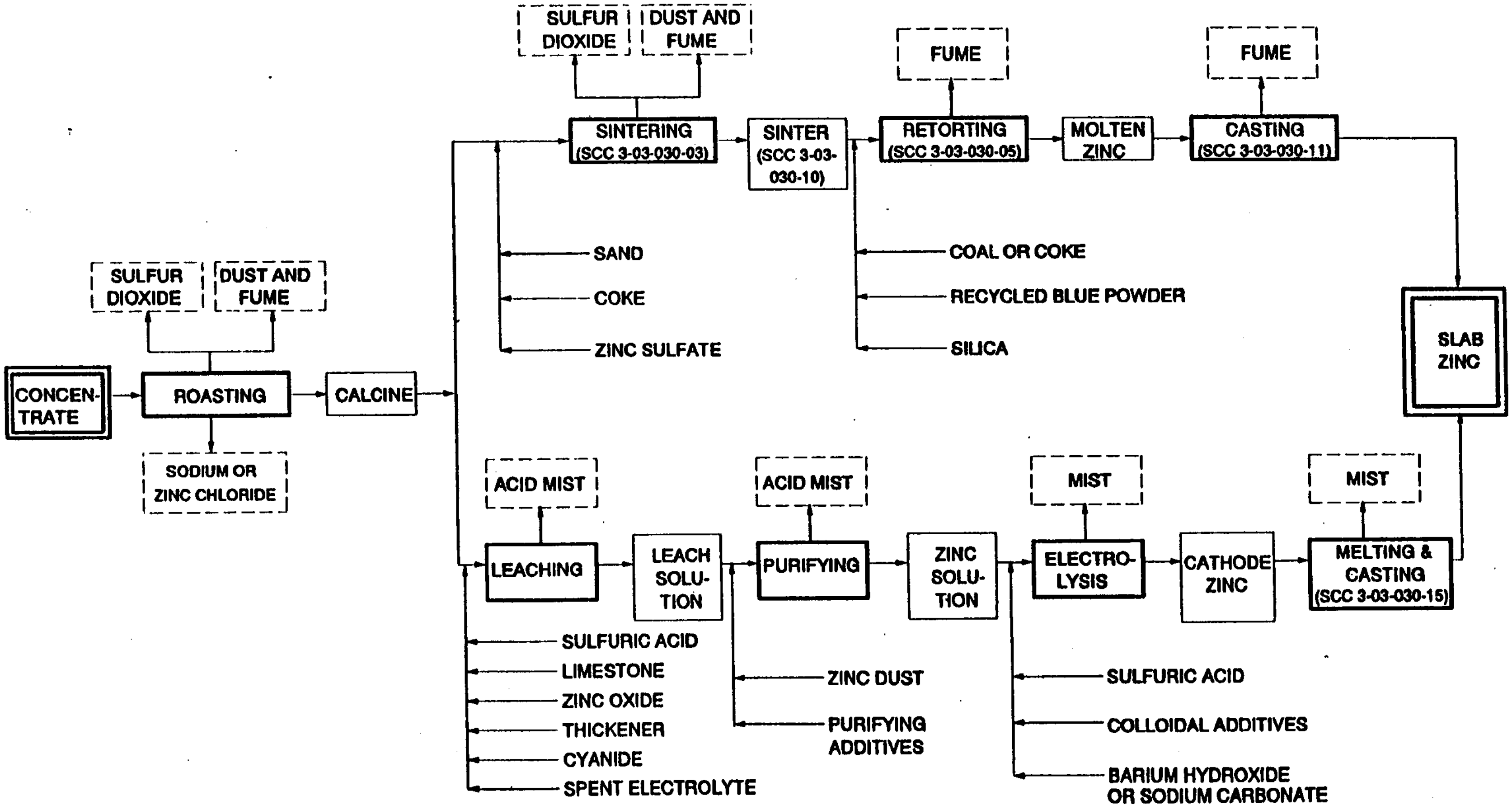

Figure 12.7-1. Generalized process flow for primary zinc smelting. (Source Classification Codes in parentheses.)

In a suspension roaster, the concentrates are blown into a combustion chamber very similar to that of a pulverized coal furnace. The roaster consists of a refractory-lined cylindrical steel shell, with a large combustion space at the top and 2 to 4 hearths in the lower portion, similar to those of a multiple hearth furnace. Additional grinding, beyond that required for a multiple hearth furnace, is normally required to ensure that heat transfer to the material is sufficiently rapid for the desulfurization and oxidation reactions to occur in the furnace chamber. Suspension roasters are unpressurized and operate at about 980°C (1800°F).

In a fluidized-bed roaster, finely ground sulfide concentrates are suspended and oxidized in a feedstock bed supported on an air column. As in the suspension roaster, the reaction rates for desulfurization are more rapid than in the older multiple-hearth processes. Fluidized-bed roasters operate under a pressure slightly lower than atmospheric and at temperatures averaging 1000°C (1800°F). In the fluidized-bed process, no additional fuel is required after ignition has been achieved. The major advantages of this roaster are greater throughput capacities and greater sulfur removal capabilities.

Electrolytic processing of desulfurized calcine consists of 3 basic steps, leaching, purification, and electrolysis. Leaching occurs in an aqueous solution of sulfuric acid, yielding a zinc sulfate solution as shown in Equation 3 below.

$$ZnO + SO_3 \rightarrow ZnSO_4 \qquad (3)$$

In double leaching, the calcine is first leached in a neutral or slightly alkaline solution, then in an acidic solution, with the liquid passing countercurrent to the flow of calcine. In the neutral leaching solution, sulfates from the calcine dissolve, but only a portion of the zinc oxide enters into solution. The acidic leaching solution dissolves the remainder of the zinc oxide, along with metallic impurities such as arsenic, antimony, cobalt, germanium, nickel, and thallium. Insoluble zinc ferrite, formed during concentrate roasting by the reaction of iron with zinc, remains in the leach residue, along with lead and silver. Lead and silver typically are shipped to a lead smelter for recovery, while the zinc is extracted from the zinc ferrite to increase recovery efficiency.

In the purification process, a number of various reagents are added to the zinc-laden electrolyte in a sequence of steps designed to precipitate the metallic impurities, which otherwise will interfere with deposition of zinc. After purification, concentrations of these impurities are limited to less than 0.05 milligram per liter (4×10^{-7} pounds per gallon). Purification is usually conducted in large agitated tanks. The process takes place at temperatures ranging from 40 to 85°C (104 to 185°F), and pressures ranging from atmospheric to 240 kilopascals (kPa) (2.4 atmospheres).

In electrolysis, metallic zinc is recovered from the purified solution by passing current through an electrolyte solution, causing zinc to deposit on an aluminum cathode. As the electrolyte is slowly circulated through the cells, water in the electrolyte dissociates, releasing oxygen gas at the anode. Zinc metal is deposited at the cathode and sulfuric acid is regenerated for recycle to the leach process. The sulfuric acid acts as a catalyst in the process as a whole.

Electrolytic zinc smelters contain as many as several hundred cells. A portion of the electrical energy is converted into heat, which increases the temperature of the electrolyte. Electrolytic cells operate at temperature ranges from 30 to 35°C (86 to 95°F) and at atmospheric pressure. A portion of the electrolyte is continuously circulated through the cooling towers both to cool and concentrate the electrolyte through evaporation of water. The cooled and concentrated electrolyte is then recycled to the cells. Every 24 to 48 hours, each cell is shut down, the zinc-coated cathodes are removed and rinsed, and the zinc is mechanically stripped from the aluminum plates.

The electrothermic distillation retort process, as it exists at 1 U. S. plant, was developed by the St. Joe Minerals Corporation in 1930. The principal advantage of this pyrometallurgical technique over electrolytic processes is its ability to accommodate a wide variety of zinc-bearing materials, including secondary items such as calcine derived from electric arc furnace (EAF) dust. Electrothermic processing of desulfurized calcine begins with a downdraft sintering operation, in which grate pallets are joined to form a continuous conveyor system. The sinter feed is essentially a mixture of roaster calcine and EAF calcine. Combustion air is drawn down through the conveyor, and impurities such as lead, cadmium, and halides in the sinter feed are driven off and collected in a bag filter. The product sinter typically includes 48 percent zinc, 8 percent iron, 5 percent aluminum, 4 percent silicon, 2.5 percent calcium, and smaller quantities of magnesium, lead, and other metals.

Electric retorting with its greater thermal efficiency than externally heated furnaces, is the only pyrometallurgical technique utilized by the U. S. primary zinc industry, now and in the future. Product sinter and, possibly, secondary zinc materials are charged with coke to an electric retort furnace. The charge moves downward from a rotary feeder in the furnace top into a refractory-lined vertical cylinder. Paired graphite electrodes protrude from the top and bottom of this cylinder, producing a current flow. The coke serves to provide electrical resistance, producing heat and generating the carbon monoxide required for the reduction process. Temperatures of 1400°C (2600°F) are attained, immediately vaporizing zinc oxides according to the following reaction:

$$ZnO + CO \rightarrow Zn\ (vapor) + CO_2 \qquad (4)$$

The zinc vapor and carbon dioxide pass to a vacuum condenser, where zinc is recovered by bubbling through a molten zinc bath. Over 95 percent of the zinc vapor leaving the retort is condensed to liquid zinc. The carbon dioxide is regenerated with carbon, and the carbon monoxide is recycled back to the retort furnace.

12.7.3 Emissions And Controls

Each of the 2 smelting processes generates emissions along the various process steps. The roasting process in a zinc smelter is typically responsible for more than 90 percent of the potential SO_2 emissions. About 93 to 97 percent of the sulfur in the feed is emitted as sulfur oxides. Concentrations of SO_2 in the offgas vary with the type of roaster operation. Typical SO_2 concentrations for multiple hearth, suspension, and fluidized bed roasters are 4.5 to 6.5 percent, 10 to 13 percent, and 7 to 12 percent, respectively. Sulfur dioxide emissions from the roasting processes at all 4 U. S. primary zinc processing facilities are recovered at on-site sulfuric acid plants. Much of the particulate matter emitted from primary zinc processing facilities is also attributable to the concentrate roasters. The amount and composition of particulate varies with operating parameters, such as air flow rate and equipment configuration. Various combinations of control devices such as cyclones, electrostatic precipitators (ESP), and baghouses can be used on roasters and on sintering machines, achieving 94 to 99 percent emission reduction.

Controlled and uncontrolled particulate emission factors for points within a zinc smelting facility are presented in Tables 12.7-1 and 12.7-2. Fugitive emission factors are presented in Tables 12.7-3 and 12.7-4. These emission factors should be applied carefully. Emission factors for sintering operations are derived from data from a single facility no longer operating. Others are estimated based on similar operations in the steel, lead, and copper industries. Testing on 1 electrothermic primary zinc smelting facility indicates that cadmium, chromium, lead, mercury, nickel, and zinc are contained in the offgases from both the sintering machine and the retort furnaces.

Table 12.7-1 (Metric Units). PARTICULATE EMISSION FACTORS FOR ZINC SMELTING[a]

Process	Uncontrolled	EMISSION FACTOR RATING	Controlled	EMISSION FACTOR RATING
Roasting				
Multiple hearth[b] (SCC 3-03-030-02)	113	E	ND	NA
Suspension[c] (SCC 3-03-030-07)	1000	E	4	E
Fluidized bed[d] (SCC 3-03-030-08)	1083	E	ND	NA
Sinter plant (SCC 3-03-030-03)				
Uncontrolled[e]	62.5	E	NA	NA
With cyclone[f]	NA	NA	24.1	E
With cyclone and ESP[f]	NA	NA	8.25	E
Vertical retort[g] (SCC 3-03-030-05)	7.15	D	ND	NA
Electric retort[h] (SCC 3-03-030-29)	10.0	E	ND	NA
Electrolytic process[j] (SCC 3-03-030-06)	3.3	E	ND	NA

[a] Factors are for kg/Mg of zinc ore processed. SCC = Source Classification Code. ESP = Electrostatic precipitator. ND = no data. NA = not applicable.

[b] References 5-7. Averaged from an estimated 10% of feed released as particulate, zinc production rate at 60% of roaster feed rate, and other estimates.

[c] References 5-7. Based on an average 60% of feed released as particulate emission and a zinc production rate at 60% of roaster feed rate. Controlled emissions based on 20% dropout in waste heat boiler and 99.5% dropout in cyclone and ESP.

[d] References 5,13. Based on an average 65% of feed released as particulate emissions and a zinc production rate of 60% of roaster feed rate.

[e] Reference 5. Based on unspecified industrial source data.

[f] Reference 8. Data not necessarily compatible with uncontrolled emissions.

[g] Reference 8.

[h] Reference 14. Based on unspecified industrial source data.

[j] Reference 10.

Table 12.7-2 (English Units). PARTICULATE EMISSION FACTORS FOR ZINC SMELTING[a]

Process	Uncontrolled	EMISSION FACTOR RATING	Controlled	EMISSION FACTOR RATING
Roasting				
Multiple hearth[b] (SCC 3-03-030-02)	227	E	ND	NA
Suspension[c] (SCC 3-03-030-07)	2000	E	8	E
Fluidized bed[d] (SCC 3-03-030-08)	2167	E	ND	NA
Sinter plant (SCC 3-03-030-03)				
Uncontrolled[e]	125	E	NA	NA
With cyclone[f]	NA	NA	48.2	E
With cyclone and ESP[f]	NA	NA	16.5	E
Vertical retort[g] (SCC 3-03-030-05)	14.3	D	ND	NA
Electric retort[h] (SCC 3-03-030-29)	20.0	E	ND	NA
Electrolytic process[j] (SCC 3-03-030-06)	6.6	E	ND	NA

[a] Factors are for lb/ton of zinc ore processed. SCC = Source Classification Code. ESP = Electrostatic precipitator. ND = no data. NA = not applicable.

[b] References 5-7. Averaged from an estimated 10% of feed released as particulate, zinc production rate at 60% of roaster feed rate, and other estimates.

[c] References 5-7. Based on an average 60% of feed released as particulate emission and a zinc production rate at 60% of roaster feed rate. Controlled emissions based on 20% dropout in waste heat boiler and 99.5% dropout in cyclone and ESP.

[d] References 5,13. Based on an average 65% of feed released as particulate emissions and a zinc production rate of 60% of roaster feed rate.

[e] Reference 5. Based on unspecified industrial source data.

[f] Reference 8. Data not necessarily compatible with uncontrolled emissions.

[g] Reference 8.

[h] Reference 14. Based on unspecified industrial source data.

[j] Reference 10.

Table 12.7-3 (Metric Units). UNCONTROLLED FUGITIVE PARTICULATE EMISSION FACTORS FOR SLAB ZINC SMELTING[a]

Process	Emissions	EMISSION FACTOR RATING
Roasting (SCC 3-03-030-24)	Negligible	NA
Sinter plant[b]		
Wind box (SCC 3-03-030-25)	0.12 - 0.55	E
Discharge screens (SCC 3-03-030-26)	0.28 - 1.22	E
Retort building[c] (SCC 3-03-030-27)	1.0 - 2.0	E
Casting[d] (SCC 3-03-030-28)	1.26	E

[a] Reference 9. Factors are in kg/Mg of product. SCC = Source Classification Code. NA = not applicable.

[b] From steel industry operations for which there are emission factors. Based on quantity of sinter produced.

[c] From lead industry operations.

[d] From copper industry operations.

Table 12.7-4 (English Units). UNCONTROLLED FUGITIVE PARTICULATE EMISSION FACTORS FOR SLAB ZINC SMELTING[a]

Process	Emissions	EMISSION FACTOR RATING
Roasting (SCC 3-03-030-24)	Negligible	NA
Sinter plant[b]		
Wind box (SCC 3-03-030-25)	0.24 - 1.10	E
Discharge screens (SCC 3-03-030-26)	0.56 - 2.44	E
Retort building[c] (SCC 3-03-030-27)	2.0 - 4.0	E
Casting[d] (SCC 3-03-030-28)	2.52	E

[a] Reference 9. Factors are in lb/ton of product. SCC = Source Classification Code. NA = not applicable.

[b] From steel industry operations for which there are emission factors. Based on quantity of sinter produced.

[c] From lead industry operations.

[d] From copper industry operations.

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12.8 Secondary Aluminum Operations

12.8.1 General[1]

Secondary aluminum producers recycle aluminum from aluminum-containing scrap, while primary aluminum producers convert bauxite ore into aluminum. The secondary aluminum industry was responsible for 27.5 percent of domestic aluminum produced in 1989. There are approximately 116 plants with a recovery capacity of approximately 2.4 million megagrams (2.6 million tons) of aluminum per year. Actual total secondary aluminum production was relatively constant during the 1980s. However, increased demand for aluminum by the automobile industry has doubled in the last 10 years to an average of 78.5 kilograms (173 pounds) per car. Recycling of used aluminum beverage cans (UBC) increased more than 26 percent from 1986 to 1989. In 1989, 1.3 million megagrams (1.4 million tons) of UBCs were recycled, representing over 60 percent of cans shipped. Recycling a ton of aluminum requires only 5 percent of the energy required to refine a ton of primary aluminum from bauxite ore, making the secondary aluminum economically viable.

12.8.2 Process Description

Secondary aluminum production involves 2 general categories of operations, scrap pretreatment and smelting/refining. Pretreatment operations include sorting, processing, and cleaning scrap. Smelting/refining operations include cleaning, melting, refining, alloying, and pouring of aluminum recovered from scrap. The processes used to convert scrap aluminum to products such as lightweight aluminum alloys for industrial castings are presented in Figure 12.8-1A and Figure 12.8-1B. Some or all the steps in these figures may be involved at any one facility. Some steps may be combined or reordered, depending on scrap quality, source of scrap, auxiliary equipment available, furnace design, and product specifications. Plant configuration, scrap type usage, and product output varies throughout the secondary aluminum industry.

12.8.2.1 Scrap Pretreatment -

Aluminum scrap comes from a variety of sources. "New" scrap is generated by pre-consumer sources, such as drilling and machining of aluminum castings, scrap from aluminum fabrication and manufacturing operations, and aluminum bearing residual material (dross) skimmed off molten aluminum during smelting operations. "Old" aluminum scrap is material that has been used by the consumer and discarded. Examples of old scrap include used appliances, aluminum foil, automobile and airplane parts, aluminum siding, and beverage cans.

Scrap pretreatment involves sorting and processing scrap to remove contaminants and to prepare the material for smelting. Sorting and processing separates the aluminum from other metals, dirt, oil, plastics, and paint. Pretreatment cleaning processes are based on mechanical, pyrometallurgical, and hydrometallurgical techniques.

12.8.2.1.1 Mechanical Cleaning -

Mechanical cleaning includes the physical separation of aluminum from other scrap, with hammer mills, ring rushers, and other machines to break scrap containing aluminum into smaller pieces. This improves the efficiency of downstream recovery by magnetic removal of iron. Other recovery processes include vibratory screens and air classifiers.

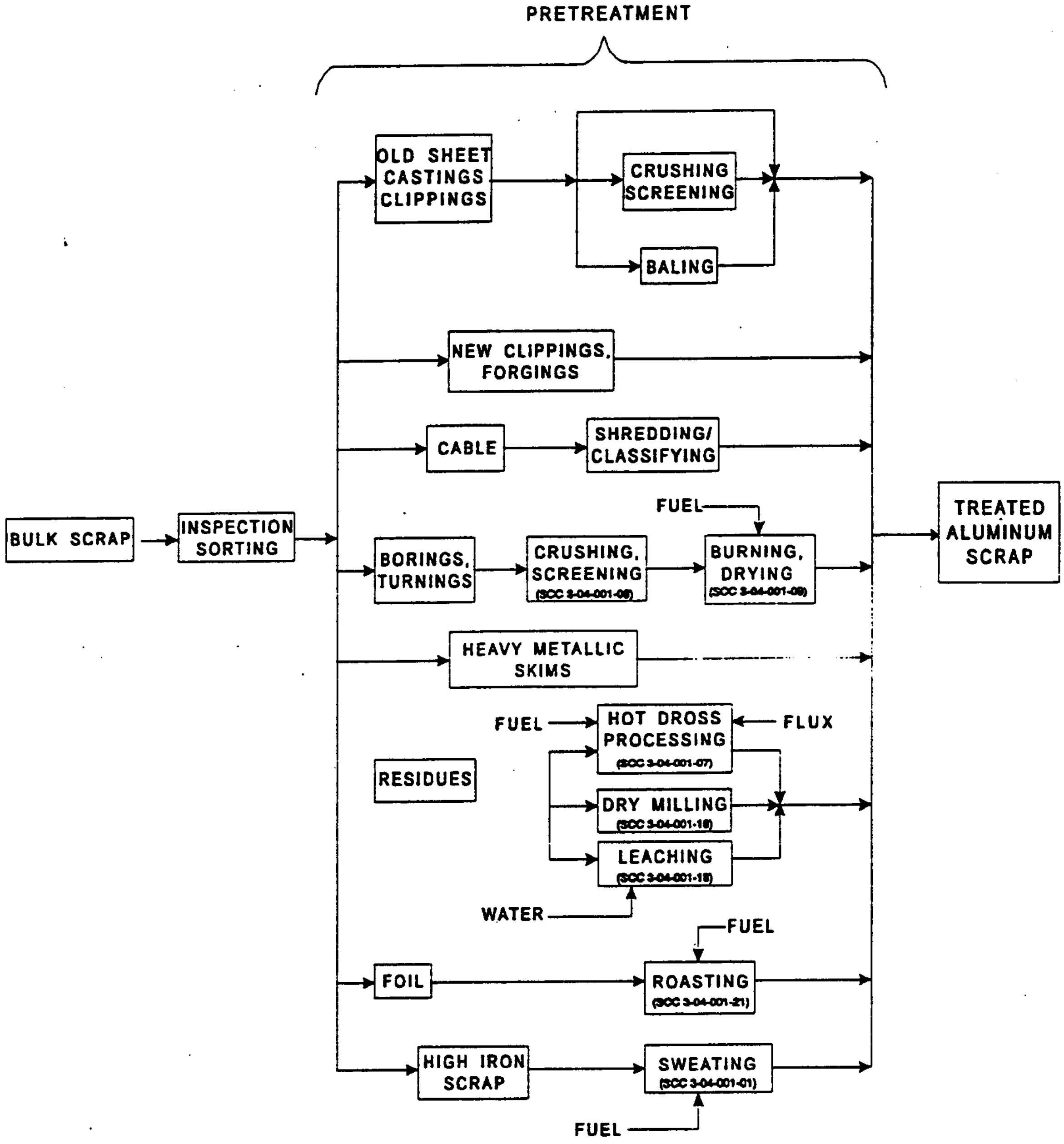

Figure 12.8-1A. Typical process diagram for secondary aluminum processing industry. (Source Classification Codes in parentheses.)

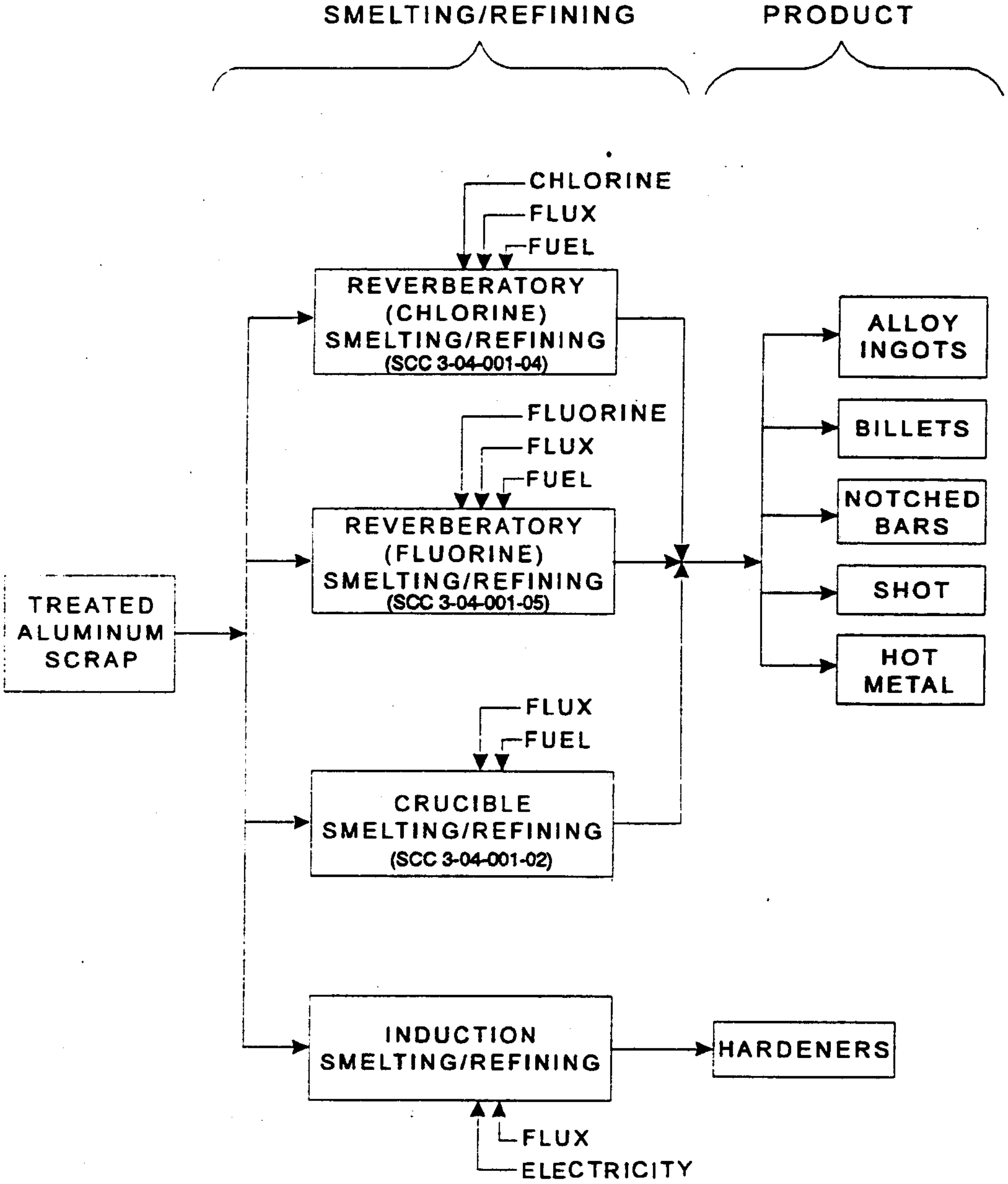

Figure 12.8-1B. Typical process diagram for secondary aluminum processing industry. (Source Classification Codes in parentheses.)

An example of mechanical cleaning is the dry milling process. Cold aluminum-laden dross and other residues are processed by milling and screening to obtain a product containing at least 60 to 70 percent aluminum. Ball, rod, or hammer mills can be used to reduce oxides and nonmetallic particles to fine powders for ease of removal during screening.

12.8.2.1.2 Pyrometallurgical Cleaning -

Pyrometallurgical techniques (called drying in the industry) use heat to separate aluminum from contaminates and other metals. Pyrometallurgical techniques include roasting and sweating. The roasting process involves heating aluminum scrap that contains organic contaminates in rotary dryers to temperatures high enough to vaporize or carbonize organic contaminates, but not high enough to melt aluminum (660°C [1220°F]). An example of roasting is the APROS delacquering and preheating process used during the processing of used beverage cans (shown in Figure 12.8-2). The sweating process involves heating aluminum scrap containing other metals in a sweat furnace to temperatures above the melting temperature of aluminum, but below that of the other metal. For example, sweating recovers aluminum from high-iron-content scrap by heating the scrap in an open flame reverberatory furnace. The temperature is raised and maintained above the melting temperature of aluminum, but below the melting temperature of iron. This condition causes aluminum and other low melting constituents to melt and trickle down the sloped hearth, through a grate and into air-cooled molds or collecting pots. This product is called "sweated pig". The higher-melting materials, including iron, brass, and the oxidation products formed during the sweating process, are periodically removed from the furnace.

In addition to roasting and sweating, a catalytic technique may also be used to clean aluminum dross. Dross is a layer of impurities and semisolid flux that has been skimmed from the surface of molten aluminum. Aluminum may be recovered from dross by batch fluxing with a salt/cryolite mixture in a mechanically rotated, refractory-lined barrel furnace. Cryolite acts as a catalyst that decreases aluminum surface tension and therefore increases recovery rates. Aluminum is tapped periodically through a hole in the base of the furnace.

12.8.2.1.3 Hydrometallurgical Cleaning -

Hydrometallurgical techniques use water to clean and process aluminum scrap. Hydrometallurgical techniques include leaching and heavy media separation. Leaching is used to recover aluminum from dross, furnace skimmings, and slag. It requires wet milling, screening, drying, and finally magnetic separation to remove fluxing salts and other waste products from the aluminum. First, raw material is fed into a long rotating drum or a wet-ball mill where water soluble contaminants are rinsed into waste water and removed (leached). The remaining washed material is then screened to remove fines and undissolved salts. The screened material is then dried and passed through a magnetic separator to remove ferrous materials.

The heavy media separation hydrometallurgical process separates high density metal from low density metal using a viscous medium, such as copper and iron, from aluminum. Heavy media separation has been used to concentrate aluminum recovered from shredded cars. The cars are shredded after large aluminum components have been removed (shredded material contains approximately 30 percent aluminum) and processed in heavy media to further concentrate aluminum to 80 percent or more.

12.8.2.2 Smelting/Refining -

After scrap pretreatment, smelting and refining is performed. Smelting and refining in secondary aluminum recovery takes place primarily in reverberatory furnaces. These furnaces are brick-lined and constructed with a curved roof. The term reverberatory is used because heat rising

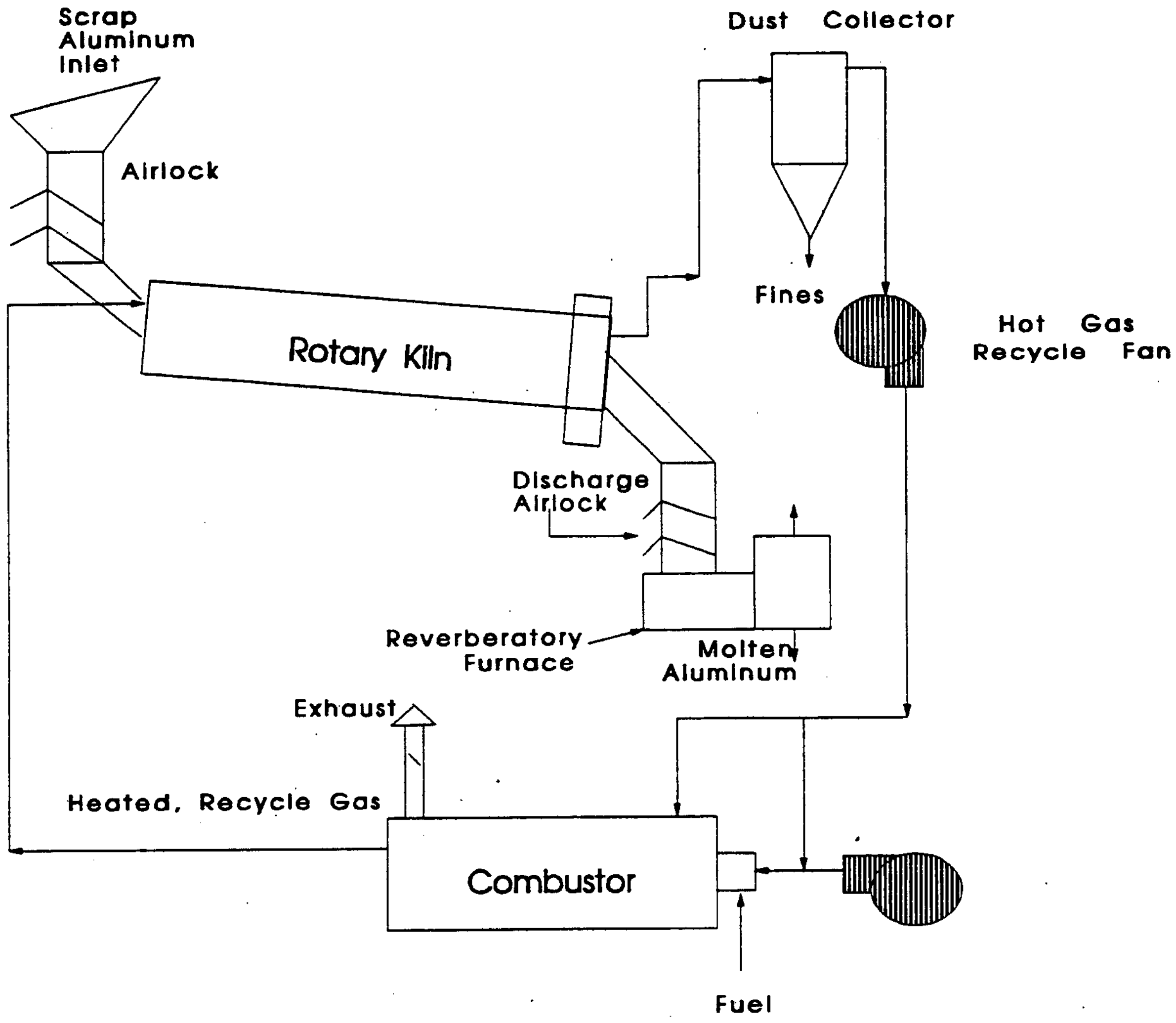

Figure 12.8-2. APROS delacquering and preheating process.

from ignited fuel is reflected (reverberated) back down from the curved furnace roof and into the melted charge. A typical reverberatory furnace has an enclosed melt area where the flame heat source operates directly above the molten aluminum. The furnace charging well is connected to the melt area by channels through which molten aluminum is pumped from the melt area into the charging well. Aluminum flows back into the melt section of the furnace under gravity.

Most secondary aluminum recovery facilities use batch processing in smelting and refining operations. It is common for 1 large melting reverberatory furnace to support the flow requirements for 2 or more smaller holding furnaces. The melting furnace is used to melt the scrap, and remove impurities and entrained gases. The molten aluminum is then pumped into a holding furnace. Holding furnaces are better suited for final alloying, and for making any additional adjustments necessary to ensure that the aluminum meets product specifications. Pouring takes place from holding furnaces, either into molds or as feedstock for continuous casters.

Smelting and refining operations can involve the following steps: charging, melting, fluxing, demagging, degassing, alloying, skimming, and pouring. Charging consists of placing pretreated aluminum scrap into a melted aluminum pool (heel) that is maintained in melting furnaces. The scrap, mixed with flux material, is normally placed into the furnace charging well, where heat from the molten aluminum surrounding the scrap causes it to melt by conduction. Flux materials combine with contaminates and float to the surface of the aluminum, trapping impurities and providing a barrier (up to 6 inches thick) that reduces oxidation of the melted aluminum. To minimize aluminum oxidation (melt loss), mechanical methods are used to submerge scrap into the heel as quickly as possible. Scrap may be charged as high density bales, loosely packed bales, or as dry shredded scrap that is continuously fed from a conveyor and into the vortex section of the charging well. The continuous feed system is advantageous when processing uniform scrap directly from a drier (such as a delacquering operation for UBCs).

Demagging reduces the magnesium content of the molten charge from approximately 0.5 percent to about 0.1 percent (a typical product specification). In the past, when demagging with liquid chlorine, chlorine was injected under pressure to react with magnesium as the chlorine bubbled to the surface. The pressurized chlorine was released through carbon lances directed under the heel surface, resulting in high chlorine emissions.

A more recent chlorine aluminum demagging process has replaced the carbon lance procedure. Molten aluminum in the furnace charging well gives up thermal energy to the scrap as scrap is melted. In order to maintain high melt rates in the charging well, a circulation pump moves high temperature molten aluminum from the melt section of the reverberatory furnace to the charging well. Chlorine gas is metered into the circulation pump's discharge pipe. By inserting chlorine gas into the turbulent flow of the molten aluminum at an angle to the aluminum pump discharge, small chlorine-filled gas bubbles are sheared off and mixed rapidly in the turbulent flow found in the pump's discharge pipe. In actual practice, the flow rate of chlorine gas is increased until a slight vapor (aluminum chloride) can be seen above the surface of the molten aluminum. Then the flow rate is decreased until no more vapor is seen. It is reported that chlorine usage approaches the stoichiometric relationship using this process. Chlorine emissions resulting from this procedure have not been made available, but it is anticipated that reductions of chlorine emissions (in the form of chloride compounds) will be reported in the future.

Other chlorinating agents or fluxes, such as anhydrous aluminum chloride or chlorinated organics, are used in demagging operations. Demagging with fluorine is similar to demagging with chlorine, except that aluminum fluoride (AlF_3) is employed instead of chlorine. The AlF_3 reacts with magnesium to produce molten metallic aluminum and solid magnesium fluoride salt that floats to the surface of the molten aluminum and is trapped in the flux layer.

Degassing is a process used to remove gases entrained in molten aluminum. High-pressure inert gases are released below the molten surface to violently agitate the melt. This agitation causes the entrained gasses to rise to the surface to be absorbed in the floating flux. In some operations, degassing is combined with the demagging operation. A combination demagging and degassing process has been developed that uses a 10 percent concentration of chlorine gas mixed with a nonreactive gas (either nitrogen or argon). The combined high-pressure gases are forced through a hand held nozzle that has a designed distribution pattern of hole sizes across the face of the nozzle. The resulting high turbulent flow and the diluted chlorine content primarily degasses the melt. Chlorine emissions resulting from this process are not available.

Alloying combines aluminum with an alloying agent in order to change its strength and ductility. Alloying agents include zinc, copper, manganese, magnesium, and silicon. The alloying steps include an analysis of the furnace charge, addition of the required alloying agents, and then a reanalysis of the charge. This iterative process continues until the correct alloy is reached.

The skimming operation physically removes contaminated semisolid fluxes (dross, slag, or skimmings) by ladling them from the surface of the melt. Skimming is normally conducted several times during the melt cycle, particularly if the pretreated scrap contains high levels of contamination. Following the last skimming, the melt is allowed to cool before pouring into molds or casting machines.

The crucible smelting/refining process is used to melt small batches of aluminum scrap, generally limited to 500 kg (1,100 lb) or less. The metal-treating process steps are essentially the same as those of reverberatory furnaces.

The induction smelting and refining process is designed to produce aluminum alloys with increased strength and hardness by blending aluminum and hardening agents in an electric induction furnace. The process steps include charging scrap, melting, adding and blending the hardening agent, skimming, pouring, and casting into notched bars. Hardening agents include manganese and silicon.

12.8.3 Emissions And Controls[2-8]

The major sources of emissions from scrap pretreatment processes are scrap crushing and screening operations, scrap driers, sweat furnaces, and UBC delacquering systems. Although each step in scrap treatment and smelting/refining is a potential source of emissions, emission factors for scrap treatment processes have not been sufficiently characterized and documented and are therefore not presented below.

Smelting and refining emission sources originate from charging, fluxing, and demagging processes. Tables 12.8-1 and 12.8-2 present emission factors for sweating furnaces, crucible furnaces, reverberatory furnaces, and chlorine demagging process.

Table 12.8-1 (Metric Units). PARTICULATE EMISSION FACTORS FOR SECONDARY ALUMINUM OPERATIONS[a]

Operation	Uncontrolled	EMISSION FACTOR RATING	Baghouse	EMISSION FACTOR RATING	Electrostatic Precipitator	EMISSION FACTOR RATING
Sweating furnace[b] (SCC 3-04-001-01)	7.25	E	1.65	E	ND	NA
Smelting						
Crucible furnace[b] (SCC 3-04-001-02)	0.95	E	ND	NA	ND	NA
Reverberatory[c] (SCC 3-04-001-03)	2.15	E	0.65[e]	E	0.65	E
Chlorine demagging[d] (SCC 3-04-001-04)	500	E	25	E	ND	E

[a] Reference 3. Emission factors for sweating and smelting furnaces expressed as kg/Mg of metal processed. For chlorine demagging, emission factor is kg/Mg of chlorine used. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Based upon averages of 2 source tests.

[c] Uncontrolled, based on averages of 10 source tests. Standard deviation of uncontrolled emission factor is 1.75 kg/Mg (3.5 lb/ton), that of controlled emission factor is 0.15 kg/Mg.

[d] Based on average of 10 source tests. Standard deviation of uncontrolled emission factor is 215 kg/Mg; that of controlled emission factor is 18 kg/Mg.

[e] This factor may be lower if a coated baghouse is used.

Table 12.8-2 (English Units). PARTICULATE EMISSION FACTORS FOR SECONDARY ALUMINUM OPERATIONS[a]

Operation	Uncontrolled	EMISSION FACTOR RATING	Baghouse	EMISSION FACTOR RATING	Electrostatic Precipitator	EMISSION FACTOR RATING
Sweating furnace[b] (SCC 3-04-001-01)	14.5	E	3.3	E	ND	NA
Smelting						
Crucible furnace[b] (SCC 3-04-001-02)	1.9	E	ND	NA	ND	NA
Reverberatory[c] (SCC 3-04-001-03)	4.3	E	1.3[e]	E	1.3	E
Chlorine demagging[d] (SCC 3-04-001-04)	1000	E	50	E	ND	NA

[a] Reference 3. Emission factors for sweating and smelting furnaces expressed as lb/ton of metal processed. For chlorine demagging, emission factor is lb/ton of chlorine used. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Based upon averages of 2 source tests.

[c] Uncontrolled, based on averages of 10 source tests. Standard deviation of uncontrolled emission factor is 3.5 lb/ton, that of controlled emission factor is 0.3 lb/ton.

[d] Based on average of 10 source tests. Standard deviation of uncontrolled emission factor is 430 lb/ton; that of controlled emission factor is 36 lb/ton.

[e] This factor may be lower if a coated baghouse is used.

12.8.3.1 Scrap Pretreatment Emissions -

Mechanical cleaning techniques involve crushing, shredding, and screening and produce metallic and nonmetallic particulates. Burning and drying operations (pyrometallurgic techniques) emit particulates and organic vapors. Afterburners are frequently used to convert unburned VOCs to carbon dioxide and water vapor. Other gases that may be present, depending on the composition of the contaminants, include chlorides, fluorides, and sulfur oxides. Specific emission factors for these gases are not presented due to lack of data. Oxidized aluminum fines blown out of the dryer by the combustion gases contain particulate emissions. Wet scrubbers or fabric filters are sometimes used in conjunction with afterburners.

Mechanically generated dust from rotating barrel dross furnaces constitutes the main air emission of hot dross processing. Some fumes are produced from the fluxing reactions. Fugitive emissions are controlled by enclosing the barrel furnace in a hood system and by ducting the emissions to a fabric filter. Furnace offgas emissions, mainly fluxing salt fume, are often controlled by a venturi scrubber.

Emissions from sweating furnaces vary with the feed scrap composition. Smoke may result from incomplete combustion of organic contaminants (e. g., rubber, oil and grease, plastics, paint, cardboard, paper) that may be present. Fumes can result from the oxidation of magnesium and zinc contaminants and from fluxes in recovered dross and skims.

In dry milling, large amounts of dust are generated from the crushing, milling, screening, air classification, and materials transfer steps. Leaching operations (hydrometallurgic techniques) may produce particulate emissions during drying. Particulate emissions from roasting result from the charring of carbonaceous materials (ash).

12.8.3.2 Smelting/Refining Emissions -

Emissions from reverberatory furnaces represent a significant fraction of the total particulate and gaseous effluent generated in the secondary aluminum industry. Emissions from the charging well consist of organic and inorganic particulate, unburned organic vapors, and carbon dioxide. Emissions from furnace burners contain carbon monoxide, carbon dioxide, sulfuric oxide, and nitrogen oxide. Furnace burner emissions are usually separated from process emissions.

Emissions that result from fluxing operations are dependent upon both the type of fluxing agents and the amount required, which are a function of scrap quality. Emissions may include common fluxing salts such as sodium chloride, potassium chloride, and cryolite. Aluminum and magnesium chloride also may be generated from the fluxing materials being added to the melt. Studies have suggested that fluxing particulate emission are typically less than 1 micrometer in diameter. Specific emission factors for these compounds are not presented due to lack of information.

In the past, demagging represented the most severe source of emissions for the secondary aluminum industry. A more recent process change where chlorine gas is mixed into molten aluminum from the furnace circulation pump discharge may reduce chlorine emissions. However, total chlorine emissions are directly related to the amount of demagging effort and product specifications (the magnesium content in the scrap and the required magnesium reduction). Also, as the magnesium percentage decreases during demagging, a disproportional increase in emissions results due to the decreased efficiency of the scavenging process.

Both the chlorine and aluminum fluoride demagging processes create highly corrosive emissions. Chlorine demagging results in the formation of magnesium chloride that contributes to fumes leaving the dross. Excess chloride combines with aluminum to form aluminum chloride, a vapor at furnace temperatures, but one that condenses into submicrometer fumes as it cools. Aluminum chloride has an extremely high affinity for water (hygroscopic) and combines with water vapor to form hydrochloric acid. Aluminum chloride and hydrochloric acid are irritants and corrosive. Free chlorine that does not form compounds may also escape from the furnace and become an emission.

Aluminum fluoride (AlF_3) demagging results in the formation of magnesium fluoride as a byproduct. Excess fluorine combines with hydrogen to form hydrogen fluoride. The principal emissions resulting from aluminum fluoride demagging is a highly corrosive fume containing aluminum fluoride, magnesium fluoride, and hydrogen fluoride. The use of $A1F_3$ rather than chlorine in the demagging step reduces demagging emissions. Fluorides are emitted as gaseous fluorides (hydrogen fluoride, aluminum and magnesium fluoride vapors, and silicon tetrafluoride) or as dusts. Venturi scrubbers are usually used for gaseous fluoride emission control.

Tables 12.8-3 and 12.8-4 present particle size distributions and corresponding emission factors for uncontrolled chlorine demagging and metal refining in secondary aluminum reverberatory furnaces.

According to the VOC/PM Speciate Data Base Management System (SPECIATE) data base, the following hazardous air pollutants (HAPs) have been found in emissions from reverberatory furnaces: chlorine, and compounds of manganese, nickel, lead, and chromium. In addition to the HAPs listed for reverberatory furnaces, general secondary aluminum plant emissions have been found to include HAPs such as antimony, cobalt, selenium, cadmium, and arsenic, but specific emission factors for these HAPs are not presented due to lack of information.

In summary, typical furnace effluent gases contain combustion products, chlorine, hydrogen chloride and metal chlorides of zinc, magnesium and aluminum, aluminum oxide and various metals and metal compounds, depending on the quality of scrap charged.

Table 12.8-3 (Metric Units). PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNCONTROLLED REVERBERATORY FURNACES IN SECONDARY ALUMINUM OPERATIONS[a]

	Particle Size Distribution[b]		Size-Specific Emission Factor[c] (kg/Mg)			
Aerodynamic Particle Diameter (μm)	Chlorine Demagging	Refining	Chlorine Demagging	EMISSION FACTOR RATING	Refining	EMISSION FACTOR RATING
2.5	19.8	50.0	99.5	E	1.08	E
6.0	36.9	53.4	184.5	E	1.15	E
10.0	53.2	60.0	266.0	E	1.30	E

[a] References 4-5.

[b] Cumulative weight percent is less than the aerodynamic particle diameter, μm.

[c] Size-specific emission factor equals total particulate emission factor multiplied by particle size distribution (percent)/100. From Table 12.8-1, total particulate emission factor for chloride demagging is 500 kg/Mg chlorine used, and for refining, 2.15 kg/Mg aluminum processed.

Table 12.8-4 (English Units). PARTICLE SIZE DISTRIBUTION AND SIZE-SPECIFIC EMISSION FACTORS FOR UNCONTROLLED REVERBERATORY FURNACES IN SECONDARY ALUMINUM OPERATIONS[a]

Aerodynamic Particle Diameter (μm)	Particle size Distribution[b]		Size-Specific Emission Factor[c] (lb/ton)			
	Chlorine Demagging	Refining	Chlorine Demagging	EMISSION FACTOR RATING	Refining	EMISSION FACTOR RATING
2.5	19.8	50.0	199	E	2.16	E
6.0	36.9	53.4	369	E	2.3	E
10.0	53.2	60.0	532	E	2.6	E

[a] References 4-5.
[b] Cumulative weight percent is less than the aerodynamic particle diameter, μm.
[c] Size-specific emission factor equals total particulate emission factor multiplied by particle size distribution (percent)/100. From Table 12.8-2, total particulate emission factor for chloride demagging is 1000 lb/ton chlorine used, and for refining, 4.3 lb/ton aluminum processed.

References For Section 12.8

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3. W. F. Hammond and S. M. Weiss, Unpublished Report On Air Contaminant Emissions From Metallurgical Operations In Los Angeles County, Los Angeles County Air Pollution Control District, July 1964.
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6. Danielson, John., "Secondary Aluminum-Melting Processes". *Air Pollution Engineering Manual*, 2nd Ed., U. S. Environmental Protection Agency, Washington, DC, Report Number AP-40, May 1973.
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12.9 Secondary Copper Smelting

12.9.1 General[1,2]

As of 1992, more than 40 percent of the U. S. supply of copper is derived from secondary sources, including such items as machine shop punchings, turnings, and borings; manufacturing facility defective or surplus goods; automobile radiators, pipes, wires, bushings, and bearings; and metallurgical process skimmings and dross. This secondary copper can be refined into relatively pure metallic copper, alloyed with zinc or tin to form brass or bronze, incorporated into chemical products, or used in a number of smaller applications. Six secondary copper smelters are in operation in the U. S.: 3 in Illinois and 1 each in Georgia, Pennsylvania, and South Carolina. A large number of mills and foundries reclaim relatively pure copper scrap for alloying purposes.

12.9.2 Process Description[2,3]

Secondary copper recovery is divided into 4 separate operations: scrap pretreatment, smelting, alloying, and casting. Pretreatment includes the cleaning and consolidation of scrap in preparation for smelting. Smelting consists of heating and treating the scrap for separation and purification of specific metals. Alloying involves the addition of 1 or more other metals to copper to obtain desirable qualities characteristic of the combination of metals. The major secondary copper smelting operations are shown in Figure 12.9-1; brass and bronze alloying operations are shown in Figure 12.9-2.

12.9.2.1 Pretreatment -

Scrap pretreatment may be achieved through manual, mechanical, pyrometallurgical, or hydrometallurgical methods. Manual and mechanical methods include sorting, stripping, shredding, and magnetic separation. The scrap may then be compressed into bricquettes in a hydraulic press. Pyrometallurgical pretreatment may include sweating (the separation of different metals by slowly staging furnace air temperatures to liquify each metal separately), burning insulation from copper wire, and drying in rotary kilns to volatilize oil and other organic compounds. Hydrometallurgical pretreatment methods include flotation and leaching to recover copper from slag. Flotation is typically used when slag contains greater than 10 percent copper. The slag is slowly cooled such that large, relatively pure crystals are formed and recovered. The remaining slag is cooled, ground, and combined with water and chemicals that facilitate flotation. Compressed air and the flotation chemicals separate the ground slag into various fractions of minerals. Additives cause the copper to float in a foam of air bubbles for subsequent removal, dewatering, and concentration.

Leaching is used to recover copper from slime, a byproduct of electrolytic refining. In this process, sulfuric acid is circulated through the slime in a pressure filter. Copper dissolves in the acid to form a solution of copper sulfate ($CuSO_4$), which can then be either mixed with the electrolyte in the refinery cells or sold as a product.

12.9.2.2 Smelting -

Smelting of low-grade copper scrap begins with melting in either a blast or a rotary furnace, resulting in slag and impure copper. If a blast furnace is used, this copper is charged to a converter, where the purity is increased to about 80 to 90 percent, and then to a reverberatory furnace, where copper of about 99 percent purity is achieved. In these fire-refining furnaces, flux is added to the copper and air is blown upward through the mixture to oxidize impurities. These impurities are then

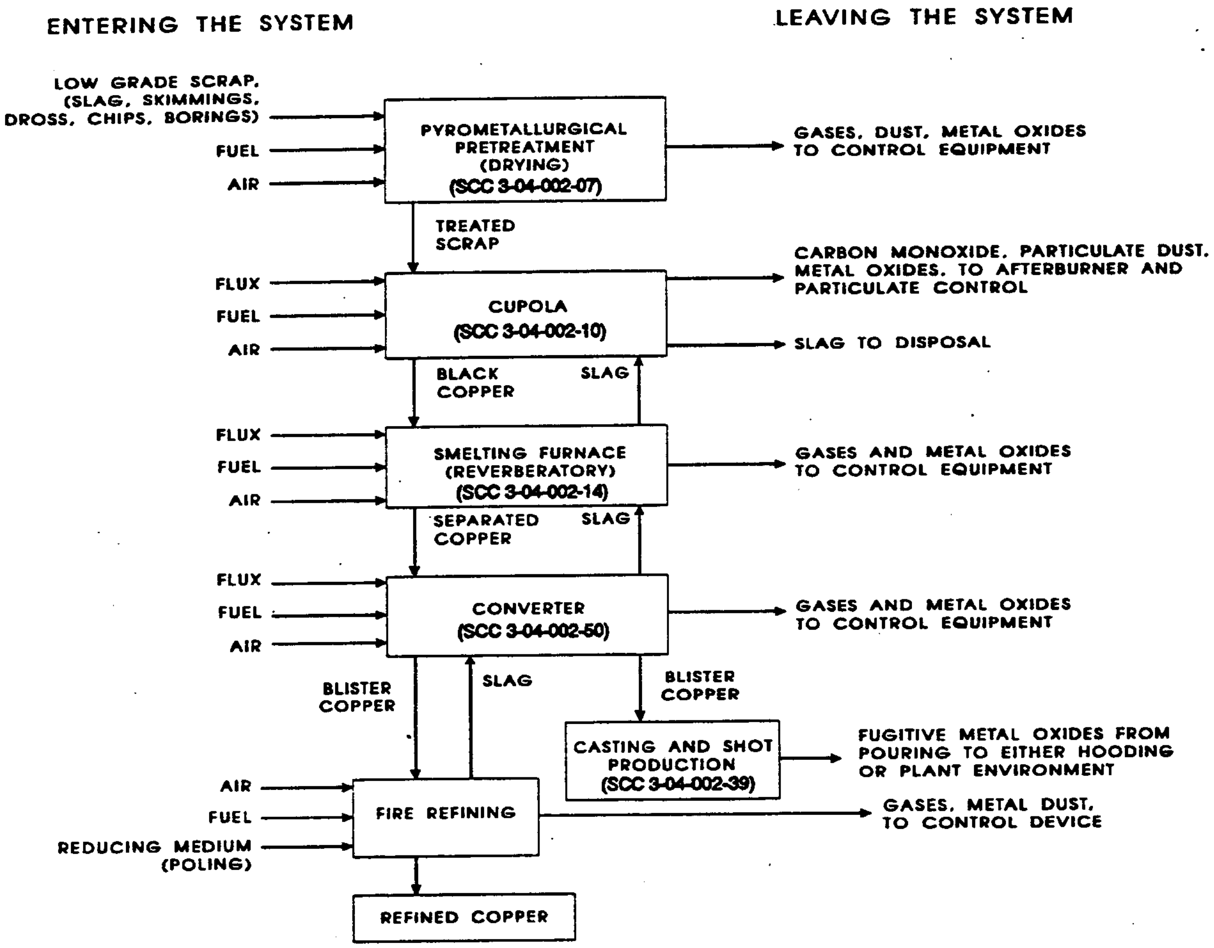

Figure 12.9-1. Low-grade copper recovery.
(Source Classification Codes in parentheses.)

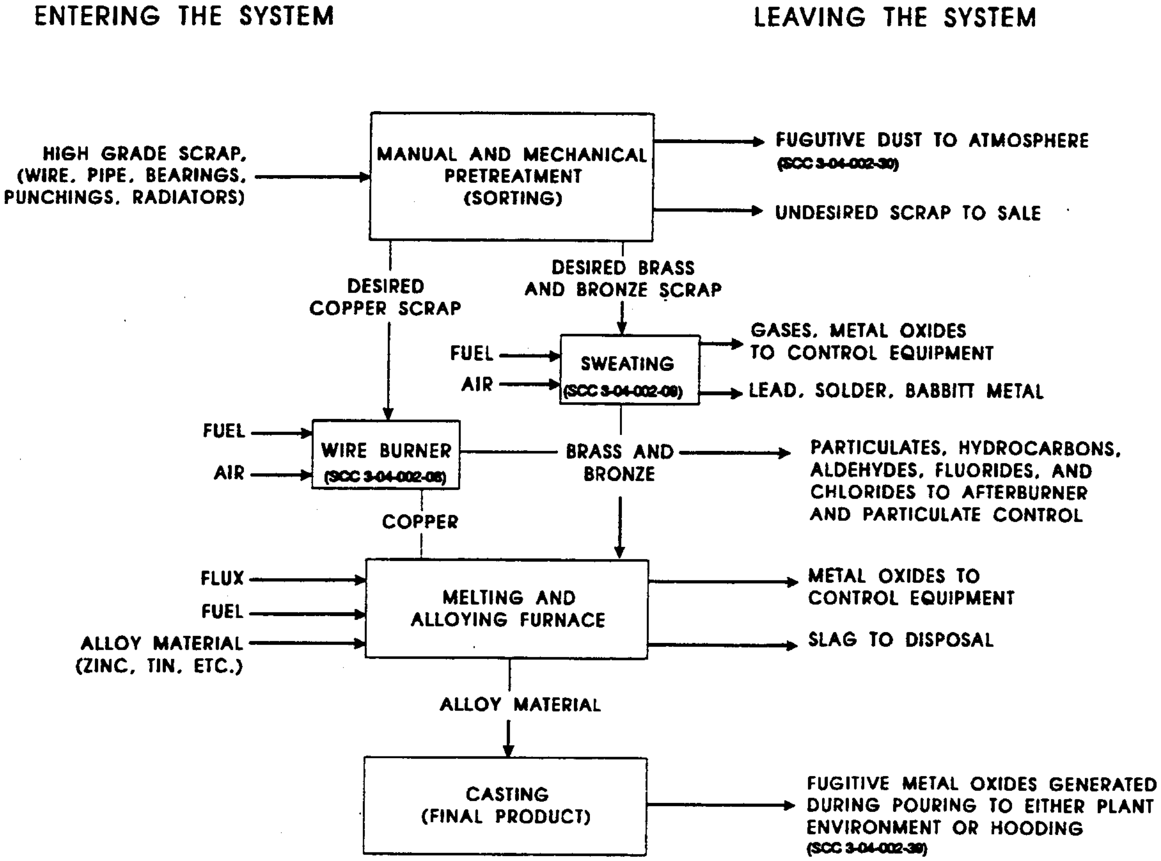

Figure 12.9-2. High-grade brass and bronze alloying.
(Source Classification Codes in parentheses.)

removed as slag. Then, by reducing the furnace atmosphere, cuprous oxide (CuO) is converted to copper. Fire-refined copper is cast into anodes, which are used during electrolysis. The anodes are submerged in a sulfuric acid solution containing copper sulfate. As copper is dissolved from the anodes, it deposits on the cathode. Then the cathode copper, which is as much as 99.99 percent pure, is extracted and recast. The blast furnace and converter may be omitted from the process if average copper content of the scrap being used is greater than about 90 percent.

The process used by 1 U. S. facility involves the use of a patented top-blown rotary converter in lieu of the blast, converting, and reverberatory furnaces and the electrolytic refining process described above. This facility begins with low-grade copper scrap and conducts its entire refining operation in a single vessel.

12.9.2.3 Alloying -

In alloying, copper-containing scrap is charged to a melting furnace along with 1 or more other metals such as tin, zinc, silver, lead, aluminum, or nickel. Fluxes are added to remove impurities and to protect the melt against oxidation by air. Air or pure oxygen may be blown through the melt to adjust the composition by oxidizing excess zinc. The alloying process is, to some extent, mutually exclusive of the smelting and refining processes described above that lead to relatively pure copper.

12.9.2.4 Casting -

The final recovery process step is the casting of alloyed or refined metal products. The molten metal is poured into molds from ladles or small pots serving as surge hoppers and flow regulators. The resulting products include shot, wirebar, anodes, cathodes, ingots, or other cast shapes.

12.9.3 Emissions And Controls[3]

The principal pollutant emitted from secondary copper smelting activities is particulate matter. As is characteristic of secondary metallurgical industries, pyrometallurgical processes used to separate or refine the desired metal, such as the burning of insulation from copper wire, result in emissions of metal oxides and unburned insulation. Similarly, drying of chips and borings to remove excess oils and cutting fluids can cause discharges of volatile organic compounds (VOC) and products of incomplete combustion.

The smelting process utilizes large volumes of air to oxidize sulfides, zinc, and other undesirable constituents of the scrap. This oxidation procedure generates particulate matter in the exhaust gas stream. A broad spectrum of particle sizes and grain loadings exists in the escaping gases due to variations in furnace design and in the quality of furnace charges. Another major factor contributing to differences in emission rates is the amount of zinc present in scrap feed materials. The low-boiling zinc volatilizes and is oxidized to produce copious amounts of zinc oxide as submicron particulate.

Fabric filter baghouses are the most effective control technology applied to secondary copper smelters. The control efficiency of these baghouses may exceed 99 percent, but cooling systems may be needed to prevent hot exhaust gases from damaging or destroying the bag filters. Electrostatic precipitators are not as well suited to this application, because they have a low collection efficiency for dense particulate such as oxides of lead and zinc. Wet scrubber installations are ineffective as pollution control devices in the secondary copper industry because scrubbers are useful for particles larger than 1 micrometer (μm), and the metal oxide fumes generated are generally submicron in size.

Particulate emissions associated with drying kilns can also be controlled with baghouses. Drying temperatures up to 150°C (300°F) produce exhaust gases that require no precooling prior to the baghouse inlet. Wire burning generates large amounts of particulate matter, primarily composed of partially combusted organic compounds. These emissions can be effectively controlled by direct-flame incinerators called afterburners. An efficiency of 90 percent or more can be achieved if the afterburner combustion temperature is maintained above 1000°C (1800°F). If the insulation contains chlorinated organics such as polyvinyl chloride, hydrogen chloride gas will be generated. Hydrogen chloride is not controlled by the afterburner and is emitted to the atmosphere.

Fugitive emissions occur from each process associated with secondary copper smelter operations. These emissions occur during the pretreating of scrap, the charging of scrap into furnaces containing molten metals, the transfer of molten copper from one operation to another, and from material handling. When charging scrap into furnaces, fugitive emissions often occur when the scrap is not sufficiently compact to allow a full charge to fit into the furnace prior to heating. The introduction of additional material onto the liquid metal surface produces significant amounts of volatile and combustible materials and smoke. If this smoke exceeds the capacity of the exiting capture devices and control equipment, it can escape through the charging door. Forming scrap bricquettes offers a possible means of avoiding the necessity of fractional charges. When fractional charging cannot be eliminated, fugitive emissions are reduced by turning off the furnace burners during charging. This reduces the flow rate of exhaust gases and allows the exhaust control system to better accommodate the additional temporary emissions.

Fugitive emissions of metal oxide fumes are generated not only during melting, but also while pouring molten metal into molds. Additional dusts may be generated by the charcoal or other lining used in the mold. The method used to make "smooth-top" ingots involves covering the metal surface with ground charcoal. This process creates a shower of sparks, releasing emissions into the plant environment at the vicinity of the furnace top and the molds being filled.

The electrolytic refining process produces emissions of sulfuric acid mist, but no data quantifying these emissions are available.

Emission factor averages and ranges for 6 different types of furnaces are presented in Tables 12.9-1 and 12.9-2, along with PM-10 emission rates and reported fugitive and lead emissions. Several of the metals contained in much of the scrap used in secondary copper smelting operations, particularly lead, nickel, and cadmium, are hazardous air pollutants (HAPs) as defined in Title III of the 1990 Clean Air Act Amendments. These metals will exist in the particulate matter emitted from these processes in proportions related to their existence in the scrap.

Table 12.9-1 (Metric Units). PARTICULATE EMISSION FACTORS FOR FURNACES USED IN SECONDARY COPPER SMELTING AND ALLOYING PROCESS[a]

Furnace And Charge Type	Control Equipment	Total Particulate	EMISSION FACTOR RATING	PM-10[b]	EMISSION FACTOR RATING	Lead[c]	EMISSION FACTOR RATING
Cupola							
Scrap iron (SCC 3-04-002-13)	None	0.002	B	ND	NA	ND	NA
Insulated copper wire (SCC 3-04-002-11)	None	120	B	105.6	E	ND	NA
	ESP[d]	5	B	ND	NA	ND	NA
Scrap copper and brass (SCC 3-04-002-12)	None	35	B	32.1	E	ND	NA
	ESP[d]	1.2	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-34)	None	ND	NA	1.1	E	ND	NA
Reverberatory furnace							
High lead alloy (58%) (SCC 3-04-002-43)	None	ND	NA	ND	NA	25	B
Red/yellow brass (SCC 3-04-002-44)	None	ND	NA	ND	NA	6.6	B
Other alloy (7%) (SCC 3-04-002-42)	None	ND	NA	ND	NA	2.5	B
Copper (SCC 3-04-002-14)	None	2.6	B	2.5	E	ND	NA
	Baghouse	0.2	B	ND	NA	ND	NA
Brass and bronze (SCC 3-04-002-15)	None	18	B	10.8	E	ND	NA
	Baghouse	1.3	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-35)	None	ND	NA	1.5	E	ND	NA
Rotary furnace							
Brass and bronze (SCC 3-04-002-17)	None	150	B	88.3	E	ND	NA
	ESP[d]	7	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-36)	None	ND	NA	1.3	E	ND	NA
Crucible and pot furnace							
Brass and bronze (SCC 3-04-002-19)	None	11	B	6.2	E	ND	NA
	ESP[d]	0.5	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-37)	None	ND	NA	0.14	E	ND	NA
Electric arc furnace							
Copper (SCC 3-04-002-20)	None	2.5	B	2.5	E	ND	NA
	Baghouse	0.5	B	ND	NA	ND	NA
Brass and bronze (SCC 3-04-002-21)	None	5.5	B	3.2	E	ND	NA
	Baghouse	3	B	ND	NA	ND	NA
Electric induction							
Copper (SCC 3-04-002-23)	None	3.5	B	3.5	E	ND	NA
	Baghouse	0.25	B	ND	NA	ND	NA
Brass and bronze (SCC 3-04-002-24)	None	10	B	10	E	ND	NA
	Baghouse	0.35	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-38)	None	ND	NA	0.04	E	ND	NA

Table 12.9-1 (cont.).

[a] Expressed as kg of pollutant/Mg ore processed. The information for particulate in Table 12.9-1 was based on unpublished data furnished by the following:
Philadelphia Air Management Services, Philadelphia, PA.
New Jersey Department of Environmental Protection, Trenton, NJ.
New Jersey Department of Environmental Protection, Metro Field Office, Springfield, NJ.
New Jersey Department of Environmental Protection, Newark Field Office, Newark, NJ.
New York State Department of Environmental Conservation, New York, NY.
The City of New York Department of Air Resources, New York, NY.
Cook County Department of Environmental Control, Maywood, IL.
Wayne County Department of Health, Air Pollution Division, Detroit, MI.
City of Cleveland Department of Public Health and Welfare, Division of Air Pollution Control, Cleveland, OH.
State of Ohio Environmental Protection Agency, Columbus, OH.
City of Chicago Department of Environmental Control, Chicago, IL.
South Coast Air Quality Management District, Los Angeles, CA.

[b] PM-10 and fugitive emissions are listed in *Airs Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants*, U.S Environmental Protection Agency, EPA 450/4-90-003, March 1990. These estimates should be considered to have an EMISSION FACTOR RATING of E.

[c] References 1,6-7. Expressed as kg of pollutant/Mg product.

[d] ESP = electrostatic precipitator.

Table 12.9-2 (English Units). PARTICULATE EMISSION FACTORS FOR FURNACES USED IN SECONDARY COPPER SMELTING AND ALLOYING PROCESS[a]

Furnace And Charge Type	Control Equipment	Total Particulate	EMISSION FACTOR RATING	PM-10[b]	EMISSION FACTOR RATING	Lead[c]	EMISSION FACTOR RATING
Cupola							
Scrap iron (SCC 3-04-002-13)	None	0.003	B	ND	NA	ND	NA
Insulated copper wire (SCC 3-04-002-11)	None	230	B	211.6	E	ND	NA
	ESP[d]	10	B	ND	NA	ND	NA
Scrap copper and brass (SCC 3-04-002-12)	None	70	B	64.4	E	ND	NA
	ESP[d]	2.4		ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-34)	None	ND	NA	2.2	E	ND	NA
Reverberatory furnace							
High lead alloy (58%) (SCC 3-04-002-43)	None	ND	NA	ND	NA	50	B
Red/yellow brass (SCC 3-04-002-44)	None	ND	NA	ND	NA	13.2	B
Other alloy (7%) (SCC 3-04-002-42)	None	ND	NA	ND	NA	5.0	B
Copper (SCC 3-04-002-14)	None	5.1	B	5.1	E	ND	NA
	Baghouse	0.4	B	ND	NA	ND	NA
Brass and bronze (SCC 3-04-002-15)	None	36	B	21.2	E	ND	NA
	Baghouse	2.6	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-35)	None	ND	NA	3.1	E	ND	NA
Rotary furnace							
Brass and bronze (SCC 3-04-002-17)	None	300	B	177.0	E	ND	NA
	ESP[d]	13	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-36)	None	ND	NA	2.6	E	ND	NA
Crucible and pot furnace							
Brass and bronze (SCC 3-04-002-19)	None	21	B	12.4	E	ND	NA
	ESP[d]	1	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-37)	None	ND	NA	0.29	E	ND	NA
Electric arc furnace							
Copper (SCC 3-04-002-20)	None	5	B	5	E	ND	NA
	Baghouse	1	B	ND	NA	ND	NA
Brass and bronze (SCC 3-04-002-21)	None	11	B	6.5	E	ND	NA
	Baghouse	6	B	ND	NA	ND	NA
Electric induction furnace							
Copper (SCC 3-04-002-23)	None	7	B	7	E	ND	NA
	Baghouse	0.5	B	ND	NA	ND	NA
Brass and bronze (SCC 3-04-002-24)	None	20	B	20	E	ND	NA
	Baghouse	0.7	B	ND	NA	ND	NA
Fugitive emissions[b] (SCC 3-04-002-38)	None	ND	NA	0.04	E	ND	NA

Table 12.9-2 (cont.).

[a] Expressed as lb of pollutant/ton ore processed. The information for particulate in Table 12.9-2 was based on unpublished data furnished by the following:
Philadelphia Air Management Services, Philadelphia, PA.
New Jersey Department of Environmental Protection, Trenton, NJ.
New Jersey Department of Environmental Protection, Metro Field Office, Springfield, NJ.
New Jersey Department of Environmental Protection, Newark Field Office, Newark, NJ.
New York State Department of Environmental Conservation, New York, NY.
The City of New York Department of Air Resources, New York, NY.
Cook County Department of Environmental Control, Maywood, IL.
Wayne County Department of Health, Air Pollution Division, Detroit, MI.
City of Cleveland Department of Public Health and Welfare, Division of Air Pollution Control, Cleveland, OH.
State of Ohio Environmental Protection Agency, Columbus, OH.
City of Chicago Department of Environmental Control, Chicago, IL.
South Coast Air Quality Management District, Los Angeles, CA.

[b] PM-10 and fugitive emissions are listed in *Airs Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants*, U.S Environmental Protection Agency, EPA 450/4-90-003, March 1990. These estimates should be considered to have an EMISSION FACTOR RATING of E.

[c] References 1,6-7. Expressed as lb of pollutant/ton product.

[d] ESP = electrostatic precipitator.

References For Section 12.9

1. *Mineral Commodity Summaries 1992*, U. S. Department Of The Interior, Bureau Of Mines.

2. *Air Pollution Aspects Of Brass And Bronze Smelting And Refining Industry*, U. S. Department Of Health, Education And Welfare, National Air Pollution Control Administration, Raleigh, NC, Publication No. AP-58, November 1969.

3. J. A. Danielson (ed.), *Air Pollution Engineering Manual (2nd Ed.)*, AP-40, U. S. Environmental Protection Agency, Research Triangle Park, NC, 1973. Out of Print.

4. *Emission Factors And Emission Source Information For Primary And Secondary Copper Smelters*, U. S. Environmental Protection Agency, Research Triangle Park, NC, Publication No. EPA-450/3-051, December 1977.

5. *Control Techniques For Lead Air Emissions*, EPA-450-2/77-012, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1977.

6. H. H. Fukubayashi, *et al.*, *Recovery Of Zinc And Lead From Brass Smelter Dust*, Report of Investigation No. 7880, Bureau Of Mines, U. S. Department Of The Interior, Washington, DC, 1974.

7. "Air Pollution Control In The Secondary Metal Industry", Presented at the First Annual National Association Of Secondary Materials Industries Air Pollution Control Workshop, Pittsburgh, PA, June 1967.

12.10 Gray Iron Foundries

12.10.1 General

Iron foundries produce high-strength castings used in industrial machinery and heavy transportation equipment manufacturing. Castings include crusher jaws, railroad car wheels, and automotive and truck assemblies.

Iron foundries cast 3 major types of iron: gray iron, ductile iron, and malleable iron. Cast iron is an iron-carbon-silicon alloy, containing from 2 to 4 percent carbon and 0.25 to 3.00 percent silicon, along with varying percentages of manganese, sulfur, and phosphorus. Alloying elements such as nickel, chromium, molybdenum, copper, vanadium, and titanium are sometimes added. Table 12.10-1 lists different chemical compositions of irons produced.

Mechanical properties of iron castings are determined by the type, amount, and distribution of various carbon formations. In addition, the casting design, chemical composition, type of melting scrap, melting process, rate of cooling of the casting, and heat treatment determine the final properties of iron castings. Demand for iron casting in 1989 was estimated at 9540 million megagrams (10,520 million tons), while domestic production during the same period was 7041 million megagrams (7761 million tons). The difference is a result of imports. Half of the total iron casting were used by the automotive and truck manufacturing companies, while half the total ductile iron castings were pressure pipe and fittings.

Table 12.10-1. CHEMICAL COMPOSITION OF FERROUS CASTINGS BY PERCENTAGES

Element	Gray Iron	Malleable Iron (As White Iron)	Ductile Iron	Steel
Carbon	2.0 - 4.0	1.8 - 3.6	3.0 - 4.0	<2.0[a]
Silicon	1.0 - 3.0	0.5 - 1.9	1.4 - 2.0	0.2 - 0.8
Manganese	0.40 - 1.0	0.25 - 0.80	0.5 - 0.8	0.5 - 1.0
Sulfur	0.05 - 0.25	0.06 - 0.20	<0.12	<0.06
Phosphorus	0.05 - 1.0	0.06 - 0.18	<0.15	<0.05

[a] Steels are classified by carbon content: low carbon is less than 0.20 percent; medium carbon is 0.20-0.5 percent; and high carbon is greater than 0.50 percent.

12.10.2 Process Description[1-5,39]

The major production operations in iron foundries are raw material handling and preparation, metal melting, mold and core production, and casting and finishing.

12.10.2.1 Raw Material Handling And Preparation -

Handling operations include the conveying of all raw materials for furnace charging, including metallics, fluxes and fuels. Metallic raw materials are pig iron, iron and steel scrap, foundry returns, and metal turnings. Fluxes include carbonates (limestone, dolomite), fluoride (fluorospar), and

12.10.2.1 Raw Material Handling And Preparation -

Handling operations include the conveying of all raw materials for furnace charging, including metallics, fluxes and fuels. Metallic raw materials are pig iron, iron and steel scrap, foundry returns, and metal turnings. Fluxes include carbonates (limestone, dolomite), fluoride (fluorospar), and carbide compounds (calcium carbide). Fuels include coal, oil, natural gas, and coke. Coal, oil, and natural gas are used to fire reverberatory furnaces. Coke, a derivative of coal, is used for electrodes required for heat production in electric arc furnaces.

As shown in Figure 12.10-1, the raw materials, metallics, and fluxes are added to the melting furnaces directly. For electric induction furnaces, however, the scrap metal added to the furnace charge must first be pretreated to remove grease and oil. Scrap metals may be degreased with solvents, by centrifugation, or by preheating to combust the organics.

12.10.2.2 Metal Melting -

The furnace charge includes metallics, fluxes, and fuels. Composition of the charge depends upon specific metal characteristics required. The basic melting process operations are furnace operations, including charging, melting, and backcharging; refining, during which the chemical composition is adjusted to meet product specifications; and slag removal and molding the molten metal.

12.10.2.2.1 Furnace Operations -

The 3 most common furnaces used in the iron foundry industry are cupolas, electric arc, and electric induction furnaces. The cupola is the major type of furnace used in the iron foundry industry. It is typically a cylindrical steel shell with a refractory-lined or water-cooled inner wall. The cupola is the only furnace type that uses coke as a fuel. Iron is melted by the burning coke and flows down the cupola. As the melt proceeds, new charges are added at the top. The flux combines with nonmetallic impurities in the iron to form slag, which can be removed. Both the molten iron and the slag are removed at the bottom of the cupola.

Electric arc furnaces (EAFs) are large, welded steel cylindrical vessels equipped with a removable roof through which 3 retractable carbon electrodes are inserted. The electrodes are lowered through the roof of the furnace and are energized by 3-phase alternating current, creating arcs that melt the metallic charge with their heat. Electric arc furnace capacities range from 5 to 345 megagrams (6 to 380 tons). Additional heat is produced by the resistance of the metal between the arc paths. Once the melting cycle is complete, the carbon electrodes are raised and the roof is removed. The vessel can then be tilted to pour the molten iron.

Electric induction furnaces are cylindrical or cup-shaped refractory-lined vessels that are surrounded by electrical coils. When these coils are energized with high frequency alternating current, they produce a fluctuating electromagnetic field which heats the metal charge. The induction furnace is simply a melting furnace to which high-grade scrap is added to make the desired product. Induction furnaces are kept closed except when charging, skimming and tapping. The molten metal is tapped by tilting and pouring through a hole in the side of the vessels.

12.10.2.2.2 Refining -

Refining is the process in which magnesium and other elements are added to molten iron to produce ductile iron. Ductile iron is formed as a steel matrix containing spheroidal particles (or nodules) of graphite. Ordinary cast iron contains flakes of graphite. Each flake acts as a crack, which makes cast iron brittle. Ductile irons have high tensile strength and are silvery in appearance.

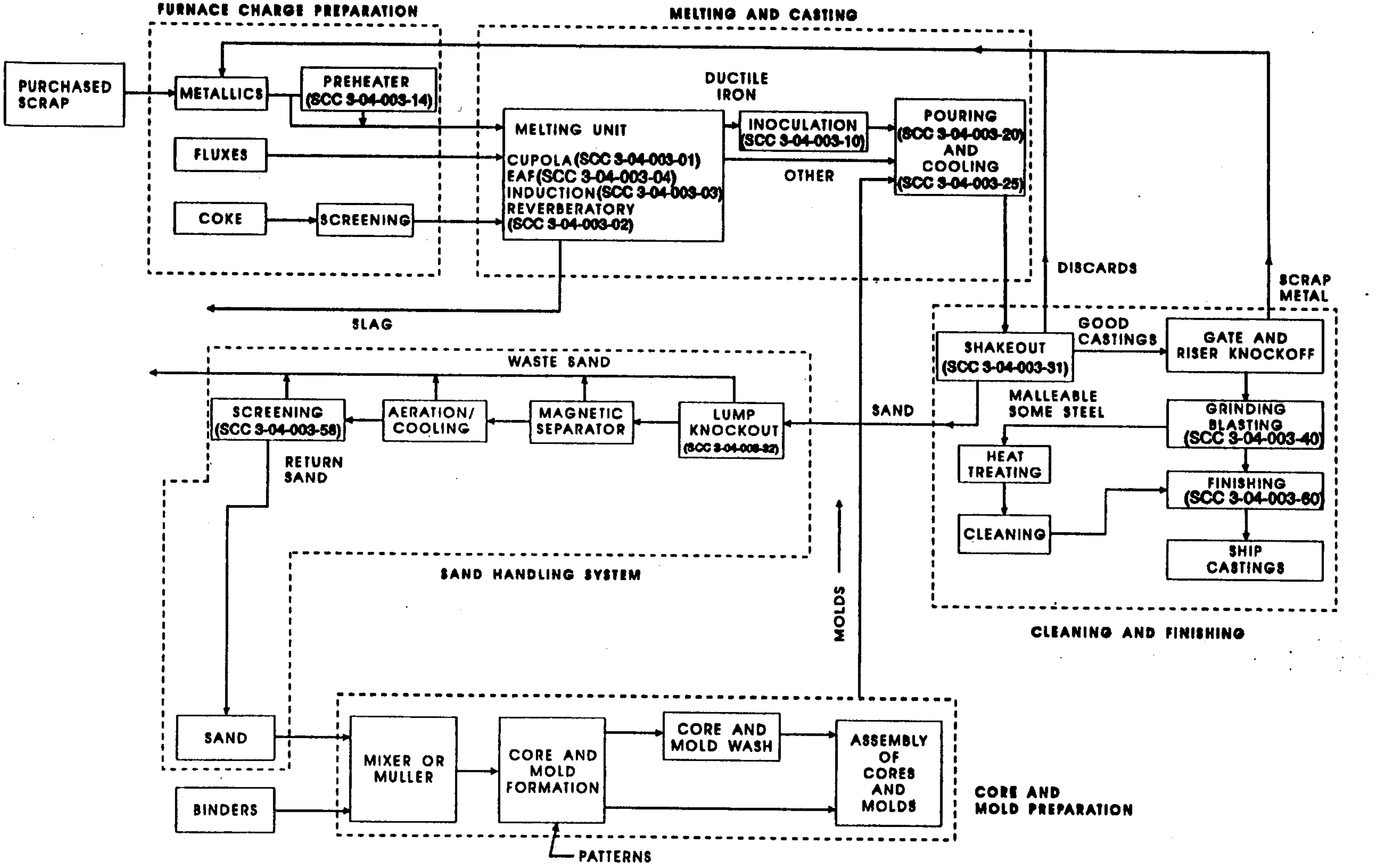

Figure 12.10-1. Flow diagram of a typical iron foundry. (Source Classification Codes in parentheses.)

Two widely used refining processes are the plunge method and the pour-over method. In plunging, magnesium or a magnesium alloy is loaded into a graphite "bell" which is plunged into a ladle of molten iron. A turbulent reaction takes place as the magnesium boils under the heat of the molten iron. As much as 65 percent of the magnesium may be evaporated. The magnesium vapor ignites in air, creating large amounts of smoke.

In the pour-over method, magnesium alloy is placed in the bottom of a vessel and molten iron is poured over it. Although this method produces more emissions and is less efficient than plunging, it requires no capital equipment other than air pollution control equipment.

12.10.2.2.3 Slag Removal And Molding -

Slag is removed from furnaces through a tapping hole or door. Since slag is lighter than molten iron, it remains on top of the molten iron and can be raked or poured out. After slag has been removed, the iron is cast into molds.

12.10.2.3 Mold And Core Production -

Molds are forms used to shape the exterior of castings. Cores are molded sand shapes used to make internal voids in castings. Molds are prepared from wet sand, clay, and organic additives, and are usually dried with hot air. Cores are made by mixing sand with organic binders or organic polymers, molding the sand into a core, and baking the core in an oven. Used sand from castings shakeout is recycled and cleaned to remove any clay or carbonaceous buildup. The sand is screened and reused to make new molds.

12.10.2.4 Casting And Finishing -

Molten iron is tapped into a ladle or directly into molds. In larger, more mechanized foundries, filled molds are conveyed automatically through a cooling tunnel. The molds are then placed on a vibrating grid to shake the mold sand and core sand loose from the casting.

12.10.3 Emissions And Controls[9,31,52]

Emission points and types of emissions from a typical foundry are shown in Figure 12.10-2. Emission factors are presented in Tables 12.10-2, 12.10-3, 12.10-4, 12.10-5, 12.10-6, 12.10-7, 12.10-8, and 12.10-9.

12.10.3.1 Raw Material Handling And Preparation -

Fugitive particulate emissions are generated from the receiving, unloading, and conveying of raw materials. These emissions can be controlled by enclosing the points of disturbance (e. g., conveyor belt transfer points) and routing air from enclosures through fabric filters or wet collectors.

Scrap preparation with heat will emit smoke, organic compounds, and carbon monoxide; scrap preparation with solvent degreasers will emit organics. Catalytic incinerators and afterburners can control about 95 percent of organic and carbon monoxide emissions (see Section 4.6, "Solvent Degreasing").

12.10.3.2 Metal Melting -

Emissions released from melting furnaces include particulate matter, carbon monoxide, organic compounds, sulfur dioxide, nitrogen oxides, and small quantities of chloride and fluoride compounds. The particulates, chlorides, and fluorides are generated from incomplete combustion of carbon additives, flux additions, and dirt and scale on the scrap charge. Organic material on scrap and furnace temperature affect the amount of carbon monoxide generated. Fine particulate fumes

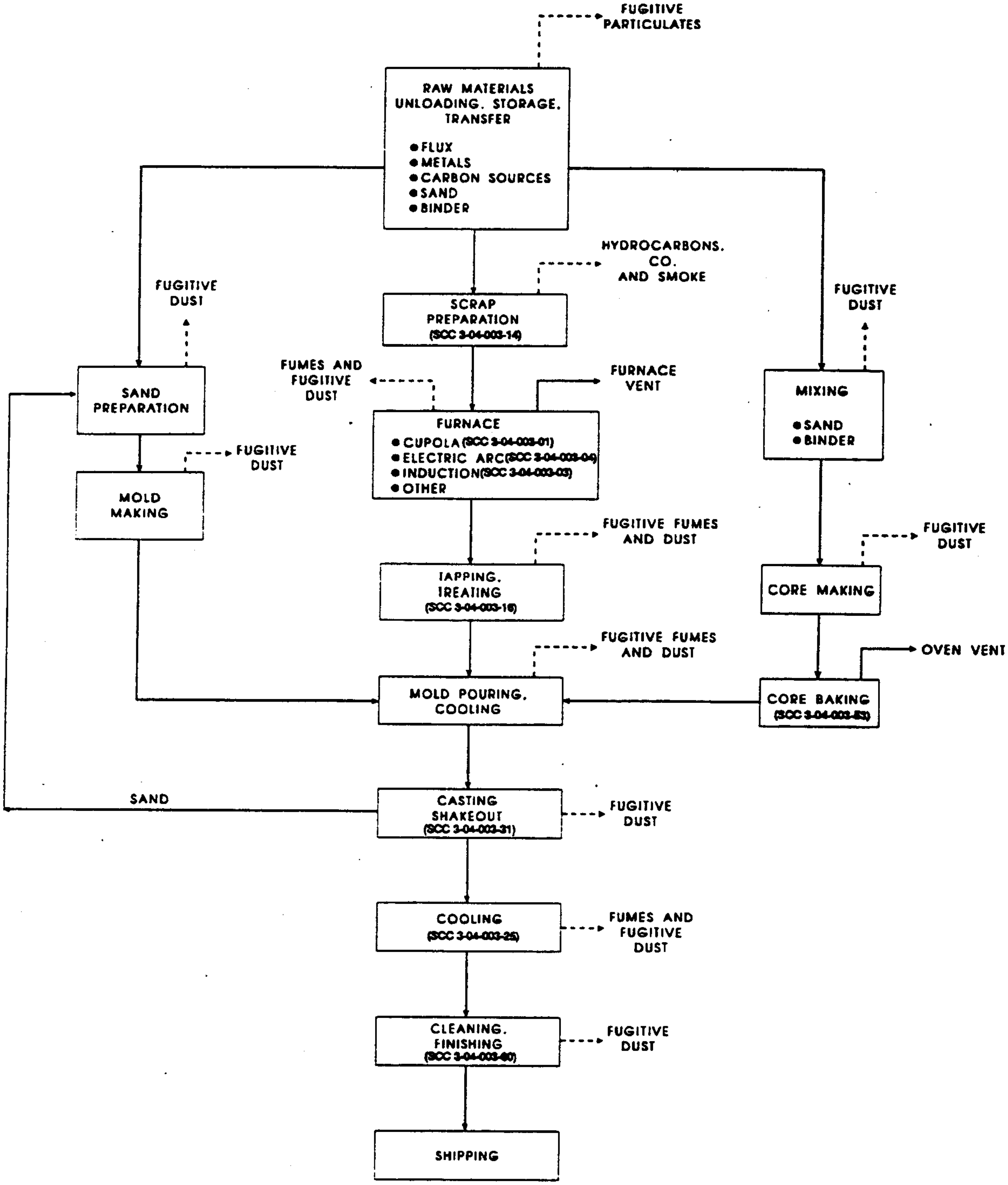

Figure 12.10-2. Emission points in a typical iron foundry.
(Source Classification Codes in parentheses.)

Table 12.10-2 (Metric Units). PARTICULATE EMISSION FACTORS FOR IRON FURNACES[a]

Process	Control Device	Total Particulate	EMISSION FACTOR RATING
Cupola (SCC 3-04-003-01)	Uncontrolled[b]	6.9	E
	Scrubber[c]	1.6	C
	Venturi scrubber[d]	1.5	C
	Electrostatic precipitator[e]	0.7	E
	Baghouse[f]	0.3	E
	Single wet cap[g]	4.0	E
	Impingement scrubber[g]	2.5	E
	High-energy scrubber[g]	0.4	E
Electric arc furnace (SCC 3-04-003-04)	Uncontrolled[h]	6.3	C
	Baghouse[j]	0.2	C
Electric induction furnace (SCC 3-04-003-03)	Uncontrolled[k]	0.5	E
	Baghouse[m]	0.1	E
Reverberatory (SCC 3-04-003-02)	Uncontrolled[n]	1.1	E
	Baghouse[m]	0.1	E

[a] Emission Factors are expressed in kg of pollutant/Mg of gray iron produced.
[b] References 1,7,9,10. SCC = Source Classification Code.
[c] References 12,15. Includes averages for wet cap and other scrubber types not already listed.
[d] References 12,17,19.
[e] References 8,11.
[f] References 12-14.
[g] References 8,11,29,30.
[h] References 1,6,23.
[j] References 6,23,24.
[k] References 1,12. For metal melting only.
[m] Reference 4.
[n] Reference 1.

Table 12.10-3 (English Units). PARTICULATE EMISSION FACTORS FOR IRON FURNACES[a]

Process	Control Device	Total Particulate	EMISSION FACTOR RATING
Cupola (SCC 3-04-003-01)	Uncontrolled[b]	13.8	E
	Scrubber[c]	3.1	C
	Venturi scrubber[d]	3.0	C
	Electrostatic precipitator[e]	1.4	E
	Baghouse[f]	0.7	E
	Single wet cap[g]	8.0	E
	Impingement scrubber[g]	5.0	E
	High energy scrubber[g]	0.8	E
Electric arc furnace (SCC 3-04-003-04)	Uncontrolled[h]	12.7	C
	Baghouse[j]	0.4	C
Electric induction furnace (SCC 3-04-003-03)	Uncontrolled[k]	0.9	E
	Baghouse[m]	0.2	E
Reverberatory (SCC 3-04-003-02)	Uncontrolled[n]	2.1	E
	Baghouse[m]	0.2	E

[a] Emission Factors expressed as lb of pollutant/ton of gray iron produced.

[b] References 1,7,9,10. SCC = Source Classification Code.

[c] References 12,15. Includes averages for wet cap and other scrubber types not already listed.

[d] References 12,17,19.

[e] References 8,11.

[f] References 12-14.

[g] References 8,11,29,30.

[h] References 1,6,23.

[j] References 6,23,24.

[k] References 1,12. For metal melting only.

[m] Reference 4.

[n] Reference 1.

Table 12.10-4 (Metric Units). CRITERIA GASEOUS AND LEAD EMISSION FACTORS FOR IRON FOUNDRIES[a]

Furnace Type	CO	EMISSION FACTOR RATING	SO_2	EMISSION FACTOR RATING	NO_x	EMISSION FACTOR RATING	VOC	EMISSION FACTOR RATING	Lead[b]	EMISSION FACTOR RATING
Cupola (SCC 3-04-003-01)										
Uncontrolled	73[c]	E	0.6S[d]	E	ND	NA	ND	NA	0.05-0.6	B
High energy scrubber	73	E	0.3S[d]	E	ND	NA	ND	NA	ND	NA
Electric arc[e] (SCC 3-04-003-04)	0.5-19	E	Neg	E	0.02-0.3	E	0.03-0.15	E	ND	NA
Electric induction[f] (SCC 3-04-003-03)	Neg	E	Neg	E	ND	NA	ND	NA	0.005-0.05	B
Reverberatory (SCC 3-04-003-02)	ND	NA	ND	NA	ND	NA	ND	NA	0.006-0.07	B

[a] Expressed as kg of pollutant/Mg of gray iron produced. SCC = Source Classification Code. Neg = negligible. ND = no data. NA = not applicable.

[b] References 11,31,34.

[c] Reference 2.

[d] Reference 4. S = % sulfur in the coke. Assumes 30% of sulfur is converted to SO_2.

[e] Reference 4,6.

[f] References 8,11,29-30.

Table 12.10-5 (English Units). CRITERIA GASEOUS AND LEAD EMISSION FACTORS FOR IRON FOUNDRIES[a]

Furnace Type	CO	EMISSION FACTOR RATING	SO_2	EMISSION FACTOR RATING	NO_x	EMISSION FACTOR RATING	VOC	EMISSION FACTOR RATING	Lead[b]	EMISSION FACTOR RATING
Cupola (SCC 3-04-003-01)										
Uncontrolled	145[c]	E	1.2S[d]	E	ND	NA	ND	NA	0.1-1.1	B
High energy scrubber	145	E	0.6S[d]	E	ND	NA	ND	NA	ND	NA
Electric arc[e] (SCC 3-04-003-04)	1-37	E	Neg	E	0.04-0.6	E	0.06-0.3	E	ND	NA
Electric induction[f] (SCC 3-04-003-03)	Neg	E	Neg	E	ND	NA	ND	NA	0.009-0.1	B
Reverberatory (SCC 3-04-003-02)	ND	NA	ND	NA	ND	NA	ND	NA	0.012-0.14	B

[a] Expressed as lb of pollutant/ton of gray iron produced. SCC = Source Classification Code. Neg = negligible. ND = no data. NA = not applicable.

[b] References 11,31,34.

[c] Reference 2.

[d] Reference 4. S = % sulfur in the coke. Assumes 30% of sulfur is converted to SO_2.

[e] Reference 4,6.

[f] References 8,11,29-30.

Table 12.10-6 (Metric Units). PARTICULATE EMISSION FACTORS FOR ANCILLARY OPERATIONS AND FUGITIVE SOURCES AT GRAY IRON FOUNDRIES[a]

Process	Control Device	Total Emission Factor	EMISSION FACTOR RATING	Emitted To Work Environment	EMISSION FACTOR RATING	Emitted To Atmosphere	EMISSION FACTOR RATING
Scrap and charge handling, heating[b] (SCC 3-04-003-15)	Uncontrolled	0.3	E	0.25	E	0.1	E
Magnesium treatment[c] (SCC 3-04-003-21)	Uncontrolled	0.9	E	0.9	E	0.2	E
Refining[d] (SCC 3-04-003-22)	Uncontrolled	1.5-2.5	E				
Pouring, cooling[e] (SCC 3-04-003-18)	Uncontrolled	2.1	E				
Shakeout[f] (SCC 3-04-003-31)	Uncontrolled[c]	1.6	E				
Cleaning, finishing[b] (SCC 3-04-003-40)	Uncontrolled	8.5	E	0.15	E	0.05	E
Sand handling (in kg/Mg sand handled) (SCC 3-04-003-50)	Uncontrolled[c] Scrubber[g] Baghouse[h]	1.8 0.023 0.10	E D E				
Core making, baking[b] (SCC 3-04-003-19)	Uncontrolled	0.6	E	0.6	E	0.6	E

[a] Expressed as kg of pollutant/Mg of gray iron produced. SCC = Source Classification Code.
[b] Reference 4.
[c] Reference 1,4.
[d] Reference 35.
[e] References 1,3,25.
[f] Reference 1.
[g] References 12,27.
[h] Reference 12.

Table 12.10-7 (English Units). PARTICULATE EMISSION FACTORS FOR ANCILLARY OPERATIONS AND FUGITIVE SOURCES AT GRAY IRON FOUNDRIES[a]

Process	Control Device	Total Emission Factor	EMISSION FACTOR RATING	Emitted To Work Environment	EMISSION FACTOR RATING	Emitted To Atmosphere	EMISSION FACTOR RATING
Scrap and charge handling, heating[b] (SCC 3-04-003-15)	Uncontrolled	0.6	E	0.5	E	0.2	E
Magnesium treatment[c] (SCC 3-04-003-21)	Uncontrolled	1.8	E	1.8	E	0.4	E
Refining[d] (SCC 3-04-003-22)	Uncontrolled	3 - 5	E				
Pouring, cooling[e] (SCC 3-04-003-18)	Uncontrolled	4.2	E				
Shakeout[f] (SCC 3-04-003-31)	Uncontrolled[c]	3.2	E				
Cleaning, finishing[b] (SCC 3-04-003-40)	Uncontrolled	17	E	0.3	E	0.1	E
Sand handling (in kg/Mg sand handled) (SCC 3-04-003-50)	Uncontrolled[c] Scrubber[g] Baghouse[h]	3.6 0.046 0.20	E D E				
Core making, baking[b] (SCC 3-04-003-19)	Uncontrolled	1.1	E	1.1	E	1.1	E

[a] Expressed as lb of pollutant/ton of gray iron produced. SCC = Source Classification Code.

[b] Reference 4.

[c] Reference 1,4.

[d] Reference 35.

[e] References 1,3,25.

[f] Reference 1.

[g] References 12,27.

[h] Reference 12.

Table 12.10-8 (Metric Units). PARTICLE SIZE DISTRIBUTION DATA AND EMISSION FACTORS FOR GRAY IRON FOUNDRIES[a]

Source	Particle Size (μm)	Cumulative Mass % ≤ Stated Size[b]	Cumulative Mass Emission Factor (kg/Mg metal)	EMISSION FACTOR RATING
Cupola furnace[b] (SCC 3-04-003-01)				
Uncontrolled	0.5	44.3	3.1	C
	1.0	69.1	4.8	
	2.0	79.6	5.5	
	2.5	84.0	5.8	
	5.0	90.1	6.2	
	10.0	90.1	6.2	
	15.0	90.6	6.3	
		100.0	6.9	
Controlled by baghouse	0.5	83.4	0.33	E
	1.0	91.5	0.37	
	2.0	94.2	0.38	
	2.5	94.9	0.38	
	5.0	94.9	0.38	
	10.0	94.9	0.38	
	15.0	95.0	0.38	
		100.0	0.4	
Controlled by venturi scrubber[c]	0.5	56.0	0.84	C
	1.0	70.2	1.05	
	2.0	77.4	1.16	
	2.5	77.7	1.17	
	5.0	77.7	1.17	
	10.0	77.7	1.17	
	15.0	77.7	1.17	
		100.0	1.50	
Electric arc furnace[d] (SCC 3-04-003-04)				
Uncontrolled	1.0	13.0	0.8	E
	2.0	57.5	3.7	
	5.0	82.0	5.2	
	10.0	90.0	5.8	
	15.0	93.5	6.0	
		100.0	6.4	

Table 12.10-8 (cont.)

Source	Particle Size (μm)	Cumulative Mass % ≤ Stated Size[b]	Cumulative Mass Emission Factor (kg/Mg metal)	EMISSION FACTOR RATING
Pouring, cooling[b] (SCC 3-04-0030-18)				
Uncontrolled	0.5	—[d]	ND	D
	1.0	19.0	0.40	
	2.0	20.0	0.42	
	2.5	24.0	0.50	
	5.0	34.0	0.71	
	10.0	49.0	1.03	
	15.0	72.0	1.51	
		100.0	2.1	
Shakeout[b] (SCC 3-04-003-31)				
Uncontrolled	0.5	23.0	0.37	E
	1.0	37.0	0.59	
	2.0	41.0	0.66	
	2.5	42.0	0.67	
	5.0	44.0	0.70	
	10.0	70.0	1.12	
	15.0	99.9	1.60	
		100.0	1.60	

[a] Emission Factor expressed as kg of pollutant/Mg of metal produced. Mass emission rate data available in Tables 12.10-2 and 12.10-6 to calculate size-specific emission factors. SCC = Source Classification Code. ND = no data.

[b] References 13,21,22,25,26.

[c] Pressure drop across venturi: approximately 25 kPa of water.

[d] Reference 3, Exhibit VI-15. Averaged from data on 2 foundries. Because original test data could not be obtained, EMISSION FACTOR RATING is E.

Table 12.10-9 (English Units). PARTICLE SIZE DISTRIBUTION DATA AND EMISSION FACTORS FOR GRAY IRON FOUNDRIES[a]

Source	Particle Size (μm)	Cumulative Mass % ≤ Stated Size[b]	Cumulative Mass Emission Factor (lb/ton metal)	EMISSION FACTOR RATING
Cupola furnace[b] (SCC 3-04-003-01)				
Uncontrolled	0.5	44.3	6.2	C
	1.0	69.1	9.6	
	2.0	79.6	11.0	
	2.5	84.0	11.6	
	5.0	90.1	12.4	
	10.0	90.1	12.4	
	15.0	90.6	12.6	
		100.0	13.8	
Controlled by baghouse	0.5	83.4	0.66	E
	1.0	91.5	0.74	
	2.0	94.2	0.76	
	2.5	94.9	0.76	
	5.0	94.9	0.76	
	10.0	95.0	0.76	
	15.0	100.0	0.80	
Controlled by venturi scrubber[c]	0.5	56.0	1.68	C
	1.0	70.2	2.10	
	2.0	77.4	2.32	
	2.5	77.7	2.34	
	5.0	77.7	2.34	
	10.0	77.7	2.34	
	15.0	77.7	2.34	
		100.0	3.0	
Electric arc furnace[d] (SCC 3-04-003-04)				
Uncontrolled	1.0	13.0	1.6	E
	2.0	57.5	7.4	
	5.0	82.0	10.4	
	10.0	90.0	11.6	
	15.0	93.5	12.0	
		100.0	12.8	

Table 12.10-9 (cont.)

Source	Particle Size (μm)	Cumulative Mass % $\leq$ Stated Size[b]	Cumulative Mass Emission Factor (lb/ton metal)	EMISSION FACTOR RATING
Pouring, cooling[b] (SCC 3-04-003-18)				
Uncontrolled	0.5	—[d]	ND	D
	1.0	19.0	0.80	
	2.0	20.0	0.84	
	2.5	24.0	1.00	
	5.0	34.0	1.42	
	10.0	49.0	2.06	
	15.0	72.0	3.02	
		100.0	4.2	
Shakeout[b] (SCC 3-04-003-31)				
Uncontrolled	0.5	23.0	0.74	E
	1.0	37.0	1.18	
	2.0	41.0	1.32	
	2.5	42.0	1.34	
	5.0	44.0	1.40	
	10.0	70.0	2.24	
	15.0	99.9	3.20	
		100.0	3.20	

[a] Emission factors are expressed as lb of pollutant/ton of metal produced. Mass emission rate data available in Tables 12.10-3 and 12.10-7 to calculate size-specific emission factors. SCC = Source Classification Code. ND = no data.

[b] References 13,21-22,25-26.

[c] Pressure drop across venturi: approximately 102 inches of water.

[d] Reference 3, Exhibit VI-15. Averaged from data on 2 foundries. Because original test data could not be obtained, EMISSION FACTOR RATING is E.

backcharging, alloying, slag removal, and tapping operations. These emissions can escape into the furnace building or can be collected and vented through roof openings. Emission controls for melting and refining operations involve venting furnace gases and fumes directly to a control device. Canopy hoods or special hoods near furnace doors and tapping points capture emissions and route them to emission control systems.

12.10.3.2.1 Cupolas -

Coke burned in cupola furnaces produces several emissions. Incomplete combustion of coke causes carbon monoxide emissions and sulfur in the coke gives rise to sulfur dioxide emissions. High energy scrubbers and fabric filters are used to control particulate emissions from cupolas and electric arc furnaces and can achieve efficiencies of 95 and 98 percent, respectively. A cupola furnace typically has an afterburner as well, which achieves up to 95 percent efficiency. The afterburner is located in the furnace stack to oxidize carbon monoxide and burn organic fumes, tars, and oils.

Reducing these contaminants protects the particulate control device from possible plugging and explosion.

Toxic emissions from cupolas include both organic and inorganic materials. Cupolas produce the most toxic emissions compared to other melting equipment.

12.10.3.2.2 Electric Arc Furnaces -

During melting in an electric arc furnace, particulate emissions of metallic and mineral oxides are generated by the vaporization of iron and transformation of mineral additives. This particulate matter is controlled by high-energy scrubbers (45 percent efficiency) and fabric filters (98 percent efficiency). Carbon monoxide emissions result from combustion of graphite from electrodes and carbon added to the charge. Hydrocarbons result from vaporization and incomplete combustion of any oil remaining on the scrap iron charge.

12.10.3.2.3 Electric Induction Furnaces -

Electric induction furnaces using clean steel scrap produce particulate emissions comprised largely of iron oxides. High emissions from clean charge emissions are due to cold charges, such as the first charge of the day. When contaminated charges are used, higher emissions rates result.

Dust emissions from electric induction furnaces also depend on the charge material composition, the melting method (cold charge or continuous), and the melting rate of the materials used. The highest emissions occur during a cold charge.

Because induction furnaces emit negligible amounts of hydrocarbon and carbon monoxide emissions and relatively little particulate, they are typically uncontrolled, except during charging and pouring operations.

12.10.3.2.4 Refining -

Particulate emissions are generated during the refining of molten iron before pouring. The addition of magnesium to molten metal to produce ductile iron causes a violent reaction between the magnesium and molten iron, with emissions of magnesium oxides and metallic fumes. Emissions from pouring consist of metal fumes from the melt, and carbon monoxide, organic compounds, and particulate evolved from the mold and core materials. Toxic emissions of particulate, arsenic, chromium, halogenated hydrocarbons, and aromatic hydrocarbons are released in the refining process. Emissions from pouring normally are captured by a collection system and vented, either controlled or uncontrolled, to the atmosphere. Emissions continue as the molds cool. A significant quantity of particulate is also generated during the casting shakeout operation. These fugitive emissions are controlled by either high energy scrubbers or fabric filters.

12.10.3.3 Mold And Core Production -

The major pollutant emitted in mold and core production operations is particulate from sand reclaiming, sand preparation, sand mixing with binders and additives, and mold and core forming. Organics, carbon monoxide, and particulate are emitted from core baking and organic emissions from mold drying. Fabric filters and high energy scrubbers generally are used to control particulate from mold and core production. Afterburners and catalytic incinerators can be used to control organics and carbon monoxide emissions.

In addition to organic binders, molds and cores may be held together in the desired shape by means of a cross-linked organic polymer network. This network of polymers undergoes thermal decomposition when exposed to the very high temperatures of casting, typically 1400°C (2550°F). At these temperatures it is likely that pyrolysis of the chemical binder will produce a complex of free radicals which will recombine to form a wide range of chemical compounds having widely differing concentrations.

There are many different types of resins currently in use having diverse and toxic compositions. There are no data currently available for determining the toxic compounds in a particular resin which are emitted to the atmosphere and to what extent these emissions occur.

12.10.3.4 Casting And Finishing -

Emissions during pouring include decomposition products of resins, other organic compounds, and particulate matter. Finishing operations emit particulates during the removal of burrs, risers, and gates, and during shot blast cleaning. These emissions are controlled by cyclone separators and fabric filters. Emissions are related to mold size, mold composition, sand to metal ratio, pouring temperature, and pouring rate.

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12.11 Secondary Lead Processing

12.11.1 General

Secondary lead smelters produce lead and lead alloys from lead-bearing scrap material. More than 60 percent of all secondary lead is derived from scrap automobile batteries. Each battery contains approximately 8.2 kg (18 lb) of lead, consisting of 40 percent lead alloys and 60 percent lead oxide. Other raw materials used in secondary lead smelting include wheel balance weights, pipe, solder, drosses, and lead sheathing. Lead produced by secondary smelting accounts for half of the lead produced in the U. S. There are 42 companies operating 50 plants with individual capacities ranging from 907 megagrams (Mg) (1,000 tons) to 109,000 Mg (120,000 tons) per year.

12.11.2 Process Description[1-7]

Secondary lead smelting includes 3 major operations: scrap pretreatment, smelting, and refining. These are shown schematically in Figure 12.11-1A, Figure 12.11-1B, and Figure 12.11-1C, respectively.

12.11.2.1 Scrap Pretreatment -

Scrap pretreatment is the partial removal of metal and nonmetal contaminants from lead-bearing scrap and residue. Processes used for scrap pretreatment include battery breaking, crushing, and sweating. Battery breaking is the draining and crushing of batteries, followed by manual separation of the lead from nonmetallic materials. Lead plates, posts, and intercell connectors are collected and stored in a pile for subsequent charging to the furnace. Oversized pieces of scrap and residues are usually put through jaw crushers. This separated lead scrap is then sweated in a gas- or oil-fired reverberatory or rotary furnace to separate lead from metals with higher melting points. Rotary furnaces are usually used to process low-lead-content scrap and residue, while reverberatory furnaces are used to process high-lead-content scrap. The partially purified lead is periodically tapped from these furnaces for further processing in smelting furnaces or pot furnaces.

12.11.2.2 Smelting -

Smelting produces lead by melting and separating the lead from metal and nonmetallic contaminants and by reducing oxides to elemental lead. Smelting is carried out in blast, reverberatory, and rotary kiln furnaces. Blast furnaces produce hard or antimonial lead containing about 10 percent antimony. Reverberatory and rotary kiln furnaces are used to produce semisoft lead containing 3 to 4 percent antimony; however, rotary kiln furnaces are rarely used in the U. S. and will not be discussed in detail.

In blast furnaces pretreated scrap metal, rerun slag, scrap iron, coke, recycled dross, flue dust, and limestone are used as charge materials to the furnace. The process heat needed to melt the lead is produced by the reaction of the charged coke with blast air that is blown into the furnace. Some of the coke combusts to melt the charge, while the remainder reduces lead oxides to elemental lead. The furnace is charged with combustion air at 3.4 to 5.2 kPa (0.5 to 0.75 psi) with an exhaust temperature ranging from 650 to 730°C (1200 to 1350°F).

As the lead charge melts, limestone and iron float to the top of the molten bath and form a flux that retards oxidation of the product lead. The molten lead flows from the furnace into a holding pot at a nearly continuous rate. The product lead constitutes roughly 70 percent of the charge. From

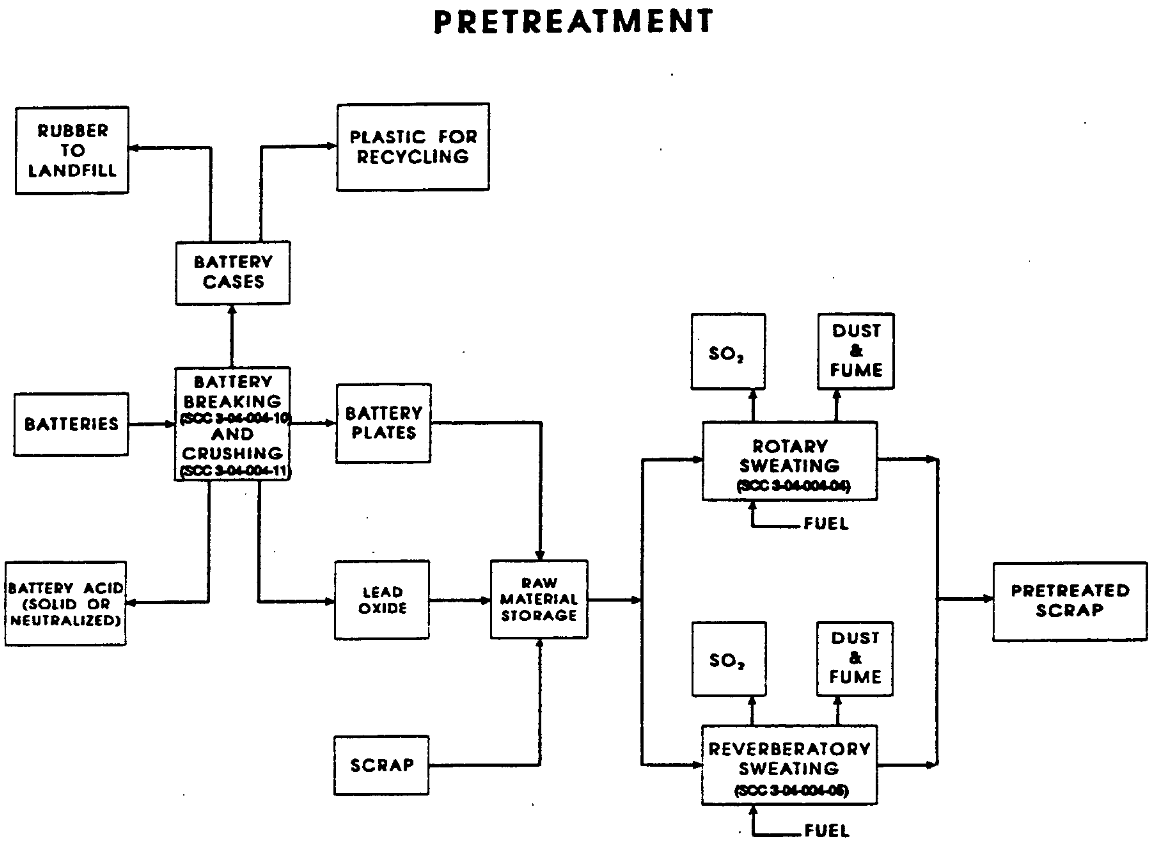

Figure 12.11-1A. Process flow for typical secondary lead smelting.
(Source Classification Codes in parentheses.)

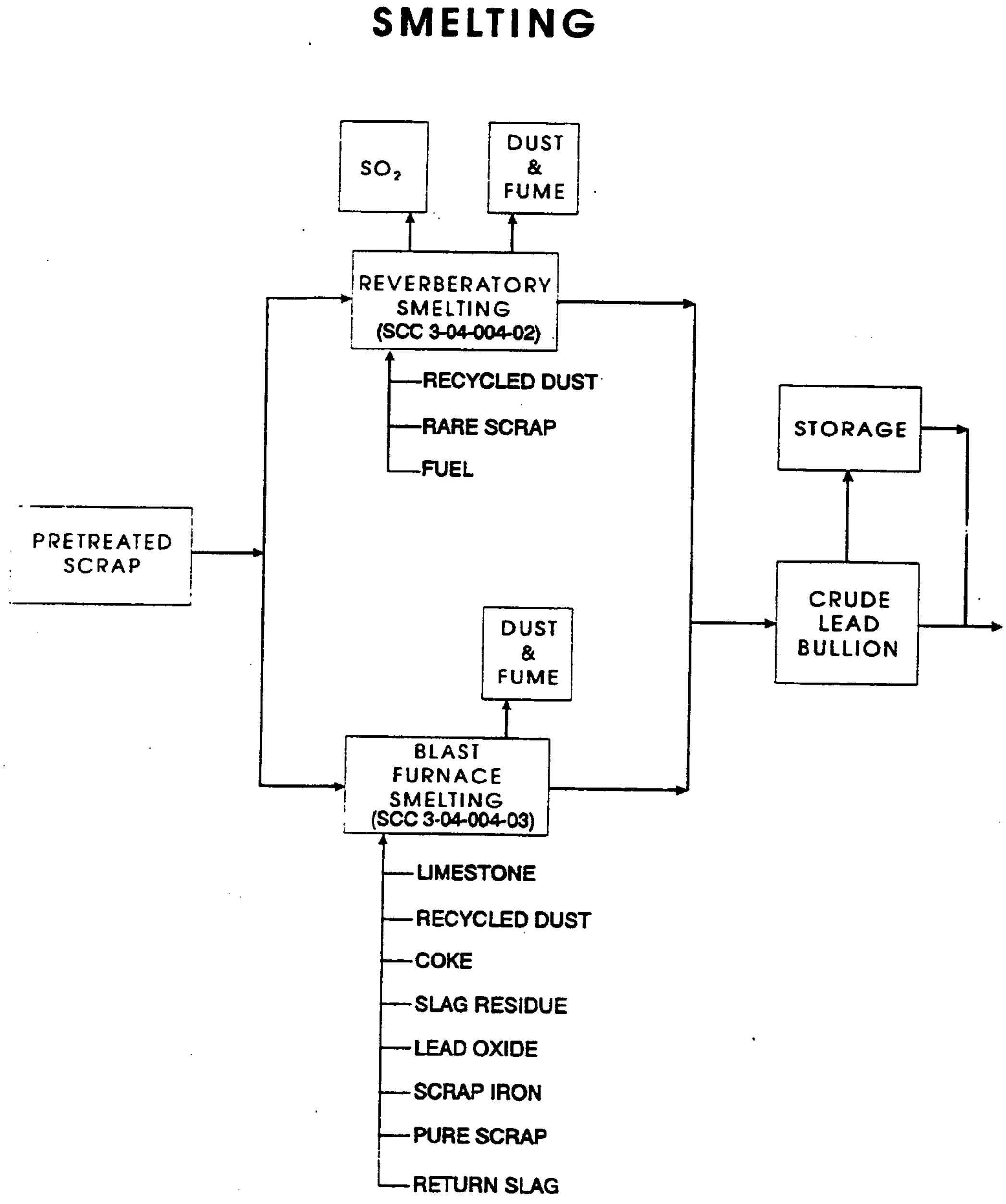

Figure 12.11-1B. Process flow for typical secondary lead smelting.
(Source Classification Codes in parentheses.)

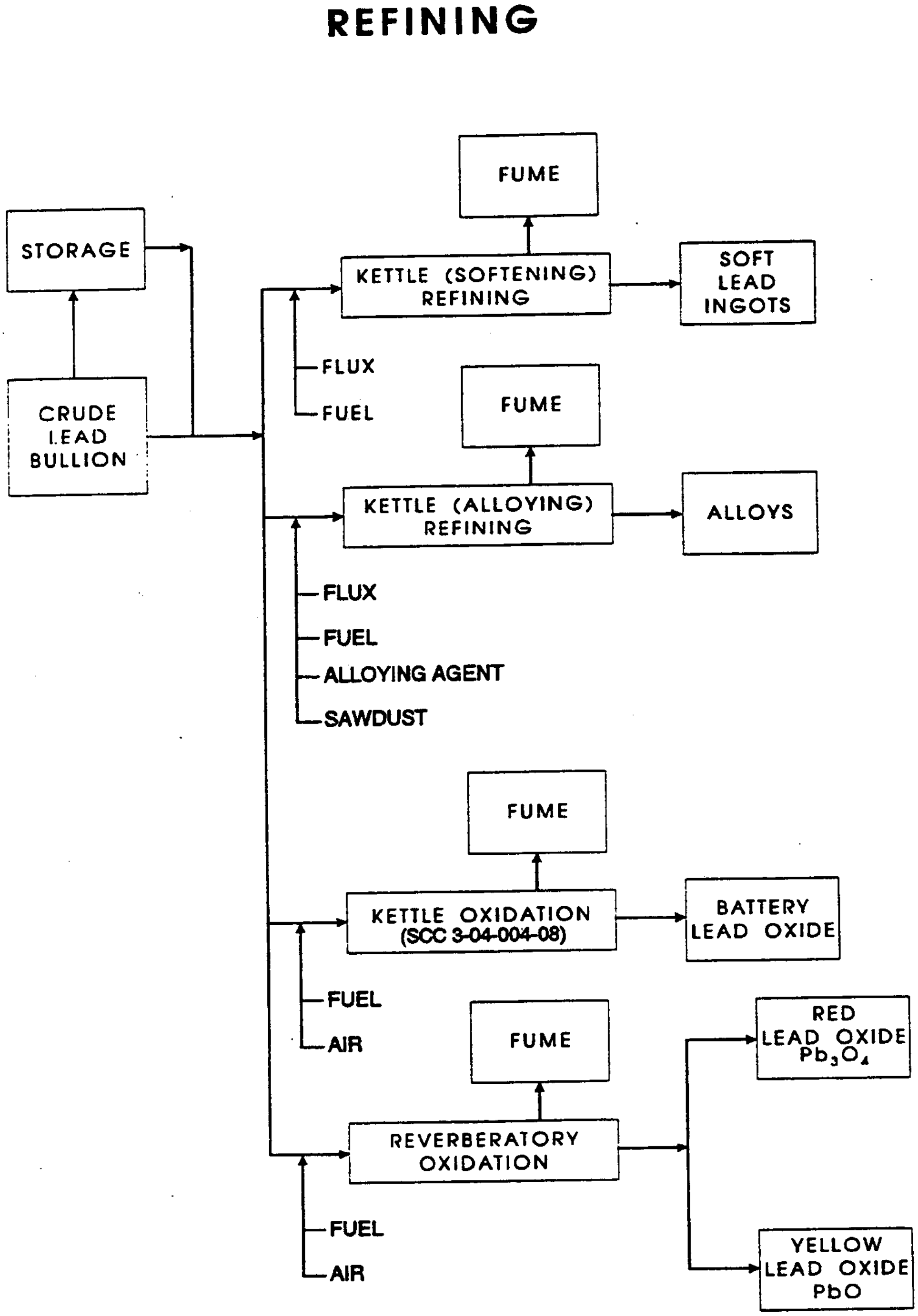

Figure 12.11-1C. Process flow for typical secondary lead smelting.
(Source Classification Codes in parentheses.)

the holding pot, the lead is usually cast into large ingots called pigs or sows. About 18 percent of the charge is recovered as slag, with about 60 percent of this being a sulfurous slag called matte. Roughly 5 percent of the charge is retained for reuse, and the remaining 7 percent of the charge escapes as dust or fume. Processing capacity of the blast furnace ranges from 18 to 73 Mg per day (20 to 80 tons per day).

The reverberatory furnace used to produce semisoft lead is charged with lead scrap, metallic battery parts, oxides, drosses, and other residues. The charge is heated directly to a temperature of 1260°C (2300°F) using natural gas, oil, or coal. The average furnace capacity is about 45 megagrams (50 tons) per day. About 47 percent of the charge is recovered as lead product and is periodically tapped into molds or holding pots. Forty-six percent of the charge is removed as slag and is later processed in blast furnaces. The remaining 7 percent of the furnace charge escapes as dust or fume.

12.11.2.3 Refining -

Refining and casting the crude lead from the smelting furnaces can consist of softening, alloying, and oxidation depending on the degree of purity or alloy type desired. These operations are batch processes requiring from 2 hours to 3 days. These operations can be performed in reverberatory furnaces; however, kettle-type furnaces are most commonly used. Remelting process is usually applied to lead alloy ingots that require no further processing before casting. Kettle furnaces used for alloying, refining, and oxidizing are usually gas- or oil-fired, and have typical capacities of 23 to 136 megagrams (25 to 150 tons) per day. Refining and alloying operating temperatures range from 320 to 700°C (600 to 1300°F). Alloying furnaces simply melt and mix ingots of lead and alloy materials. Antimony, tin, arsenic, copper, and nickel are the most common alloying materials.

Refining furnaces are used to either remove copper and antimony for soft lead production, or to remove arsenic, copper, and nickel for hard lead production. Sulfur may be added to the molten lead bath to remove copper. Copper sulfide skimmed off as dross may subsequently be processed in a blast furnace to recover residual lead. Aluminum chloride flux may be used to remove copper, antimony, and nickel. The antimony content can be reduced to about 0.02 percent by bubbling air through the molten lead. Residual antimony can be removed by adding sodium nitrate and sodium hydroxide to the bath and skimming off the resulting dross. Dry drossing consists of adding sawdust to the agitated mass of molten metal. The sawdust supplies carbon to help separate globules of lead suspended in the dross and to reduce some of the lead oxide to elemental lead.

Oxidizing furnaces, either kettle or reverberatory units, are used to oxidize lead and to entrain the product lead oxides in the combustion air stream for subsequent recovery in high-efficiency baghouses.

12.11.3 Emissions And Controls[1,4-5]

Emission factors for controlled and uncontrolled processes and fugitive particulate are given in Tables 12.11-1, 12.11-2, 12.11-3, and 12.11-4. Particulate emissions from most processes are based on accumulated test data, whereas fugitive particulate emissions are based on the assumption that 5 percent of uncontrolled stack emissions are released as fugitive emissions.

Reverberatory and blast furnaces account for the vast majority of the total lead emissions from the secondary lead industry. The relative quantities emitted from these 2 smelting processes cannot be specified, because of a lack of complete information. Most of the remaining processes are small emission sources with undefined emission characteristics.

Table 12.11-1 (Metric Units). EMISSION FACTORS FOR SECONDARY LEAD PROCESSING[a]

Process	Particulate[b]				Lead[b]				SO_2	
	Uncontrolled	EMISSION FACTOR RATING	Controlled	EMISSION FACTOR RATING	Uncontrolled	EMISSION FACTOR RATING	Controlled	EMISSION FACTOR RATING	Uncontrolled	EMISSION FACTOR RATING
Sweating[c] (kg/Mg charge) (SCC 3-04-004-04)	16-35	E	ND	NA	4-8[d]	E	ND	NA	ND	ND
Reverberatory smelting (SCC 3-04-004-02)	162 (87-242)[e]	C	0.50 (0.26-0.77)[f]	C	32 (17-48)[g]	C	ND	NA	40 (36-44)[f]	C
Blast smelting-cupola[h] (SCC 3-04-004-03)	153 (92-207)[j]	C	1.12 (0.11-2.49)[k]	C	52 (31-70)[m]	C	0.15 (0.02-0.32)[n]	C	27 (9-55)[e]	C
Kettle refining (SCC 3-04-004-26)	0.02[p]	C	ND	NA	0.006[p]	C	ND	NA	ND	NA
Kettle Oxidation (SCC 3-04-004-08)	≤ 20[q]	E	ND	NA	ND	NA	ND	NA	ND	NA
Casting (SCC 3-04-004-09)	0.02[p]	C	ND	NA	0.007[p]	C	ND	NA	ND	NA

[a] Emission factor units expressed as kg of pollutant/Mg metal produced. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Particulate and lead emission factors are based on quantity of lead product produced, except as noted.

[c] Reference 1. Estimated from sweating furnace emissions from nonlead secondary nonferrous processing industries.

[d] References 3,5. Based on assumption that uncontrolled reverberatory furnace flue emissions are 23% lead.

[e] References 8-11.

[f] References 6,8-11.

[g] Reference 13. Uncontrolled reverberatory furnace flue emissions assumed to be 23% lead. Blast furnace emissions have lead content of 34%, based on single uncontrolled plant test.

[h] Blast furnace emissions are combined flue gases and associated ventilation hood streams (charging and tapping).

[j] References 8,11-12.

[k] References 6,8,11-12,14-15.

[m] Reference 13. Blast furnace emissions have lead content of 26%, based on single controlled plant test.

[n] Based on quantity of material charged to furnaces.

[p] Reference 13. Lead content of kettle refining emissions is 40% and of casting emissions is 36%.

[q] References 1-2. Essentially all product lead oxide is entrained in an air stream and subsequently recovered by baghouse with average collection efficiency >99%. Factor represents emissions of lead oxide that escape a baghouse used to collect the lead oxide product. Represents approximate upper limit for emissions.

Table 12.11-2 (English Units). EMISSION FACTORS FOR SECONDARY LEAD PROCESSING[a]

Process	Particulate[b]				Lead[b]				SO_2	
	Uncontrolled	EMISSION FACTOR RATING	Controlled	EMISSION FACTOR RATING	Uncontrolled	EMISSION FACTOR RATING	Controlled	EMISSION FACTOR RATING	Uncontrolled	EMISSION FACTOR RATING
Sweating[c] (kg/Mg charge) (SCC 3-04-004-04)	32-70	E	ND	NA	7-16[d]	E	ND	NA	ND	NA
Reverberatory smelting (SCC 3-04-004-02)	323 (173-483)[e]	C	1.01 (0.53-1.55)[f]	C	65 (35-97)[g]	C	ND	NA	80 (71-88)[f]	C
Blast smelting-cupola[h] (SCC 3-04-004-03)	307 (184-413)[j]	C	2.24 (0.22-4.88)[k]	C	104 (64-140)[m]	C	0.29 (0.03-0.64)[n]	C	53 (18-110)[e]	C
Kettle refining (SCC 3-04-004-26)	0.03[p]	C	ND	NA	0.01[p]	C	ND	NA	ND	NA
Kettle Oxidation (SCC 3-04-004-08)	≤ 40[p]	E	ND	NA	ND	NA	ND	NA	ND	NA
Casting (SCC 3-04-004-09)	0.04[p]	C	ND	NA	0.01[p]	C	ND	NA	ND	NA

[a] Emission factors expressed as lb of pollutant/ton of metal produced. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Particulate and lead emission factors are based on quantity of lead product produced, except as noted.

[c] Reference 1. Estimated from sweating furnace emissions from nonlead secondary nonferrous processing industries.

[d] References 3,5. Based on assumption that uncontrolled reverberatory furnace flue emissions are 23% lead.

[e] References 8-11.

[f] References 6,8-11.

[g] Reference 13. Uncontrolled reverberatory furnace flue emissions assumed to be 23% lead. Blast furnace emissions have lead content of 34%, based on single uncontrolled plant test.

[h] Blast furnace emissions are combined flue gases and associated ventilation hood streams (charging and tapping).

[j] References 8,11-12.

[k] References 6,8,11-12,14-15.

[m] Reference 13. Blast furnace emissions have lead content of 26%, based on single controlled plant test.

[n] Based on quantity of material charged to furnaces.

[p] Reference 13. Lead content of kettle refining emissions is 40% and of casting emissions is 36%.

[q] References 1-2. Essentially all product lead oxide is entrained in an air stream and subsequently recovered by baghouse with average collection efficiency >99%. Factor represents emissions of lead oxide that escape a baghouse used to collect the lead oxide product. Represents approximate upper limit for emissions.

Table 12.11-3 (Metric Units). FUGITIVE EMISSION FACTORS FOR SECONDARY LEAD PROCESSING[a]

EMISSION FACTOR RATING: E

Operation	Particulate	Lead
Sweating (SCC 3-04-004-12)	0.8-1.8[b]	0.2-0.9[c]
Smelting (SCC 3-04-004-13)	4.3-12.1	0.1-0.3[d]
Kettle refining (SCC 3-04-004-14)	0.001	0.0003[e]
Casting (SCC 3-04-004-25)	0.001	0.0004[e]

[a] Reference 16. Based on amount of lead product except for sweating, which is based on quantity of material charged to furnace. Fugitive emissions estimated to be 5% of uncontrolled stack emissions. SCC= Source Classification Code.

[b] Reference 1. Sweating furnace emissions estimated from nonlead secondary nonferrous processsing industries.

[c] References 3,5. Assumes 23% lead content of uncontrolled blast furnace flue emissions.

[d] Reference 24.

[e] Reference 13.

Table 12.11-4 (English Units). FUGITIVE EMISSION FACTORS FOR SECONDARY LEAD PROCESSING[a]

EMISSION FACTOR RATING: E

Operation	Particulate	Lead
Sweating (SCC 3-04-004-12)	1.6-3.5[b]	0.4-1.8[c]
Smelting (SCC 3-04-004-13)	8.6-24.2	0.2-0.6[d]
Kettle refining (SCC 3-04-004-14)	0.002	0.0006[e]
Casting (SCC 3-04-004-25)	0.002	0.0007[e]

[a] Reference 16. Based on amount of lead product, except for sweating, which is based on quantity of material charged to furnace. Fugitive emissions estimated to be 5% of uncontrolled stack emissions. SCC = Source Classification Code.

[b] Reference 1. Sweating furnace emissions estimated from nonlead secondary nonferrous processsing industries.

[c] References 3,5. Assumes 23% lead content of uncontrolled blast furnace flue emissions.

[d] Reference 24.

[e] Reference 13.

Emissions from battery breaking are mainly of sulfuric acid mist and dusts containing dirt, battery case material, and lead compounds. Emissions from crushing are also mainly dusts.

Emissions from sweating operations are fume, dust, soot particles, and combustion products, including sulfur dioxide (SO_2). The SO_2 emissions come from combustion of sulfur compounds in the scrap and fuel. Dust particles range in size from 5 to 20 micrometers (μm) and unagglomerated lead fumes range in size from 0.07 to 0.4 μm, with an average diameter of 0.3 μm. Particulate loadings in the stack gas from reverberatory sweating range from 3.2 to 10.3 grams per cubic meter (1.4 to 4.5 grains per cubic foot). Baghouses are usually used to control sweating emissions, with removal efficiencies exceeding 99 percent. The emission factors for lead sweating in Tables 12.11-1 and 12.11-2 are based on measurements at similar sweating furnaces in other secondary metal processing industries, not on measurements at lead sweating furnaces.

Reverberatory smelting furnaces emit particulate and oxides of sulfur and nitrogen. Particulate consists of oxides, sulfides and sulfates of lead, antimony, arsenic, copper, and tin, as well as unagglomerated lead fume. Particulate loadings range from to 16 to 50 grams per cubic meter (7 to 22 grains per cubic foot). Emissions are generally controlled with settling and cooling chambers, followed by a baghouse. Control efficiencies generally exceed 99 percent. Wet scrubbers are sometimes used to reduce SO_2 emissions. However, because of the small particles emitted from reverberatory furnaces, baghouses are more often used than scrubbers for particulate control.

Two chemical analyses by electron spectroscopy have shown the particulate to consist of 38 to 42 percent lead, 20 to 30 percent tin, and about 1 percent zinc.[17] Particulate emissions from reverberatory smelting furnaces are estimated to contain 20 percent lead.

Emissions from blast furnaces occur at charging doors, the slag tap, the lead well, and the furnace stack. The emissions are combustion gases (including carbon monoxide, hydrocarbons, and oxides of sulfur and nitrogen) and particulate. Emissions from the charging doors and the slag tap are hooded and routed to the devices treating the furnace stack emissions. Blast furnace particulate is smaller than that emitted from reverberatory furnaces and is suitable for control by scrubbers or fabric filters downstream of coolers. Efficiencies for various control devices are shown in Table 12.11-5. In one application, fabric filters alone captured over 99 percent of the blast furnace particulate emissions.

Particulate recovered from the uncontrolled flue emissions at 6 blast furnaces had an average lead content of 23 percent.[3,5] Particulate recovered from the uncontrolled charging and tapping hoods at 1 blast furnace had an average lead content of 61 percent.[13] Based on relative emission rates, lead is 34 percent of uncontrolled blast furnace emissions. Controlled emissions from the same blast furnace had lead content of 26 percent, with 33 percent from flues, and 22 percent from charging and tapping operations.[13] Particulate recovered from another blast furnace contained 80 to 85 percent lead sulfate and lead chloride, 4 percent tin, 1 percent cadmium, 1 percent zinc, 0.5 percent antimony, 0.5 percent arsenic, and less than 1 percent organic matter.[18]

Kettle furnaces for melting, refining, and alloying are relatively minor emission sources. The kettles are hooded, with fumes and dusts typically vented to baghouses and recovered at efficiencies exceeding 99 percent. Twenty measurements of the uncontrolled particulates from kettle furnaces showed a mass median aerodynamic particle diameter of 18.9 micrometers, with particle size ranging from 0.05 to 150 micrometers. Three chemical analyses by electron spectroscopy showed the composition of particulate to vary from 12 to 17 percent lead, 5 to 17 percent tin, and 0.9 to 5.7 percent zinc.[16]

Table 12.11-5. EFFICIENCIES OF PARTICULATE CONTROL EQUIPMENT ASSOCIATED WITH SECONDARY LEAD SMELTING FURNACES

Control Equipment	Furnace Type	Control Efficiency (%)
Fabric filter[a]	Blast Blast Reverberatory	98.4 99.2
Dry cyclone plus fabric filter[a]	Blast	99.0
Wet cyclone plus fabric filter[b]	Reverberatory	99.7
Settling chamber plus dry cyclone plus fabric filter[c]	Reverberatory	99.8
Venturi scrubber plus demister[d]	Blast	99.3

[a] Reference 8.
[b] Reference 9.
[c] Reference 10.
[d] Reference 14.

Emissions from oxidizing furnaces are economically recovered with baghouses. The particulates are mostly lead oxide, but they also contain amounts of lead and other metals. The oxides range in size from 0.2 to 0.5 μm. Controlled emissions have been estimated to be 0.1 kilograms per megagram (0.2 pounds per ton) of lead product, based on a 99 percent efficient baghouse.

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12.12 Secondary Magnesium Smelting

12.12.1 General[1,2]

Secondary magnesium smelters process scrap which contains magnesium to produce magnesium alloys. Sources of scrap for magnesium smelting include automobile crankcase and transmission housings, beverage cans, scrap from product manufacture, and sludges from various magnesium-melting operations. This form of recovery is becoming an important factor in magnesium production. In 1983, only 13 percent of the U. S. magnesium supply came from secondary production; in 1991, this number increased to 30 percent, primarily due to increased recycling of beverage cans.

12.12.2 Process Description[3,4]

Magnesium scrap is sorted and charged into a steel crucible maintained at approximately 675°C (1247°F). As the charge begins to burn, flux must be added to control oxidation. Fluxes usually contain chloride salts of potassium, magnesium, barium, and magnesium oxide and calcium fluoride. Fluxes are floated on top of the melt to prevent contact with air. The method of heating the crucible causes the bottom layer of scrap to melt first while the top remains solid. This semi-molten state allows cold castings to be added without danger of "shooting", a violent reaction that occurs when cold metals are added to hot liquid metals. As soon as the surface of the feed becomes liquid, a crusting flux must be added to inhibit surface burning.

The composition of the melt is carefully monitored. Steel, salts, and oxides coagulate at the bottom of the furnace. Additional metals are added as needed to reach specifications. Once the molten metal reaches the desired levels of key components, it is poured, pumped, or ladled into ingots.

12.12.3 Emissions And Controls[5,6]

Emissions for a typical magnesium smelter are given in Tables 12.12-1 and 12.12-2. Emissions from magnesium smelting include particulate magnesium oxides (MgO) and from the melting and fluxing processes, and nitrogen oxides from the fixation of atmospheric nitrogen by the furnace temperatures. Carbon monoxide and nonmethane hydrocarbons have also been detected. The type of flux used on the molten material, the amount of contamination of the scrap (especially oil and other hydrocarbons), and the type and extent of control equipment affect the amount of emissions produced.

Table 12.12-1 (Metric Units). EMISSION FACTORS FOR SECONDARY MAGNESIUM SMELTING

Type of Furnace	Particulate Emission Factor[a]	EMISSION FACTOR RATING
Pot Furnace (SCC 3-04-006-01)		
Uncontrolled	2	C
Controlled	0.2	C

[a] References 5 and 6. Emission factors are expressed as kg of pollutant/Mg of metal processed. SCC = Source Classification Code.

Table 12.12-2 (English Units). EMISSION FACTORS FOR SECONDARY MAGNESIUM SMELTING

Type of Furnace	Particulate Emission Factor[a]	EMISSION FACTOR RATING
Pot Furnace (SCC 3-04-006-01)		
Uncontrolled	4	C
Controlled	0.4	C

[a] References 5 and 6. Emission factors are expressed as lb of pollutant/ton of metal processed. SCC = Source Classification Code.

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12.13 Steel Foundries

12.13.1 General

Steel foundries produce steel castings weighing from a few ounces to over 180 megagrams (Mg) (200 tons). These castings are used in machinery, transportation, and other industries requiring parts that are strong and reliable. In 1989, 1030 million Mg (1135 million tons) of steel (carbon and alloy) were cast by U. S. steel foundries, while demand was calculated at 1332 Mg (1470 million tons). Imported steel accounts for the difference between the amount cast and the demand amount. Steel casting is done by small- and medium-size manufacturing companies.

Commercial steel castings are divided into 3 classes: (1) carbon steel, (2) low-alloy steel, and (3) high-alloy steel. Different compositions and heat treatments of steel castings result in a tensile strength range of 400 to 1700 MPa (60,000 to 250,000 psi).

12.13.2 Process Description[1]

Steel foundries produce steel castings by melting scrap, alloying, molding, and finishing. The process flow diagram of a typical steel foundry with fugitive emission points is presented in Figure 12.13-1. The major processing operations of a typical steel foundry are raw materials handling, metal melting, mold and core production, and casting and finishing.

12.13.2.1 Raw Materials Handling -
Raw material handling operations include receiving, unloading, storing, and conveying all raw materials for the foundry. Some of the raw materials used by steel foundries are iron and steel scrap, foundry returns, metal turnings, alloys, carbon additives, fluxes (limestone, soda ash, fluorspar, calcium carbide), sand, sand additives, and binders. These raw materials are received in ships, railcars, trucks, and containers, and are transferred by trucks, loaders, and conveyors to both open-pile and enclosed storage areas. They are then transferred by similar means from storage to the subsequent processes.

12.13.2.2 Metal Melting[9] -
Metal melting process operations are: (1) scrap preparation; (2) furnace charging, in which metal, scrap, alloys, carbon, and flux are added to the furnace; (3) melting, during which the furnace remains closed; (4) backcharging, which is the addition of more metal and possibly alloys; (5) refining by single (oxidizing) slag or double (oxidizing and reducing) slagging operations; (6) oxygen lancing, which is injecting oxygen into the molten steel to adjust the chemistry of the metal and speed up the melt; and (7) tapping the molten metal into a ladle or directly into molds. After preparation, the scrap, metal, alloy, and flux are weighed and charged to the furnace.

Electric furnaces are used almost exclusively in the steel foundry for melting and formulating steel. There are 2 types of electric furnaces: direct arc and induction.

Electric arc furnaces are charged with raw materials by removing the lid through a chute opening in the lid or through a door in the side. The molten metal is tapped by tilting and pouring through a spout on the side. Melting capacities range up to 10 Mg (11 tons) per hour.

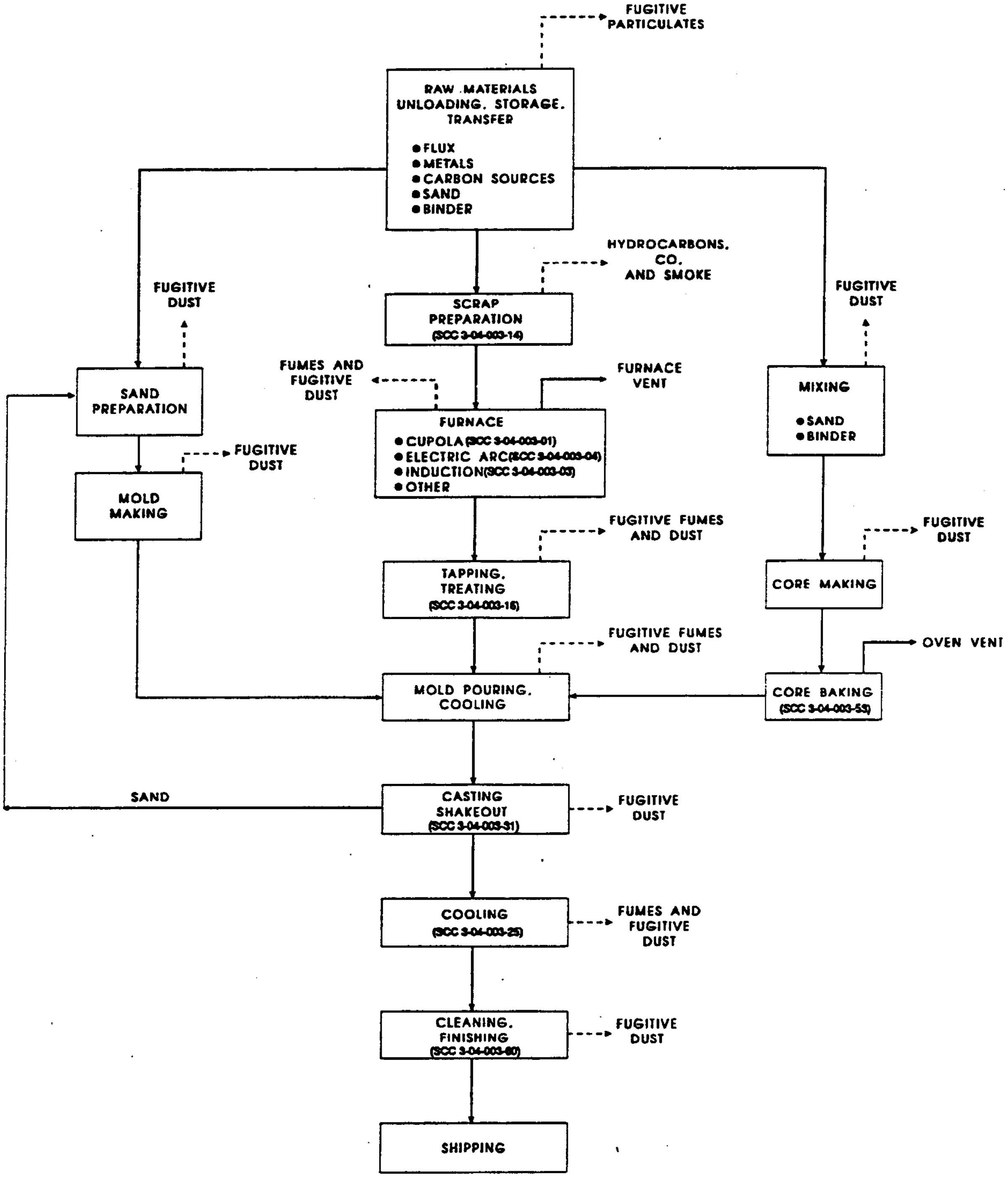

Figure 12.13-1. Flow diagram of a typical steel foundry.
(Source Classification Codes in parentheses.)

A direct electric arc furnace is a large refractory-lined steel pot, fitted with a refractory roof through which 3 vertical graphite electrodes are inserted, as shown in Figure 12.13-2. The metal charge is melted with resistive heating generated by electrical current flowing among the electrodes and through the charge.

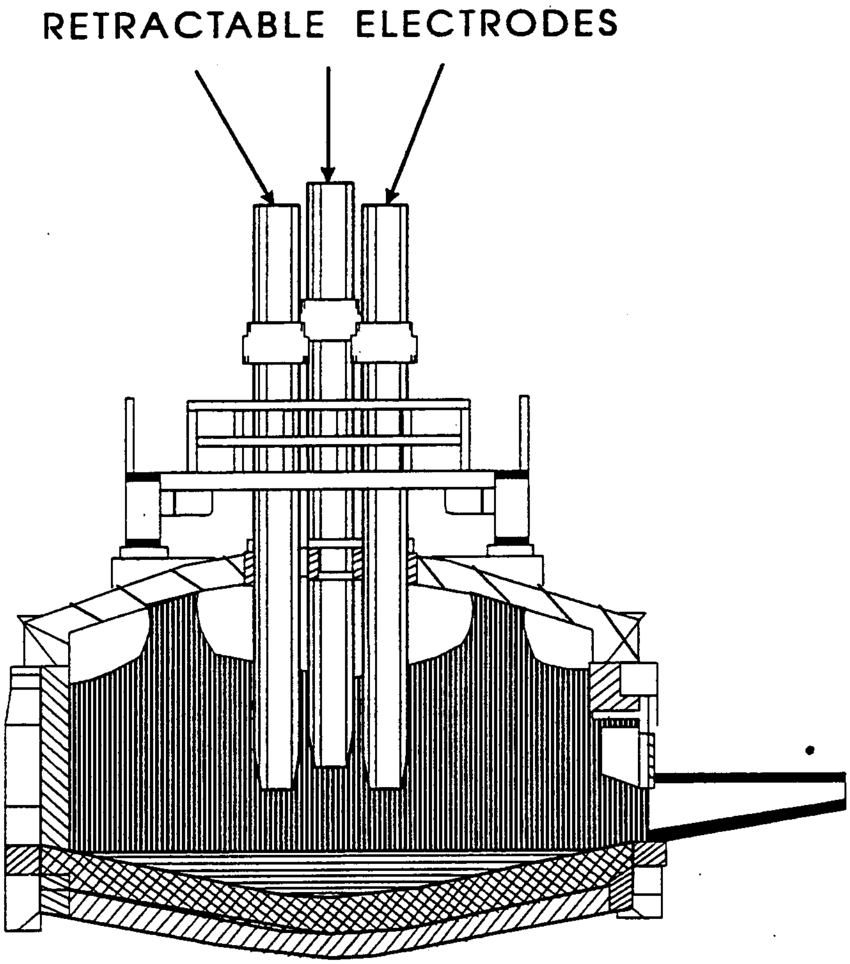

Figure 12.13-2. Electric arc steel furnace.

An induction furnace is a vertical refractory-lined cylinder surrounded by coils energized with alternating current. The resulting fluctuating magnetic field heats the metal. Induction furnaces are kept closed except when charging, skimming, and tapping. The molten metal is tapped by tilting and pouring through a spout on the side. Induction furnaces are also used in conjunction with other furnaces, to hold and superheat a charge, previously melted and refined in another furnace. A very small fraction of the secondary steel industry also uses crucible and pneumatic converter furnaces. A less common furnace used in steel foundries is the open hearth furnace, a very large shallow refractory-lined batch operated vessel. The open hearth furnace is fired at alternate ends, using the hot waste combustion gases to heat the incoming combustion air.

12.13.2.3 Mold And Core Production -

Cores are forms used to make the internal features in castings. Molds are forms used to shape the casting exterior. Cores are made of sand with organic binders, molded into a core and baked in an oven. Molds are made of sand with clay or chemical binders. Increasingly, chemical binders are being used in both core and mold production. Used sand from castings shakeout operations is usually recycled to the sand preparation area, where it is cleaned, screened, and reused.

12.13.2.4 Casting And Finishing -

When the melting process is complete, the molten metal is tapped and poured into a ladle. The molten metal may be treated in the ladle by adding alloys and/or other chemicals. The treated metal is then poured into molds and allowed to partially cool under carefully controlled conditions. When cooled, the castings are placed on a vibrating grid and the sand of the mold and core are shaken away from the casting.

In the cleaning and finishing process, burrs, risers, and gates are broken or ground off to match the contour of the casting. Afterward, the castings can be shot-blasted to remove remaining mold sand and scale.

12.13.3 Emissions And Controls[1,16]

Emissions from the raw materials handling operations are fugitive particulates generated from receiving, unloading, storing, and conveying all raw materials for the foundry. These emissions are controlled by enclosing the major emission points and routing the air from the enclosures through fabric filters.

Emissions from scrap preparation consist of hydrocarbons if solvent degreasing is used and consist of smoke, organics, and carbon monoxide (CO) if heating is used. Catalytic incinerators and afterburners of approximately 95 percent control efficiency for carbon monoxide and organics can be applied to these sources.

Emissions from melting furnaces are particulates, carbon monoxide, organics, sulfur dioxide, nitrogen oxides, and small quantities of chlorides and fluorides. The particulates, chlorides, and fluorides are generated by the flux. Scrap contains volatile organic compounds (VOCs) and dirt particles, along with oxidized phosphorus, silicon, and manganese. In addition, organics on the scrap and the carbon additives increase CO emissions. There are also trace constituents such as nickel, hexavalent chromium, lead, cadmium, and arsenic. The highest concentrations of furnace emissions occur when the furnace lids and doors are opened during charging, backcharging, alloying, oxygen lancing, slag removal, and tapping operations. These emissions escape into the furnace building and are vented through roof vents. Controls for emissions during the melting and refining operations focus on venting the furnace gases and fumes directly to an emission collection duct and control system. Controls for fugitive furnace emissions involve either the use of building roof hoods or special hoods near the furnace doors, to collect emissions and route them to emission control systems. Emission control systems commonly used to control particulate emissions from electric arc and induction furnaces are bag filters, cyclones, and venturi scrubbers. The capture efficiencies of the collection systems are presented in Tables 12.13-1 and 12.13-2. Usually, induction furnaces are uncontrolled.

Molten steel is tapped from a furnace into a ladle. Alloying agents can be added to the ladle. These include aluminum, titanium, zirconium, vanadium, and boron. Ferroalloys are used to produce steel alloys and adjust the oxygen content while the molten steel is in the ladle. Emissions consist of iron oxides during tapping in addition to oxide fumes from alloys added to the ladle.

The major pollutant from mold and core production are particulates from sand reclaiming, sand preparation, sand mixing with binders and additives, and mold and core forming. Particulate,

Table 12.13-1 (Metric Units). EMISSION FACTORS FOR STEEL FOUNDRIES

Process	Filterable Particulate[a] (TSP)	EMISSION FACTOR RATING	Nitrogen Oxides	EMISSION FACTOR RATING	Filterable PM-10	EMISSION FACTOR RATING
Melting						
Electric arc[b,c] (SCC 3-04-007-01)	6.5 (2 to 20)	E	0.1	E	ND	NA
Open hearth[d,e] (SCC 3-04-007-02)	5.5 (1 to 10)	E	0.005	E	ND	NA
Open hearth oxygen lanced[f,g] (SCC 3-04-007-03)	5 (4 to 5.5)	E	ND	NA	ND	NA
Electric induction[h] (SCC 3-04-007-05)	0.05	E	ND	NA	0.045	E
Sand grinding/handling in mold and core making[j] (SCC 3-04-007-06)	ND	NA	NA	NA	0.27[k] 3.0	E E
Core ovens[j] (SCC 3-04-007-07)	ND	NA	ND	NA	1.11[k] 0.45	E E
Pouring and casting[j] (SCC 3-04-007-08)	ND	NA	ND	NA	1.4	E
Casting cleaning[j] (SCC 3-04-007-11)	ND	NA	NA	NA	0.85	E
Charge handling[j] (SCC 3-04-007-12)	ND	NA	NA	NA	0.18	E
Casting cooling[j] (SCC 3-04-007-13)	ND	NA	NA	NA	0.7	E

[a] Expressed as kg/Mg of metal processed. If the scrap metal is very dirty or oily, or if increased oxygen lancing is employed, the emission factor should be chosen from the high side of the factor range. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Electrostatic precipitator, 92 to 98% control efficiency; baghouse (fabric filter), 98 to 99% control efficiency; venturi scrubber, 94 to 98% control efficiency.

[c] References 2-7.

[d] Electrostatic precipitator, 95 to 98% control efficiency; baghouse , 99.9% control efficiency; venturi scrubber, 96 to 99% control efficiency.

[e] References 2,8-10.

[f] Electrostatic precipitator, 95 to 98% control efficiency; baghouse, 99% control efficiency; venturi scrubber, 95 to 98% control efficiency.

[g] References 5,11.

[h] Usually not controlled.

[j] Reference 13.

[k] Emission factor expressed as kg of pollutant/Mg of sand handled.

Table 12.13-2 (English Units). EMISSION FACTORS FOR STEEL FOUNDRIES

Process	Filterable Particulate[a]	EMISSION FACTOR RATING	Nitrogen Oxides	EMISSION FACTOR RATING	Filterable PM-10	EMISSION FACTOR RATING
Melting						
Electric arc[b,c] (SCC 3-04-007-01)	13 (4 to 40)	E	0.2	E	ND	NA
Open hearth[d,e] (SCC 3-04-007-02)	11 (2 to 20)	E	0.01	E	ND	NA
Open hearth oxygen lanced[f,g] (SCC 3-04-007-03)	10 (8 to 11)	E	ND	NA	ND	NA
Electric induction[h] (SCC 3-04-007-05)	0.1	E	ND	NA	0.09	E
Sand grinding/handling in mold and core making[j] (SCC 3-04-007-06)	ND	NA	NA	NA	0.54[k] 6.0	E E
Core ovens[j] (SCC 3-04-007-07)	ND	NA	ND	NA	2.22[k] 0.90	E E
Pouring and casting[j] (SCC 3-04-007-08)	ND	NA	ND	NA	2.8	E
Casting cleaning[j] (SCC 3-04-007-11)	ND	NA	NA	NA	1.7	E
Charge handling[j] (SCC 3-04-007-12)	ND	NA	NA	NA	0.36	E
Casting cooling[j] (SCC 3-04-007-13)	ND	NA	NA	NA	1.4	E

[a] Expressed as lb/ton of metal processed. If the scrap metal is very dirty or oily, or if increased oxygen lancing is employed, the emission factor should be chosen from the high side of the factor range. SCC = Source Classification Code.

[b] Electrostatic precipitator, 92 to 98% control efficiency; baghouse (fabric filter), 98 to 99% control efficiency; venturi scrubber, 94 to 98% control efficiency.

[c] References 2-7.

[d] Electrostatic precipitator, 95 to 98% control efficiency; baghouse , 99.9% control efficiency; venturi scrubber, 96 to 99% control efficiency.

[e] References 2,8-10.

[f] Electrostatic precipitator, 95 to 98% control efficiency; baghouse, 99% control efficiency; venturi scrubber, 95 to 98% control efficiency.

[g] References 5,11.

[h] Usually not controlled.

[j] Reference 13.

[k] Emission factor expressed as lb of pollutant/ton of sand handled.

VOC, and CO emissions result from core baking and VOC emissions occur during mold drying. Bag filters and scrubbers can be used to control particulates from mold and core production. Afterburners and catalytic incinerators can be used to control VOC and CO emissions.

During casting operations, large quantities of particulates can be generated in the steps prior to pouring. Emissions from pouring consist of fumes, CO, VOCs, and particulates from the mold and core materials when contacted by the molten steel. As the mold cools, emissions continue. A significant quantity of particulate emissions is generated during the casting shakeout operation. The particulate emissions from the shakeout operations can be controlled by either high-efficiency cyclone separators or bag filters. Emissions from pouring are usually uncontrolled.

Emissions from finishing operations consist of particulates resulting from the removal of burrs, risers, and gates and during shot blasting. Particulates from finishing operations can be controlled by cyclone separators.

Nonfurnace emissions sources in steel foundries are very similar to those in iron foundries. Nonfurnace emissions factors and particle size distributions for iron foundry emission sources for criteria and toxic pollutants are presented in Section 12.10, "Gray Iron Foundries".

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12.14 Secondary Zinc Processing

12.14.1 General[1]

The secondary zinc industry processes scrap metals for the recovery of zinc in the form of zinc slabs, zinc oxide, or zinc dust. There are currently 10 secondary zinc recovery plants operating in the U. S., with an aggregate capacity of approximately 60 megagrams (60 tons) per year.

12.14.2 Process Description[2-3]

Zinc recovery involves 3 general operations performed on scrap, pretreatment, melting, and refining. Processes typically used in each operation are shown in Figure 12.14-1.

12.14.2.1 Scrap Pretreatment -

Scrap metal is delivered to the secondary zinc processor as ingots, rejected castings, flashing, and other mixed metal scrap containing zinc. Scrap pretreatment includes: (1) sorting, (2) cleaning, (3) crushing and screening, (4) sweating, and (5) leaching.

In the sorting operation, zinc scrap is manually separated according to zinc content and any subsequent processing requirements. Cleaning removes foreign materials to improve product quality and recovery efficiency. Crushing facilitates the ability to separate the zinc from the contaminants. Screening and pneumatic classification concentrates the zinc metal for further processing.

A sweating furnace (rotary, reverberatory, or muffle furnace) slowly heats the scrap containing zinc and other metals to approximately 364°C (687°F). This temperature is sufficient to melt zinc but is still below the melting point of the remaining metals. Molten zinc collects at the bottom of the sweat furnace and is subsequently recovered. The remaining scrap metal is cooled and removed to be sold to other secondary processors.

Leaching with sodium carbonate solution converts dross and skimmings to zinc oxide, which can be reduced to zinc metal. The zinc-containing material is crushed and washed with water, separating contaminants from zinc-containing metal. The contaminated aqueous stream is treated with sodium carbonate to convert zinc chloride into sodium chloride (NaCl) and insoluble zinc hydroxide [$Zn(OH)_2$]. The NaCl is separated from the insoluble residues by filtration and settling. The precipitate zinc hydroxide is dried and calcined (dehydrated into a powder at high temperature) to convert it into crude zinc oxide (ZnO). The ZnO product is usually refined to zinc at primary zinc smelters. The washed zinc-containing metal portion becomes the raw material for the melting process.

12.14.2.2 Melting -

Zinc scrap is melted in kettle, crucible, reverberatory, and electric induction furnaces. Flux is used in these furnaces to trap impurities from the molten zinc. Facilitated by agitation, flux and impurities float to the surface of the melt as dross, and is skimmed from the surface. The remaining molten zinc may be poured into molds or transferred to the refining operation in a molten state.

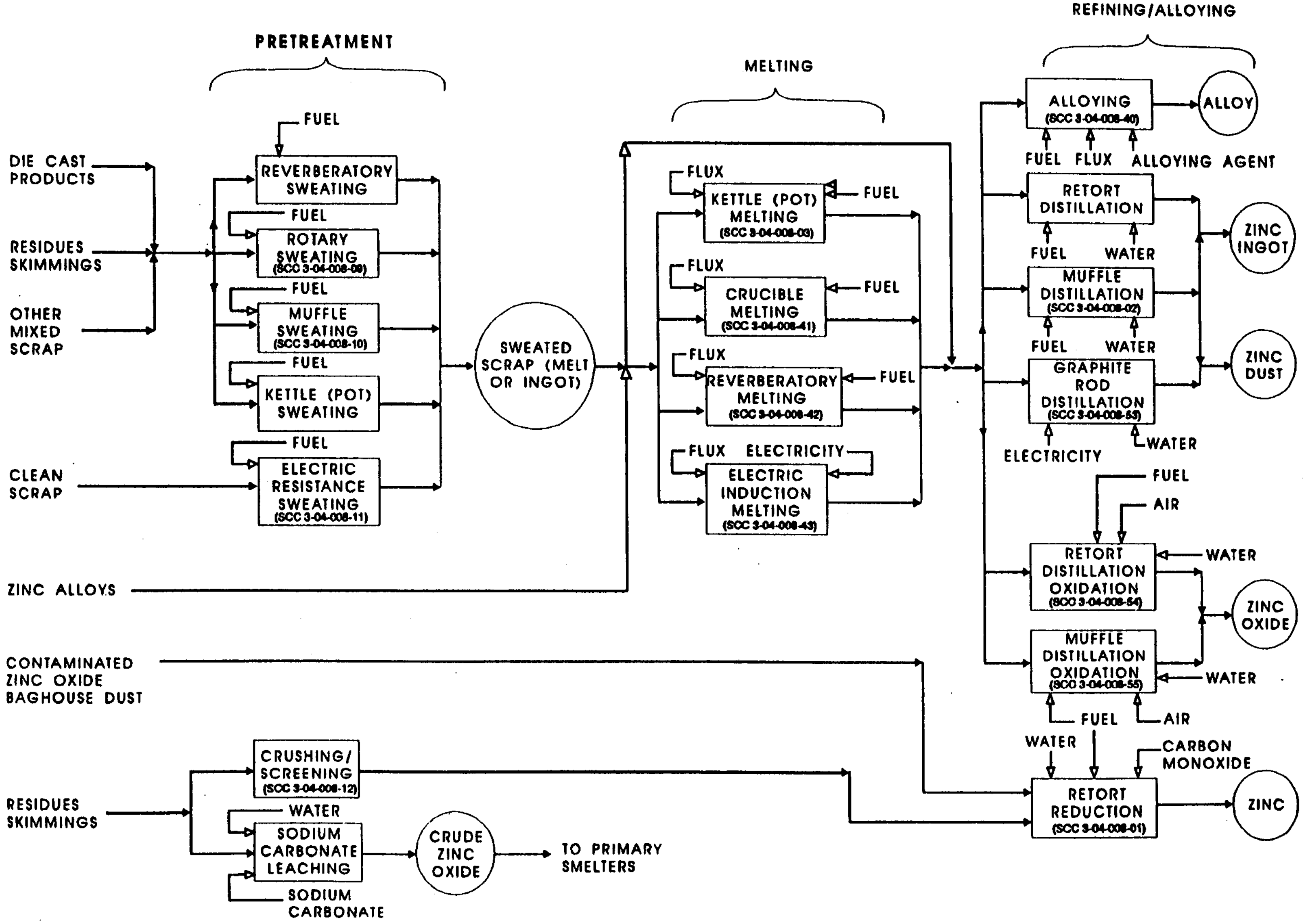

Figure 12.14-1. Process flow diagram of secondary zinc processing. (Source Classification Codes in parentheses.)

Zinc alloys are produced from pretreated scrap during sweating and melting processes. The alloys may contain small amounts of copper, aluminum, magnesium, iron, lead, cadmium, and tin. Alloys containing 0.65 to 1.25 percent copper are significantly stronger than unalloyed zinc.

12.14.2.3 Refining -

Refining processes remove further impurities in clean zinc alloy scrap and in zinc vaporized during the melt phase in retort furnaces, as shown in Figure 12.14-2. Molten zinc is heated until it vaporizes. Zinc vapor is condensed and recovered in several forms, depending upon temperature, recovery time, absence or presence of oxygen, and equipment used during zinc vapor condensation. Final products from refining processes include zinc ingots, zinc dust, zinc oxide, and zinc alloys.

Distillation retorts and furnaces are used either to reclaim zinc from alloys or to refine crude zinc. Bottle retort furnaces consist of a pear-shaped ceramic retort (a long-necked vessel used for distillation). Bottle retorts are filled with zinc alloys and heated until most of the zinc is vaporized, sometimes as long as 24 hours. Distillation involves vaporization of zinc at temperatures from 982 to 1249°C (1800 to 2280°F) and condensation as zinc dust or liquid zinc. Zinc dust is produced by vaporization and rapid cooling, and liquid zinc results when the vaporous product is condensed slowly at moderate temperatures. The melt is cast into ingots or slabs.

A muffle furnace, as shown in Figure 12.14-3, is a continuously charged retort furnace, which can operate for several days at a time. Molten zinc is charged through a feed well that also acts as an airlock. Muffle furnaces generally have a much greater vaporization capacity than bottle retort furnaces. They produce both zinc ingots and zinc oxide of 99.8 percent purity.

Pot melting, unlike bottle retort and muffle furnaces, does not incorporate distillation as a part of the refinement process. This method merely monitors the composition of the intake to control the composition of the product. Specified die-cast scraps containing zinc are melted in a steel pot. Pot melting is a simple indirect heat melting operation where the final alloy cast into zinc alloy slabs is controlled by the scrap input into the pot.

Furnace distillation with oxidation produces zinc oxide dust. These processes are similar to distillation without the condenser. Instead of entering a condenser, the zinc vapor discharges directly into an air stream leading to a refractory-lined combustion chamber. Excess air completes the oxidation and cools the zinc oxide dust before it is collected in a fabric filter.

Zinc oxide is transformed into zinc metal though a retort reduction process using coke as a reducing agent. Carbon monoxide produced by the partial oxidation of the coke reduces the zinc oxide to metal and carbon dioxide. The zinc vapor is recovered by condensation.

12.14.3 Emissions And Controls[2-5]

Process and fugitive emission factors for secondary zinc operations are tabulated in Tables 12.14-1, 12.14-2, 12.14-3, and 12.14-4. Emissions from sweating and melting operations consist of particulate, zinc fumes, other volatile metals, flux fumes, and smoke generated by the incomplete combustion of grease, rubber, and plastics in zinc scrap. Zinc fumes are negligible at low furnace temperatures. Flux emissions may be minimized by using a nonfuming flux. In production requiring special fluxes that do generate fumes, fabric filters may be used to collect emissions. Substantial emissions may arise from incomplete combustion of carbonaceous material in the zinc scrap. These contaminants are usually controlled by afterburners.

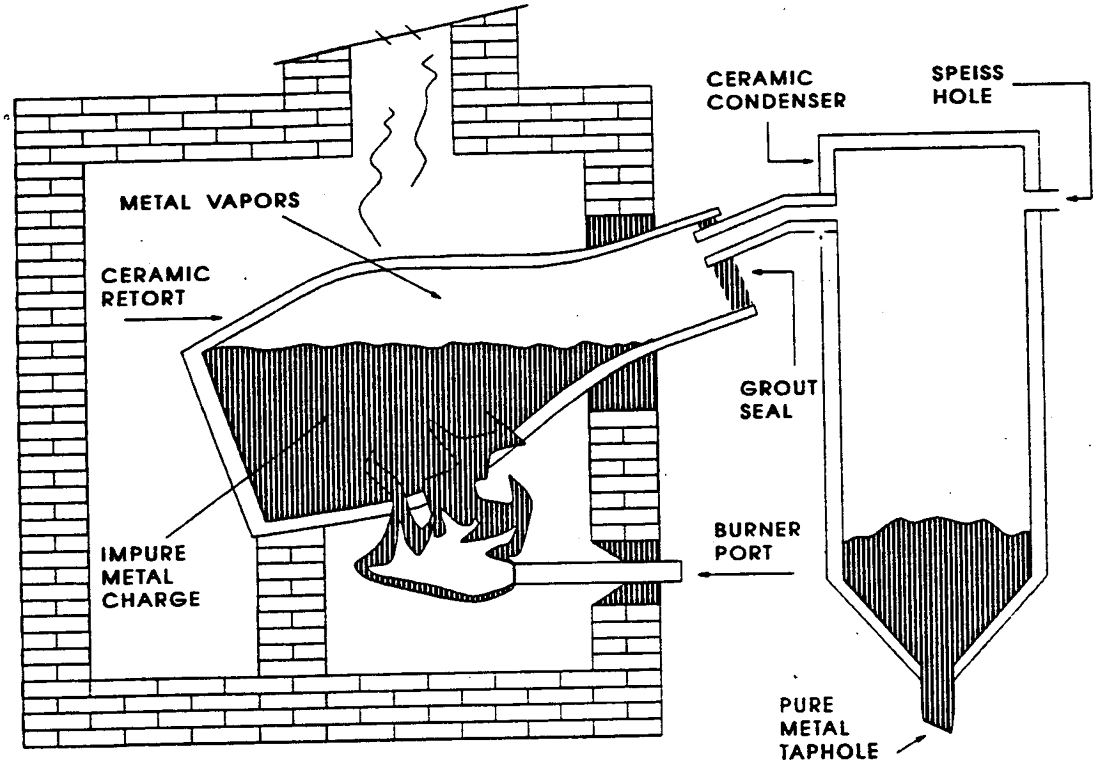

Figure 12.14-2. Zinc retort distillation furnace.

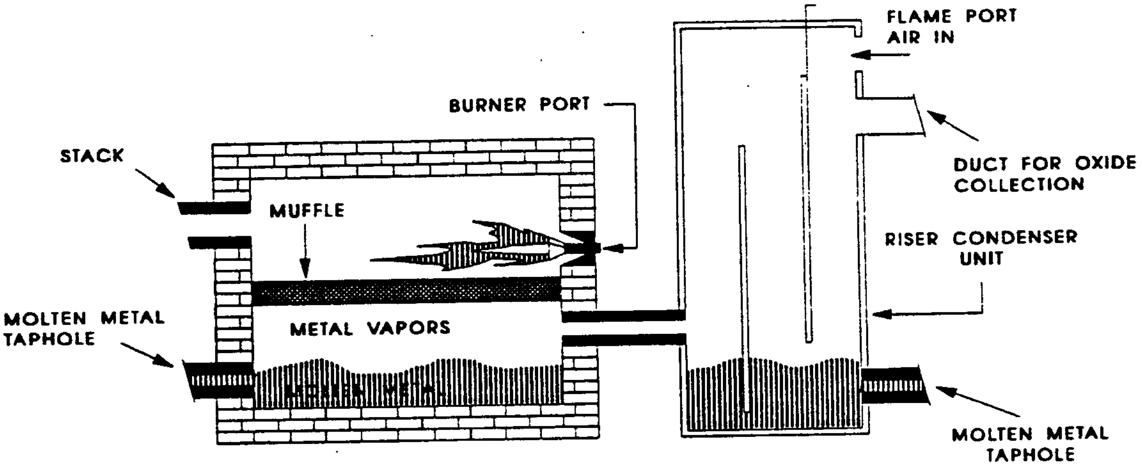

Figure 12.14-3. Muffle furnace and condenser.

Table 12.14-1 (Metric Units). UNCONTROLLED PARTICULATE EMISSION FACTORS FOR SECONDARY ZINC SMELTING[a]

Operation	Emissions	EMISSION FACTOR RATING
Reverberatory sweating[b] (in mg/Mg feed material)		
Clean metallic scrap (SCC 3-04-008-18)	Negligible	C
General metallic scrap (SCC 3-04-008-28)	6.5	C
Residual scrap (SCC 3-04-008-38)	16	C
Rotary sweating[c] (SCC 3-04-008-09)	5.5 - 12.5	C
Muffle sweating[c] (SCC 3-04-008-10)	5.4 - 16	C
Kettle sweating[b]		
Clean metallic scrap (SCC 3-04-008-14)	Negligible	C
General metallic scrap (SCC 3-04-008-24)	5.5	C
Residual scrap (SCC 3-04-008-34)	12.5	C
Electric resistance sweating[c] (SCC 3-04-008-11)	< 5	C
Sodium carbonate leaching calcining[d] (SCC 3-04-008-06)	44.5	C
Kettle pot[d], mg/Mg product (SCC 3-04-008-03)	0.05	C
Crucible melting (SCC 3-04-008-41)	ND	NA
Reverberatory melting (SCC 3-04-008-42)	ND	NA
Electric induction melting (SCC 3-04-008-43)	ND	NA
Alloying (SCC 3-04-008-40)	ND	NA
Retort and muffle distillation, in kg/Mg of product		
Pouring[c] (SCC 3-04-008-51)	0.2 - 0.4	C
Casting[c] (SCC 3-04-008-52)	0.1 - 0.2	C
Muffle distillation[d] (SCC 3-04-008-02)	22.5	C
Graphite rod distillation[c,e] (SCC 3-04-008-53)	Negligible	C
Retort distillation/oxidation[f] (SCC 3-04-008-54)	10 - 20	C
Muffle distillation/oxidation[f] (SCC 3-04-008-55)	10 - 20	C
Retort reduction (SCC 3-04-008-01)	23.5	C
Galvanizing[d] (SCC 3-04-008-05)	2.5	C

[a] Factors are for kg/Mg of zinc used, except as noted. SCC = Source Classification Code. ND = no data. NA = not applicable.
[b] Reference 4.
[c] Reference 5.
[d] References 6-8.
[e] Reference 2.
[f] Reference 5. Factors are for kg/Mg of ZnO produced. All product zinc oxide dust is carried over in the exhaust gas from the furnace and is recovered with 98 - 99% efficiency.

Table 12.14-2 (English Units). UNCONTROLLED PARTICULATE EMISSION FACTORS FOR SECONDARY ZINC SMELTING[a]

Operation	Emissions	EMISSION FACTOR RATING
Reverberatory sweating[b] (in mg/Mg feed material)		
Clean metallic scrap (SCC 3-04-008-18)	Negligible	C
General metallic scrap (SCC 3-04-008-28)	13	C
Residual scrap (SCC 3-04-008-38)	32	C
Rotary sweating[c] (SCC 3-04-008-09)	11 - 25	C
Muffle sweating[c] (SCC 3-04-008-10)	10.8 - 32	C
Kettle sweating[b]		
Clean metallic scrap (SCC 3-04-008-14)	Negligible	C
General metallic scrap (SCC 3-04-008-24)	11	C
Residual scrap (SCC 3-04-008-34)	25	C
Electric resistance sweating[c] (SCC 3-04-008-11)	<10	C
Sodium carbonate leaching calcining[d] (SCC 3-04-008-06)	89	C
Kettle pot[d], mg/Mg product (SCC 3-04-008-03)	0.1	C
Crucible melting (SCC 3-04-008-41)	ND	NA
Reverberatory melting (SCC 3-04-008-42)	ND	NA
Electric induction melting (SCC 3-04-008-43)	ND	NA
Alloying (SCC 3-04-008-40)	ND	NA
Retort and muffle distillation, in lb/ton of product		
Pouring[c] (SCC 3-04-008-51)	0.4 - 0.8	C
Casting[c] (SCC 3-04-008-52)	0.2 - 0.4	C
Muffle distillation[d] (SCC 3-04-008-02)	45	C
Graphite rod distillation[c,e] (SCC 3-04-008-53)	Negligible	C
Retort distillation/oxidation[f] (SCC 3-04-008-54)	20 - 40	C
Muffle distillation/oxidation[f] (SCC 3-04-008-55)	20 - 40	C
Retort reduction (SCC 3-04-008-01)	47	C
Galvanizing[d] (SCC 3-04-008-05)	5	C

[a] Factors are for lb/ton of zinc used, except as noted. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 4.

[c] Reference 5.

[d] References 6-8.

[e] Reference 2.

[f] Reference 5. Factors are for lb/ton of ZnO produced. All product zinc oxide dust is carried over in the exhaust gas from the furnace and is recovered with 98 - 99% efficiency.

Table 12.14-3 (Metric Units). FUGITIVE PARTICULATE EMISSION FACTORS FOR SECONDARY ZINC SMELTING[a]

Operation	Emissions	EMISSION FACTOR RATING
Reverberatory sweating[b] (SCC 3-04-008-61)	0.63	E
Rotary sweating[b] (SCC 3-04-008-62)	0.45	E
Muffle sweating[b] (SCC 3-04-008-63)	0.54	E
Kettle (pot) sweating[b] (SCC 3-04-008-64)	0.28	E
Electrical resistance sweating, per kg processed[b] (SCC 3-04-008-65)	0.25	E
Crushing/screening[c] (SCC 3-04-008-12)	2.13	E
Sodium carbonate leaching (SCC 3-04-008-66)	ND	NA
Kettle (pot) melting furnace[b] (SCC 3-04-008-67)	0.0025	E
Crucible melting furnace[d] (SCC 3-04-008-68)	0.0025	E
Reverberatory melting furnace[b] (SCC 3-04-008-69)	0.0025	E
Electric induction melting[b] (SCC 3-04-008-70)	0.0025	E
Alloying retort distillation (SCC 3-04-008-71)	ND	NA
Retort and muffle distillation (SCC 3-04-008-72)	1.18	E
Casting[b] (SCC 3-04-008-73)	0.0075	E
Graphite rod distillation (SCC 3-04-008-74)	ND	NA
Retort distillation/oxidation (SCC 3-04-008-75)	ND	NA
Muffle distillation/oxidation (SCC 3-04-008-76)	ND	NA
Retort reduction (SCC 3-04-008-77)	ND	NA

[a] Reference 9. Factors are kg/Mg of end product, except as noted. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Estimate based on stack emission factor given in Reference 2, assuming fugitive emissions to be equal to 5% of stack emissions.

[c] Reference 2. Factors are for kg/Mg of scrap processed. Average of reported emission factors.

[d] Engineering judgment, assuming fugitive emissions from crucible melting furnace to be equal to fugitive emissions from kettle (pot) melting furnace.

Particulate emissions from sweating and melting are most commonly recovered by fabric filter. In 1 application on a muffle sweating furnace, a cyclone and fabric filter achieved particulate recovery efficiencies in excess of 99.7 percent. In 1 application on a reverberatory sweating furnace, a fabric filter removed 96.3 percent of the particulate. Fabric filters show similar efficiencies in removing particulate from exhaust gases of melting furnaces.

Table 12.14-4 (English Units). FUGITIVE PARTICULATE EMISSION FACTORS FOR SECONDARY ZINC SMELTING[a]

Operation	Emissions	EMISSION FACTOR RATING
Reverberatory sweating[b] (SCC 3-04-008-61)	1.30	E
Rotary sweating[b] (SCC 3-04-008-62)	0.90	E
Muffle sweating[b] (SCC 3-04-008-63)	1.07	E
Kettle (pot) sweating[b] (SCC 3-04-008-64)	0.56	E
Electrical resistance sweating, per ton processed[b] (SCC 3-04-008-65)	0.50	E
Crushing/screening[c] (SCC 3-04-008-12)	4.25	E
Sodium carbonate leaching (SCC 3-04-008-66)	ND	NA
Kettle (pot) melting furnace[b] (SCC 3-04-008-67)	0.005	E
Crucible melting furnace[d] (SCC 3-04-008-68)	0.005	E
Reverberatory melting furnace[b] (SCC 3-04-008-69)	0.005	E
Electric induction melting[b] (SCC 3-04-008-70)	0.005	E
Alloying retort distillation (SCC 3-04-008-71)	ND	NA
Retort and muffle distillation (SCC 3-04-008-72)	2.36	E
Casting[b] (SCC 3-04-008-73)	0.015	E
Graphite rod distillation (SCC 3-04-008-74)	ND	NA
Retort distillation/oxidation (SCC 3-04-008-75)	ND	NA
Muffle distillation/oxidation (SCC 3-04-008-76)	ND	NA
Retort reduction (SCC 3-04-008-77)	ND	NA

[a] Reference 9. Factors are lb/ton of end product, except as noted. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Estimate based on stack emission factor given in Reference 2, assuming fugitive emissions to be equal to 5% of stack emissions.

[c] Reference 2. Factors are for lb/ton of scrap processed. Average of reported emission factors.

[d] Engineering judgment, assuming fugitive emissions from crucible melting furnace to be equal to fugitive emissions from kettle (pot) melting furnace.

Crushing and screening operations are also sources of dust emissions. These emissions are composed of zinc, aluminum, copper, iron, lead, cadmium, tin, and chromium. They can be recovered by hooded exhausts used as capture devices and can be controlled with fabric filters.

The sodium carbonate leaching process emits zinc oxide dust during the calcining operation (oxidizing precipitate into powder at high temperature). This dust can be recovered in fabric filters, although zinc chloride in the dust may cause plugging problems.

Emissions from refining operations are mainly metallic fumes. Distillation/oxidation operations emit their entire zinc oxide product in the exhaust gas. Zinc oxide is usually recovered in fabric filters with collection efficiencies of 98 to 99 percent.

References For Section 12.14

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12.15 Storage Battery Production

12.15.1 General[1-2]

The battery industry is divided into 2 main sectors: starting, lighting, and ignition (SLI) batteries and industrial/traction batteries. SLI batteries are primarily used in automobiles. Industrial batteries include those used for uninterruptible power supply and traction batteries are used to power electric vehicles such as forklifts. Lead consumption in the U. S. in 1989 was 1.28 million megagrams (1.41 million tons); between 75 and 80 percent of this is attributable to the manufacture of lead acid storage batteries.

Lead acid storage battery plants range in production capacity from less than 500 batteries per day to greater than 35,000 batteries per day. Lead acid storage batteries are produced in many sizes, but the majority are produced for use in automobiles and fall into a standard size range. A standard automobile battery contains an average of about 9.1 kilograms (20 lb) of lead, of which about half is present in the lead grids and connectors and half in the lead oxide paste.

12.15.2 Process Description[3,12]

Lead acid storage batteries are produced from lead alloy ingots and lead oxide. The lead oxide may be prepared by the battery manufacturer, as is the case for many larger battery manufacturing facilities, or may be purchased from a supplier. (See Section 12.16, "Lead Oxide And Pigment Production".)

Battery grids are manufactured by either casting or stamping operations. In the casting operation, lead alloy ingots are charged to a melting pot, from which the molten lead flows into molds that form the battery grids. The stamping operation involves cutting or stamping the battery grids from lead sheets. The grids are often cast or stamped in doublets and split apart (slitting) after they have been either flash dried or cured. The pastes used to fill the battery grids are made in batch-type processes. A mixture of lead oxide powder, water, and sulfuric acid produces a positive paste, and the same ingredients in slightly different proportions with the addition of an expander (generally a mixture of barium sulfate, carbon black, and organics), make the negative paste. Pasting machines then force these pastes into the interstices of the grids, which are made into plates. At the completion of this process, a chemical reaction starts in the paste and the mass gradually hardens, liberating heat. As the setting process continues, needle-shaped crystals of lead sulfate ($PbSO_4$) form throughout the mass. To provide optimum conditions for the setting process, the plates are kept at a relative humidity near 90 percent and a temperature near 32°C (90°F) for about 48 hours and are then allowed to dry under ambient conditions.

After the plates are cured they are sent to the 3-process operation of plate stacking, plate burning, and element assembly in the battery case (see Figure 12.15-1). In this process the doublet plates are first cut apart and depending upon whether they are dry-charged or to be wet-formed, are stacked in an alternating positive and negative block formation, with insulators between them. These insulators are made of materials such as non-conductive plastic, or glass fiber. Leads are then welded to tabs on each positive or negative plate or in an element during the burning operation. An alternative to this operation, and more predominantly used than the manual burning operation, is the cast-on connection, and positive and negative tabs are then independently welded to produce an element. The elements are automatically placed into a battery case. A top is placed on the

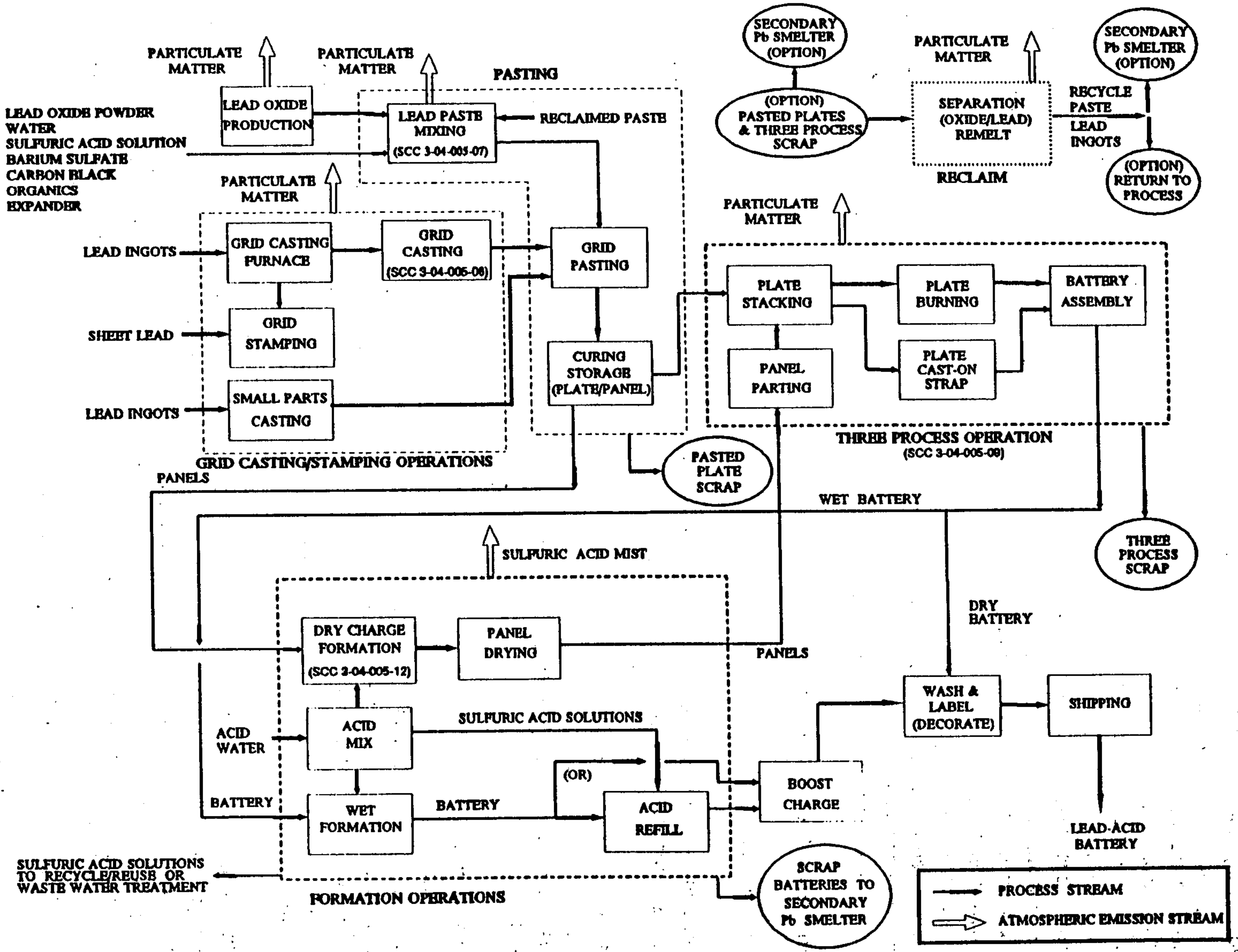

Figure 12.15-1. Process flow diagram for storage battery production. (Source Classification Codes in parentheses.)

batterycase. The posts on the case top then are welded to 2 individual points that connect the positive and negative plates to the positive and negative posts, respectively.

During dry-charge formation, the battery plates are immersed in a dilute sulfuric acid solution; the positive plates are connected to the positive pole of a direct current (DC) source and the negative plates connected to the negative pole of the DC source. In the wet formation process, this is done with the plates in the battery case. After forming, the acid may be dumped and fresh acid is added, and a boost charge is applied to complete the battery. In dry formation, the individual plates may be assembled into elements first and then formed in tanks or formed as individual plates. In this case of formed elements, the elements are then placed in the battery cases, the positive and negative parts of the elements are connected to the positive and negative terminals of the battery, and the batteries are shipped dry. Defective parts are either reclaimed at the battery plant or are sent to a secondary lead smelter (See Section 12.11, "Secondary Lead Processing"). Lead reclamation facilities at battery plants are generally small pot furnaces for non-oxidized lead. Approximately 1 to 4 percent of the lead processed at a typical lead acid battery plant is recycled through the reclamation operation as paste or metal. In recent years, however, the general trend in the lead-acid battery manufacturing industry has been to send metals to secondary lead smelters for reclamation.

12.15.3 Emissions And Controls[3-9,13-16]

Lead oxide emissions result from the discharge of air used in the lead oxide production process. A cyclone, classifier, and fabric filter is generally used as part of the process/control equipment to capture particulate emissions from lead oxide facilities. Typical air-to-cloth ratios of fabric filters used for these facilities are in the range of 3:1.

Lead and other particulate matter are generated in several operations, including grid casting, lead reclamation, slitting, and small parts casting, and during the 3-process operation. This particulate is usually collected by ventilation systems and ducted through fabric filtration systems (baghouses) also.

The paste mixing operation consists of 2 steps. The first, in which dry ingredients are charged to the mixer, can result in significant emissions of lead oxide from the mixer. These emissions are usually collected and ducted through a baghouse. During the second step, when moisture is present in the exhaust stream from acid addition, emissions from the paste mixer are generally collected and ducted to either an impingement scrubber or fabric filter. Emissions from grid casting machines and lead reclamation facilities are sometimes processed by impingement scrubbers as well.

Sulfuric acid mist emissions are generated during the formation step. Acid mist emissions are significantly higher for dry formation processes than for wet formation processes because wet formation is conducted in battery cases, while dry formation is conducted in open tanks. Although wet formation process usually do not require control, emissions of sulfuric acid mist from dry formation processes can be reduced by more than 95 percent with mist eliminators. Surface foaming agents are also commonly used in dry formation baths to strap process, in which molten lead is poured around the plate tabs to form the control acid mist emissions.

Emission reductions of 99 percent and above can be obtained when fabric filtration is used to control slitting, paste mixing, and the 3-process operation. Applications of scrubbers to paste mixing, grid casting, and lead reclamation facilities can result in emission reductions of 85 percent or better.

Tables 12.15-1 and 12.15-2 present uncontrolled emission factors for grid casting, paste mixing, lead reclamation, dry formation, and the 3-process operation as well as a range of controlled emission factors for lead oxide production. The emission factors presented in the tables include lead and its compounds, expressed as elemental lead.

Table 12.15-1 (Metric Units). UNCONTROLLED EMISSION FACTORS FOR STORAGE BATTERY PRODUCTION[a]

Process	Particulate ($kg/10^3$ batteries)	Lead ($kg/10^3$ batteries)	EMISSION FACTOR RATING
Grid casting (SCC 3-04-005-06)	0.8 - 1.42	0.35 - 0.40	B
Paste mixing (SCC 3-04-005-07)	1.00 - 1.96	0.50 - 1.13	B
Lead oxide mill (baghouse outlet)[b] (SCC 3-04-005-08)	0.05 - 0.10	0.05	C
3-Process operation (SCC 3-04-005-09)	13.2 - 42.00	4.79 - 6.60	B
Lead reclaim furnace[c] (SCC 3-04-005-10)	0.70 - 3.03	0.35 - 0.63	B
Dry formation[d] (SCC 3-04-005-12)	14.0 - 14.70	ND	B
Small parts casting (SCC 3-04-005-11)	0.09	0.05	C
Total production (SCC 3-04-005-05)	56.82 - 63.20	6.94 - 8.00	NA

[a] References 3-10,13-16. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 7. Emissions measured for a "state-of-the-art" facility (fabric filters with an average air-to-cloth ratio of 3:1) were 0.025 kg particulate/1000 batteries and 0.024 kg lead/1000 batteries. Factors represent emissions from a facility with typical controls (fabric filtration with an air-to-cloth ratio of about 4:1). Emissions from a facility with typical controls are estimated to be about 2-10 times higher than those from a "state-of-the-art" facility (Reference 3).

[c] Range due to variability of the scrap quality.

[d] For sulfates in aerosol form, expressed as sulfuric acid or particulate, and not accounting for water and other substances which might be present.

Table 12.15-2 (English Units). UNCONTROLLED EMISSION FACTORS FOR STORAGE BATTERY PRODUCTION[a]

Process	Particulate (lb/10^3 batteries)	Lead (lb/10^3 batteries)	EMISSION FACTOR RATING
Grid casting (SCC 3-04-005-06)	1.8 - 3.13	0.77 - 0.90	B
Paste mixing (SCC 3-04-005-07)	2.20 - 4.32	1.10 - 2.49	B
Lead oxide mill (baghouse outlet)[b] (SCC 3-04-005-08)	0.11 - 0.24	0.11 - 0.12	C
3-Process operation (SCC 3-04-005-09)	29.2 - 92.60	10.60 - 14.60	B
Lead reclaim furnace[c] (SCC 3-04-005-10)	1.54 - 6.68	0.77 - 1.38	B
Dry formation[d] (SCC 3-04-005-12)	32.1 - 32.40	ND	B
Small parts casting (SCC 3-04-005-11)	0.19	0.10	C
Total production (SCC 3-04-005-05)	125.00 - 139.00	15.30 - 17.70	NA

[a] References 3-10, 13-16. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Reference 7. Emissions measured for a "state-of-the-art" facility (fabric filters with an average air-to-cloth ratio of 3:1) were 0.055 lb particulate/1000 batteries and 0.053 lb lead/1000 batteries. Factors represent emissions from a facility with typical controls (fabric filtration with an air-to-cloth ratio of about 4:1). Emissions from a facility with typical controls are estimated to be about 2-10 times higher than those from a "state-of-the-art" facility (Reference 3).

[c] Range due to variability of the scrap quality.

[d] For sulfates in aerosol form, expressed as sulfuric acid, and not accounting for water and other substances which might be present.

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12.16 Lead Oxide And Pigment Production

12.16.1 General[1-2,7]

Lead oxide is a general term and can be either lead monoxide or "litharge" (PbO); lead tetroxide or "red lead" (Pb_3O_4); or black or "gray" oxide which is a mixture of 70 percent lead monoxide and 30 percent metallic lead. Black lead is made for specific use in the manufacture of lead acid storage batteries. Because of the size of the lead acid battery industry, lead monoxide is the most important commercial compound of lead, based on volume. Total oxide production in 1989 was 57,984 megagrams (64,000 tons).

Litharge is used primarily in the manufacture of various ceramic products. Because of its electrical and electronic properties, litharge is also used in capacitors, Vidicon® tubes, and electrophotographic plates, as well as in ferromagnetic and ferroelectric materials. It is also used as an activator in rubber, a curing agent in elastomers, a sulfur removal agent in the production of thioles and in oil refining, and an oxidation catalyst in several organic chemical processes. It also has important markets in the production of many lead chemicals, dry colors, soaps (i. e., lead stearate), and driers for paint. Another important use of litharge is the production of lead salts, particularly those used as stabilizers for plastics, notably polyvinyl chloride materials.

The major lead pigment is red lead (Pb_3O_4), which is used principally in ferrous metal protective paints. Other lead pigments include white lead and lead chromates. There are several commercial varieties of white lead including leaded zinc oxide, basic carbonate white lead, basic sulfate white lead, and basic lead silicates. Of these, the most important is leaded zinc oxide, which is used almost entirely as white pigment for exterior oil-based paints.

12.16.2 Process Description[8]

Black oxide is usually produced by a Barton Pot process. Basic carbonate white lead production is based on the reaction of litharge with acetic acid or acetate ions. This product, when reacted with carbon dioxide, will form lead carbonate. White leads (other than carbonates) are made either by chemical, fuming, or mechanical blending processes. Red lead is produced by oxidizing litharge in a reverberatory furnace. Chromate pigments are generally manufactured by precipitation or calcination as in the following equation:

$$Pb(NO_3)_2 + Na_2(CrO_4) \rightarrow PbCrO_4 + 2\ NaNO_3 \qquad (1)$$

Commercial lead oxides can all be prepared by wet chemical methods. With the exception of lead dioxide, lead oxides are produced by thermal processes in which lead is directly oxidized with air. The processes may be classified according to the temperature of the reaction: (1) low temperature, below the melting point of lead; (2) moderate temperature, between the melting points of lead and lead monoxide; and (3) high temperature, above the melting point of lead monoxide.

12.16.2.1 Low Temperature Oxidation -

Low temperature oxidation of lead is accomplished by tumbling slugs of metallic lead in a ball mill equipped with an air flow. The air flow provides oxygen and is used as a coolant. If some form of cooling were not supplied, the heat generated by the oxidation of the lead plus the mechanical heat of the tumbling charge would raise the charge temperature above the melting point of lead. The ball mill product is a "leady" oxide with 20 to 50 percent free lead.

12.16.2.2 Moderate Temperature Oxidation -

Three processes are used commercially in the moderate temperature range: (1) refractory furnace, (2) rotary tube furnace, and (3) the Barton Pot process. In the refractory furnace process, a cast steel pan is equipped with a rotating vertical shaft and a horizontal crossarm mounted with plows. The plows move the charge continuously to expose fresh surfaces for oxidation. The charge is heated by a gas flame on its surface. Oxidation of the charge supplies much of the reactive heat as the reaction progresses. A variety of products can be manufactured from pig lead feed by varying the feed temperature, and time of furnacing. Yellow litharge (orthorhombic) can be made by cooking for several hours at 600 to 700°C (1112 to 1292°F) but may contain traces of red lead and/or free metallic lead.

In the rotary tube furnace process, molten lead is introduced into the upper end of a refractory-lined inclined rotating tube. An oxidizing flame in the lower end maintains the desired temperature of reaction. The tube is long enough so that the charge is completely oxidized when it emerges from the lower end. This type of furnace has been used commonly to produce lead monoxide (tetragonal type), but it is not unusual for the final product to contain traces of both free metallic and red lead.

The Barton Pot process (Figure 12.16-1) uses a cast iron pot with an upper and lower stirrer rotating at different speeds. Molten lead is fed through a port in the cover into the pot, where it is broken up into droplets by high-speed blades. Heat is supplied initially to develop an operating temperature from 370 to 480°C (698 to 896°F). The exothermic heat from the resulting oxidation of the droplets is usually sufficient to maintain the desired temperature. The oxidized product is swept out of the pot by an air stream.

The operation is controlled by adjusting the rate of molten lead feed, the speed of the stirrers, the temperature of the system, and the rate of air flow through the pot. The Barton Pot produces either litharge or leady litharge (litharge with 50 percent free lead). Since it operates at a higher temperature than a ball mill unit, the oxide portion will usually contain some orthorhombic litharge. It may also be operated to obtain almost entirely orthorhombic product.

12.16.2.3 High Temperature Oxidation -

High temperature oxidation is a fume-type process. A very fine particle, high-purity orthorhombic litharge is made by burning a fine stream of molten lead in a special blast-type burner. The flame temperature is around 1200°C (2192°F). The fume is swept out of the chamber by an air stream, cooled in a series of "goosenecks" and collected in a baghouse. The median particle diameter is from 0.50 to 1.0 micrometers, as compared with 3.0 to 16.0 micrometers for lead monoxide manufactured by other methods.

12.16.3 Emissions And Controls[3-4,6]

Emission factors for lead oxide and pigment production processes are given in Tables 12.16-1 and 12.16-2. The emission factors were assigned an E rating because of high variabilities in test run results and nonisokinetic sampling. Also, since storage battery production facilities produce lead oxide using the Barton Pot process, a comparison of the lead emission factors from both industries has been performed. The lead oxide emission factors from the battery plants were found to be considerably lower than the emission factors from the lead oxide and pigment industry. Since lead battery production plants are covered under federal regulations, one would expect lower emissions from these sources.

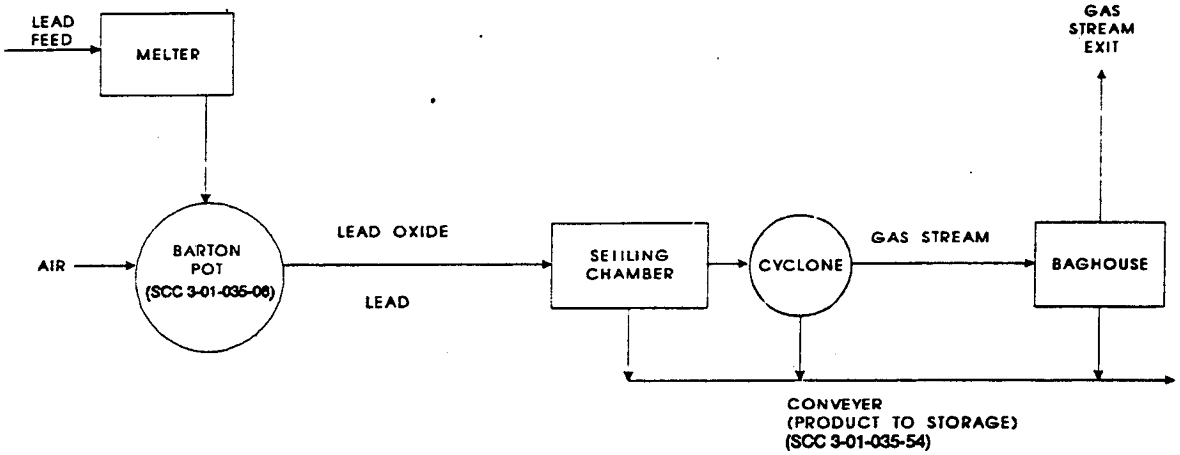

Figure 12.16-1. Lead oxide Barton Pot process.
(Source Classification Codes in parentheses.)

Automatic shaker-type fabric filters, often preceded by cyclone mechanical collectors or settling chambers, are the common choice for collecting lead oxides and pigments. Control efficiencies of 99 percent are achieved with these control device combinations. Where fabric filters are not appropriate, scrubbers may be used to achieve control efficiencies from 70 to 95 percent. The ball mill and Barton Pot processes of black oxide manufacturing recover the lead product by these 2 means. Collection of dust and fumes from the production of red lead is likewise an economic necessity, since particulate emissions, although small, are about 90 percent lead. Emissions data from the production of white lead pigments are not available, but they have been estimated because of health and safety regulations. The emissions from dryer exhaust scrubbers account for over 50 percent of the total lead emitted in lead chromate production.

Table 12.16-1 (Metric Units). CONTROLLED EMISSIONS FROM LEAD OXIDE AND PIGMENT PRODUCTION[a]

Process	Particulate		Lead		References
	Emissions	EMISSION FACTOR RATING	Emissions	EMISSION FACTOR RATING	
Lead Oxide Production					
Barton Pot[b] (SCC 3-01-035-06)	0.21 - 0.43	E	0.22	E	4,6
Calcining (SCC 3-01-035-07)					
Baghouse Inlet	7.13	E	7.00	E	6
Baghouse Outlet	0.032	E	0.024	E	6
Pigment Production					
Red lead[b] (SCC 3-01-035-10)	0.5[c]	B	0.50	B	4,5
White lead[b] (SCC 3-01-035-15)	ND	NA	0.28	B	4,5
Chrome pigments (SCC 3-01-035-20)	ND	NA	0.065	B	4,5

[a] Factors are for kg/Mg of product. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Measured at baghouse outlet. Baghouse is considered process equipment.

[c] Only PbO and oxygen are used in red lead production, so particulate emissions are assumed to be about 90% lead.

Table 12.16-2 (English Units). CONTROLLED EMISSIONS FROM LEAD OXIDE AND PIGMENT PRODUCTION[a]

Process	Particulate		Lead		References
	Emissions	EMISSION FACTOR RATING	Emissions	EMISSION FACTOR RATING	
Lead Oxide Production					
Barton Pot[b] (SCC 3-01-035-06)	0.43 - 0.85	E	0.44	E	4,6
Calcining (SCC 3-01-035-07)					
Baghouse Inlet	14.27	E	14.00	E	6
Baghouse Outlet	0.064	E	0.05	E	6
Pigment Production					
Red lead[b] (SCC 3-01-035-10)	1.0[c]	B	0.90	B	4,5
White lead[b] (SCC 3-01-035-15)	ND	NA	0.55	B	4,5
Chrome pigments (SCC 3-01-035-20)	ND	NA	0.13	B	4,5

[a] Factors are for lb/ton of product. SCC = Source Classification Code. ND = no data. NA = not applicable.

[b] Measured at baghouse outlet. Baghouse is considered process equipment.

[c] Only PbO and oxygen are used in red lead production, so particulate emissions are assumed to be about 90% lead.

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12.17 Miscellaneous Lead Products

12.17.1 General[1]

In 1989 the following categories (in decreasing order of lead usage) were significant in the miscellaneous lead products group: ammunition, cable covering, solder, and type metal. However, in 1992, U. S. can manufacturers no longer use lead solder. Therefore, solder will not be included as a miscellaneous lead product in this section. Lead used in ammunition (bullets and shot) and for shot used at nuclear facilities in 1989 was 62,940 megagrams (Mg) (69,470 tons). The use of lead sheet in construction and lead cable sheathing in communications also increased to a combined total of 43,592 Mg (48,115 tons).

12.17.2 Process Description

12.17.2.1 Ammunition And Metallic Lead Products[8] -

Lead is consumed in the manufacture of ammunition, bearing metals, and other lead products, with subsequent lead emissions. Lead used in the manufacture of ammunition is melted and alloyed before it is cast, sheared, extruded, swaged, or mechanically worked. Some lead is also reacted to form lead azide, a detonating agent. Lead is used in bearing manufacture by alloying it with copper, bronze, antimony, and tin, although lead usage in this category is relatively small.

Other lead products include terne metal (a plating alloy), weights and ballasts, caulking lead, plumbing supplies, roofing materials, casting metal foil, collapsible metal tubes, and sheet lead. Lead is also used for galvanizing, annealing, and plating. In all of these cases lead is usually melted and cast prior to mechanical forming operations.

12.17.2.2 Cable Covering[8,11] -

About 90 percent of the lead cable covering produced in the United States is lead-cured jacketed cables, the remaining 10 percent being lead sheathed cables. The manufacture of cured jacketed cables involves a stripping/remelt operation as an unalloyed lead cover that is applied in the vulcanizing treatment during the manufacture of rubber-insulated cable must be stripped from the cable and remelted.

Lead coverings are applied to insulated cable by hydraulic extrusion of solid lead around the cable. Extrusion rates of typical presses average 1360 to 6800 Mg/hr (3,000 to 15,000 lb/hr). The molten lead is continuously fed into the extruder or screw press, where it solidifies as it progresses. A melting kettle supplies lead to the press.

12.17.2.3 Type Metal Production[8] -

Lead type, used primarily in the letterpress segment of the printing industry, is cast from a molten lead alloy and remelted after use. Linotype and monotype processes produce a mold, while the stereotype process produces a plate for printing. All type is an alloy consisting of 60 to 85 percent recovered lead, with antimony, tin, and a small amount of virgin metal.

12.17.3 Emissions And Controls

Tables 12.17-1 and 12.17-2 present emission factors for miscellaneous lead products.

Table 12.17-1 (Metric Units). EMISSION FACTORS FOR MISCELLANEOUS SOURCES[a]

Process	Particulate	EMISSION FACTOR RATING	Lead	EMISSION FACTOR RATING	Reference
Type Metal Production (SCC 3-60-001-01)	0.4[b]	C	0.13	C	2,7
Cable Covering (SCC 3-04-040-01)	0.3[c]	C	0.25	C	3,5,7
Metallic Lead Products:					
Ammunition (SCC 3-04-051-01)	ND	NA	≤ 0.5	C	3,7
Bearing Metals (SCC 3-04-051-02)	ND	NA	Negligible	NA	3,7
Other Sources of Lead (SCC 3-04-051-03)	ND	NA	0.8	C	3,7

[a] Factors are expressed as kg/Mg lead (Pb) processed. ND = no data. NA = not applicable.
[b] Calculated on the basis of 35% of the total (Reference 2). SCC = Source Classification Code.
[c] Reference 8, p. 4-301.

Table 12.17-2 (English Units). EMISSION FACTORS FOR MISCELLANEOUS SOURCES[a]

Process	Particulate	EMISSION FACTOR RATING	Lead	EMISSION FACTOR RATING	Reference
Type Metal Production	0.7 [b]	C	0.25	C	2,7
Cable Covering (SCC 3-04-040-01)	0.6 [c]	C	0.5	C	3,5,7
Metallic Lead Products:					
Ammunition (SCC 3-04-051-01)	ND	NA	1.0	C	3,7
Bearing Metals (SCC 3-04-051-02)	ND	NA	Negligible	NA	3,7
Other Sources of Lead (SCC 3-04-051-03)	ND	NA	1.5	C	3,7

[a] Factors are expressed as lb/ton lead (Pb) processed. ND = no data. NA = not applicable.
[b] Calculated on the basis of 35% of the total (Reference 2). SCC = Source Classification Code.
[c] Reference 8, p. 4-301.

12.17.3.1 Ammunition And Metallic Lead Products[8] -

Little or no air pollution control equipment is currently used by manufacturers of metallic lead products. Emissions from bearing manufacture are negligible, even without controls.

12.17.3.2 Cable Covering[8,11] -

The melting kettle is the only source of atmospheric lead emissions and is generally uncontrolled. Average particle size is approximately 5 micrometers, with a lead content of about 70 to 80 percent.

Cable covering processes do not usually include particulate collection devices. However, fabric filters, rotoclone wet collectors, and dry cyclone collectors can reduce lead emissions at control efficiencies of 99.9 percent, 75 to 85 percent, and greater than 45 percent, respectively. Lowering and controlling the melt temperature, enclosing the melting unit and using fluxes to provide a cover on the melt can also minimize emissions.

12.17.3.3 Type Metal Production[2,3] -

The melting pot is again the major source of emissions, containing hydrocarbons as well as lead particulates. Pouring the molten metal into the molds involves surface oxidation of the metal, possibly producing oxidized fumes, while the trimming and finishing operations emit lead particles. It is estimated that 35 percent of the total emitted particulate is lead.

Approximately half of the current lead type operations control lead emissions, by approximately 80 percent. The other operations are uncontrolled. The most frequently controlled sources are the main melting pots and drossing areas. Linotype equipment does not require controls when operated properly. Devices in current use on monotype and stereotype lines include rotoclones, wet scrubbers, fabric filters, and electrostatic precipitators, all of which can be used in various combinations.

Additionally, the VOC/PM Speciation Data Base has identified phosphorus, chlorine, chromium, manganese, cobalt, nickel, arsenic, selenium, cadmium, antimony, mercury, and lead as occurring in emissions from type metal production and lead cable coating operations. All of these metals/chemicals are listed in CAA Title III as being hazardous air pollutants (HAPs) and should be the subject of air emissions testing by industry sources.

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12.18 Leadbearing Ore Crushing And Grinding

12.18.1 General[1]

Leadbearing ore is mined from underground or open pit mines. After extraction, the ore is processed by crushing, screening, and milling. Domestic lead mine production for 1991 totaled 480,000 megagrams (Mg) (530,000 tons) of lead in ore concentrates, a decrease of some 15,000 Mg (16,500 tons) from 1990 production.

Except for mines in Missouri, lead ore is closely interrelated with zinc and silver. Lead ores from Missouri mines are primarily associated with zinc and copper. Average grades of metal from Missouri mines have been reported as high as 12.2 percent lead, 1 percent zinc, and 0.6 percent copper. Due to ore body formations, lead and zinc ores are normally deep-mined (underground), whereas copper ores are mined in open pits. Lead, zinc, copper, and silver are usually found together (in varying percentages) in combination with sulfur and/or oxygen.

12.18.2 Process Description[2,5-7]

In underground mines the ore is disintegrated by percussive drilling machines, processed through a primary crusher, and then conveyed to the surface. In open pit mines, ore and gangue are loosened and pulverized by explosives, scooped up by mechanical equipment, and transported to the concentrator. A trend toward increased mechanical excavation as a substitute for standard cyclic mine development, such as drill-and-blast and surface shovel-and-truck routines has surfaced as an element common to most metal mine cost-lowering techniques.

Standard crushers, screens, and rod and ball mills classify and reduce the ore to powders in the 65 to 325 mesh range. The finely divided particles are separated from the gangue and are concentrated in a liquid medium by gravity and/or selective flotation, then cleaned, thickened, and filtered. The concentrate is dried prior to shipment to the smelter.

12.18.3 Emissions And Controls[2-4,8]

Lead emissions are largely fugitive and are caused by drilling, loading, conveying, screening, unloading, crushing, and grinding. The primary means of control are good mining techniques and equipment maintenance. These practices include enclosing the truck loading operation, wetting or covering truck loads and stored concentrates, paving the road from mine to concentrator, sprinkling the unloading area, and preventing leaks in the crushing and grinding enclosures. Cyclones and fabric filters can be used in the milling operations.

Particulate and lead emission factors for lead ore crushing and materials handling operations are given in Tables 12.18-1 and 12.18-2.

Table 12.18-1 (Metric Units). EMISSION FACTORS FOR ORE CRUSHING AND GRINDING

Type Of Ore And Lead Content (wt %)		Particulate Emission Factor[a]	EMISSION FACTOR RATING	Lead Emission Factor[b]	EMISSION FACTOR RATING
Lead[c] (SCC 3-03-031-01)	5.1	3.0	B	0.15	B
Zinc[d] (SCC 3-03-031-02)	0.2	3.0	B	0.006	B
Copper[e] (SCC 3-03-031-03)	0.2	3.2	B	0.006	B
Lead-Zinc[f] (SCC 3-03-031-04)	2.0	3.0	B	0.06	B
Copper-Lead[g] (SCC 3-03-031-05)	2.0	3.2	B	0.06	B
Copper-Zinc[h] (SCC 3-03-031-06)	0.2	3.2	B	0.006	B
Copper-Lead-Zinc[i] (SCC 3-03-031-07)	2.0	3.2	B	0.06	B

[a] Reference 2. Units are expressed as kg of pollutant/Mg ore processed. SCC = Source Classification Code.
[b] Reference 2,3,5,7.
[c] Refer to Section 12.6.
[d] Characteristic of some mines in Colorado.
[e] Characteristic of some mines in Alaska, Idaho, and New York.
[f] Characteristic of Arizona mines.
[g] Characteristic of some mines in Missouri, Idaho, Colorado, and Montana.
[h] Characteristic of some mines in Missouri.
[i] Does not appear in ore characterization of the top 25 domestic lead producing mines.

Table 12.18-2 (English Units). EMISSION FACTORS FOR ORE CRUSHING AND GRINDING

Type Of Ore And Lead Content (wt %)		Particulate Emission Factor[a]	EMISSION FACTOR RATING	Lead Emission Factor[b]	EMISSION FACTOR RATING
Lead[c] (SCC 3-03-031-01)	5.1	6.0	B	0.30	B
Zinc[d] (SCC 3-03-031-02)	0.2	6.0	B	0.012	B
Copper[e] (SCC 3-03-031-03)	0.2	6.4	B	0.012	B
Lead-Zinc[f] (SCC 3-03-031-04)	2.0	6.0	B	0.12	B
Copper-Lead[g] (SCC 3-03-031-05)	2.0	6.4	B	0.12	B
Copper-Zinc[h] (SCC 3-03-031-06)	0.2	6.4	B	0.012	B
Copper-Lead-Zinc[i] (SCC 3-03-031-07)	2.0	6.4	B	0.12	B

[a] Reference 2. Units are expressed as lb of pollutant/ton ore processed. SCC = Source Classification Code.
[b] Reference 2,3,5,7.
[c] Refer to Section 12.6.
[d] Characteristic of some mines in Colorado.
[e] Characteristic of some mines in Alaska, Idaho, and New York.
[f] Characteristic of Arizona mines.
[g] Characteristic of some mines in Missouri, Idaho, Colorado, and Montana.
[h] Characteristic of some mines in Missouri.
[i] Does not appear in ore characterization of the top 25 domestic lead producing mines.

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12.19 Electric Arc Welding

NOTE: Because of the many Source Classification Codes (SCCs) associated with electric arc welding, the text of this Section will give only the first 3 of the 4 SCC number fields. The last field of each applicable SCC will be found in Tables 12.19-1 and 12.19-2 below.

12.19.1 Process Description[1-2]

Welding is the process by which 2 metal parts are joined by melting the parts at the points of contact and simultaneously forming a connection with molten metal from these same parts or from a consumable electrode. In welding, the most frequently used methods for generating heat employ either an electric arc or a gas-oxygen flame.

There are more than 80 different types of welding operations in commercial use. These operations include not only arc and oxyfuel welding, but also brazing, soldering, thermal cutting, and gauging operations. Figure 12.19-1 is a diagram of the major types of welding and related processes, showing their relationship to one another.

Of the various processes illustrated in Figure 12.19-1, electric arc welding is by far the most often found. It is also the process that has the greatest emission potential. Although the national distribution of arc welding processes by frequency of use is not now known, the percentage of electrodes consumed in 1991, by process type, was as follows:

Shielded metal arc welding (SMAW) - 45 percent
Gas metal arc welding (GMAW) - 34 percent
Flux cored arc welding (FCAW) - 17 percent
Submerged arc welding (SAW) - 4 percent

12.19.1.1 Shielded Metal Arc Welding (SMAW)[3] -

SMAW uses heat produced by an electric arc to melt a covered electrode and the welding joint at the base metal. During operation, the rod core both conducts electric current to produce the arc and provides filler metal for the joint. The core of the covered electrode consists of either a solid metal rod of drawn or cast material or a solid metal rod fabricated by encasing metal powders in a metallic sheath. The electrode covering provides stability to the arc and protects the molten metal by creating shielding gases by vaporization of the cover.

12.19.1.2 Gas Metal Arc Welding (GMAW)[3] -

GMAW is a consumable electrode welding process that produces an arc between the pool of weld and a continuously supplied filler metal. An externally supplied gas is used to shield the arc.

12.19.1.3 Flux Cored Arc Welding (FCAW)[3] -

FCAW is a consumable electrode welding process that uses the heat generated by an arc between the continuous filler metal electrode and the weld pool to bond the metals. Shielding gas is provided from flux contained in the tubular electrode. This flux cored electrode consists of a metal sheath surrounding a core of various powdered materials. During the welding process, the electrode core material produces a slag cover on the face of the weld bead. The welding pool can be protected from the atmosphere either by self-shielded vaporization of the flux core or with a separately supplied shielding gas.

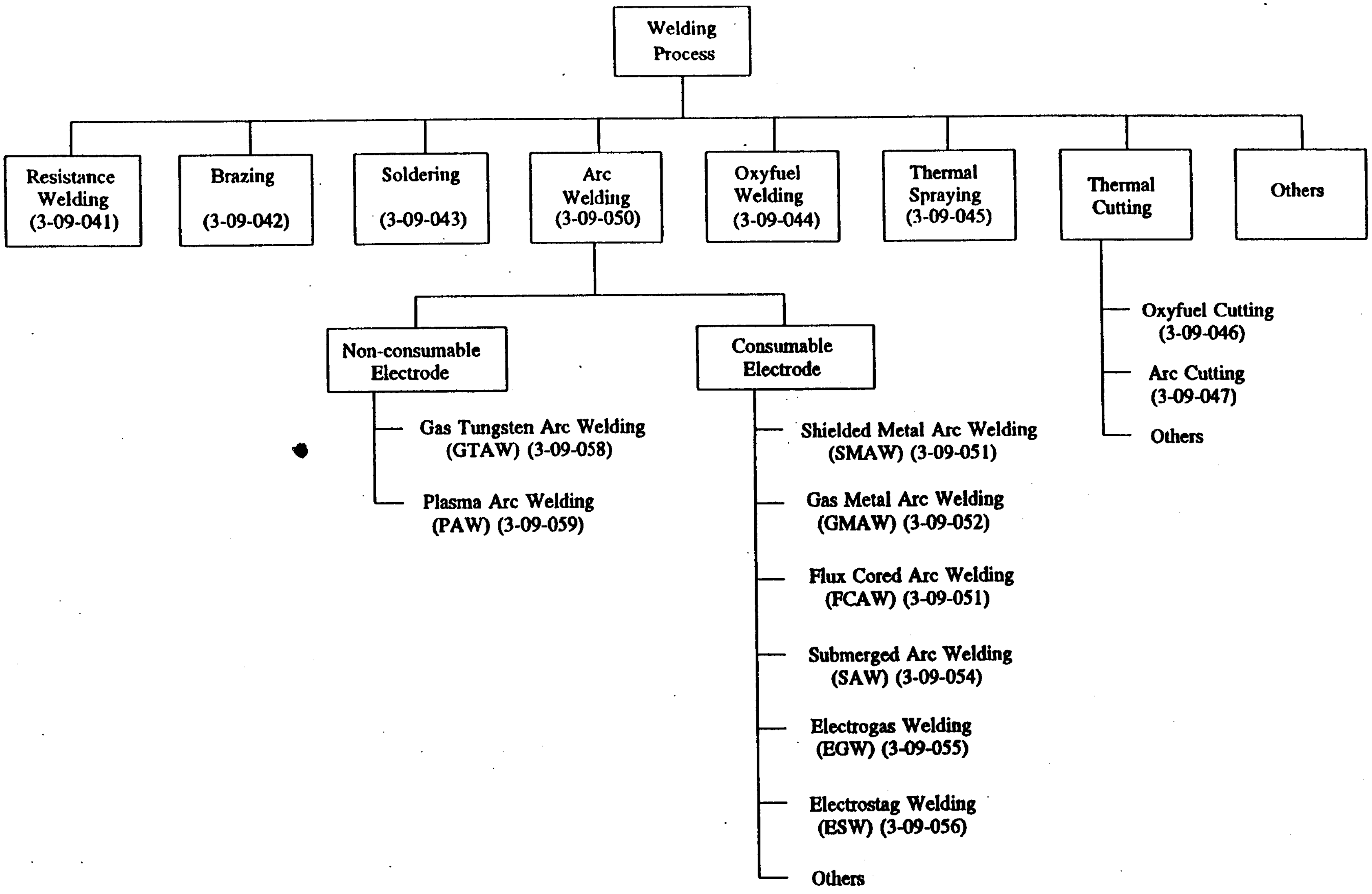

Figure 12.19-1. Welding and allied processes. (Source Classification Codes in parentheses.)

12.19.1.4 Submerged Arc Welding (SAW)[4] -

SAW produces an arc between a bare metal electrode and the work contained in a blanket of granular fusible flux. The flux submerges the arc and welding pool. The electrode generally serves as the filler material. The quality of the weld depends on the handling and care of the flux. The SAW process is limited to the downward and horizontal positions, but it has an extremely low fume formation rate.

12.19.2 Emissions And Controls[4-8]

12.19.2.1 Emissions -

Particulate matter and particulate-phase hazardous air pollutants are the major concerns in the welding processes. Only electric arc welding generates these pollutants in substantial quantities. The lower operating temperatures of the other welding processes cause fewer fumes to be released. Most of the particulate matter produced by welding is submicron in size and, as such, is considered to be all PM-10 (i. e., particles $\leq$ 10 micrometers in aerodynamic diameter).

The elemental composition of the fume varies with the electrode type and with the workpiece composition. Hazardous metals designated in the 1990 Clean Air Act Amendments that have been recorded in welding fume include manganese (Mg), nickel (Ni), chromium (Cr), cobalt (Co), and lead (Pb).

Gas phase pollutants are also generated during welding operations, but little information is available on these pollutants. Known gaseous pollutants (including "greenhouse" gases) include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and ozone (O_3).

Table 12.19-1 presents PM-10 emission factors from SMAW, GMAW, FCAW, and SAW processes, for commonly used electrode types. Table 12.19-2 presents similar factors for hazardous metal emissions. Actual emissions will depend not only on the process and the electrode type, but also on the base metal material, voltage, current, arc length, shielding gas, travel speed, and welding electrode angle.

12.19.2.2 Controls -

The best way to control welding fumes is to choose the proper process and operating variables for the given task. Also, capture and collection systems may be used to contain the fume at the source and to remove the fume with a collector. Capture systems may be welding booths, hoods, torch fume extractors, flexible ducts, and portable ducts. Collection systems may be high efficiency filters, electrostatic precipitators, particulate scrubbers, and activated carbon filters.

Table 12.19-1 (Metric And English Units). PM-10 EMISSION FACTORS FOR WELDING OPERATIONS^{a}

Welding Process	Electrode Type (With Last 2 Digits Of SCC)		Total Fume Emission Factor (g/kg [lb/10^3 lb] Of Electrode Consumed)^{b}	EMISSION FACTOR RATING
SMAW^{c} (SCC 3-09-051)	14Mn-4Cr	(-04)	81.6	C
	E11018	(-08)^{h}	16.4	C
	E308	(-12)^{j}	10.8	C
	E310	(-16)^{k}	15.1	C
	E316	(-20)^{m}	10.0	C
	E410	(-24)^{n}	13.2	D
	E6010	(-28)	25.6	B
	E6011	(-32)	38.4	C
	E6012	(-36)	8.0	D
	E6013	(-40)	19.7	B
	E7018	(-44)	18.4	C
	E7024	(-48)	9.2	C
	E7028	(-52)	18.0	C
	E8018	(-56)^{p}	17.1	C
	E9015	(-60)^{q}	17.0	D
	E9018	(-64)^{r}	16.9	C
	ECoCr	(-68)^{s}	27.9	C
	ENi-Cl	(-72)	18.2	C
	ENiCrMo	(-76)^{t}	11.7	C
	ENi-Cu	(-80)^{u}	10.1	C
GMAW^{d,e} (SCC 3-09-052)	E308L	(-12)^{v}	5.4	C
	E70S	(-54)^{w}	5.2	A
	ER1260	(-10)	20.5	D
	ER5154	(-26)	24.1	D
	ER316	(-20)^{x}	3.2	C
	ERNiCrMo	(-76)^{y}	3.9	C
	ERNiCu	(-80)^{z}	2.0	C

Table 12.19-1 (cont.).

Welding Process	Electrode Type (With Last 2 Digits Of SCC)		Total Fume Emission Factor (g/kg [lb/10^3 lb] Of Electrode Consumed)[b]	EMISSION FACTOR RATING
FCAW[f,g] (SCC 3-09-053)	E110	(-06)[aa]	20.8	D
	E11018	(-08)	57.0	D
	E308LT	(-12)[bb]	9.1	C
	E316LT	(-20)[cc]	8.5	B
	E70T	(-54)[dd]	15.1	B
	E71T	(-55)[ee]	12.2	B
SAW[g] (SCC 3-09-054)	EM12K	(-10)[ff]	0.05	C

[a] References 7-18. SMAW = shielded metal arc welding; GMAW = gas metal arc welding; FCAW = flux cored arc welding; SAW = submerged arc welding. SCC = Source Classification Code.

[b] Mass of pollutant emitted per unit mass of electrode consumed. All welding fume is considered to be PM-10 (particles ≤ 10 μm in aerodynamic diameter).

[c] Current = 102 to 229 A; voltage = 21 to 34 V.

[d] Current = 160 to 275 A; voltage = 20 to 32 V.

[e] Current = 275 to 460 A; voltage = 19 to 32 V.

[f] Current = 450 to 550 A; voltage = 31 to 32 V.

[g] Type of shielding gas employed will influence emission factor.

[h] Includes E11018-M

[j] Includes E308-16 and E308L-15

[k] Includes E310-16

[m] Includes E316-15, E316-16, and E316L-16

[n] Includes E410-16

[p] Includes E8018C3

[q] Includes E9015B3

[r] Includes E9018B3 and E9018G

[s] Includes ECoCr-A

[t] Includes ENiCrMo-4

[u] Includes ENi-Cu-2

[v] Includes E308LSi

[w] Includes E70S-3, E70S-5, and E70S-6

[x] Includes ER316I-Si and ER316L-Si

[y] Includes ENiCrMo-3 and ENi-CrMo-4

[z] Includes ERNiCu-7

[aa] Includes E110TS-K3

[bb] Includes E308LT-3

[cc] Includes E316LT-3

[dd] Includes E70T-1, E70T-2, E70T-4, E70T-5, E70T-7, and E70T-G

[ee] Includes E71T-1 and E71T-11

[ff] Includes EM12K1 and F72-EM12K2

Table 12.19-2. HAZARDOUS AIR POLLUTANT (HAP) EMISSION FACTORS FOR WELDING OPERATIONS[a]

Welding Process	Electrode Type (With Last 2 Digits Of SCC)	HAP Emission Factor (10^{-1} g/kg [$10^{-1}/10^{3}$ lb] Of Electrode Consumed)[b]						EMISSION FACTOR RATING
		Cr	Cr(VI)	Co	Mn	Ni	Pb	
SMAW[c] (SCC 3-09-051)	14Mn-4Cr (-04)	13.9	ND	ND	232	17.1	ND	C
	E11018 (-08)[h]	ND	ND	ND	13.8	ND	ND	C
	E308 (-12)[j]	3.93	3.59	0.01	2.52	0.43	ND	D
	E310 (-16)[k]	25.3	18.8	ND	22.0	1.96	0.24	C
	E316 (-20)[m]	5.22	3.32	ND	5.44	0.55	ND	D
	E410 (-24)[n]	ND	ND	ND	6.85	0.14	ND	C
	E6010 (-28)	0.03	0.01	ND	9.91	0.04	ND	B
	E6011 (-32)	0.05	ND	0.01	9.98	0.05	ND	C
	E6012 (-36)	ND	ND	ND	ND	ND	ND	ND
	E6013 (-40)	0.04	ND	< 0.01	9.45	0.02	ND	B
	E7018 (-44)	0.06	ND	< 0.01	10.3	0.02	ND	C
	E7024 (-48)	0.01	ND	ND	6.29	ND	ND	C
	E7028 (-52)	0.13	ND	ND	8.4612	ND	1.62	C
	E8018 (-56)[p]	0.17	ND	ND	0.3	0.51	ND	C
	E9016 (-60)	ND	ND	ND	ND	ND	ND	ND
	E9018 (-64)[q]	2.12	ND	ND	7.83	0.13	ND	C
	ECoCr (-68)	ND	ND	ND	ND	ND	ND	ND
	ENi-Cl (-72)	ND	ND	ND	0.39	8.90	ND	C
	ENiCrMo (-76)[r]	4.20	ND	ND	0.43	2.47	ND	C
	ENi-Cu-2 (-80)[s]	ND	ND	ND	2.12	4.23	ND	C
GMAW[d,e] (SCC 3-09-052)	E308 (-12)[t]	5.24	ND	< 0.01	3.46	1.84	ND	C
	E70S (-54)[u]	0.01	ND	< 0.01	3.18	0.01	ND	A
	ER1260 (-10)	0.04	ND	ND	ND	ND	ND	D
	ER5154 (-26)	0.10	ND	ND	0.34	ND	ND	D
	ER316 (-20)[v]	5.28	0.10	ND	2.45	2.26	ND	D
	ERNiCrMo (-76)[w]	3.53	ND	ND	0.70	12.5	ND	B
	ERNiCu (-80)[x]	< 0.01	ND	ND	0.22	4.51	ND	C

Table 12.19-2 (cont.).

Welding Process	Electrode Type (With Last 2 Digits Of SCC)	HAP Emission Factor (10^{-1} g/kg [10^{-1} lb/10^3 lb] Of Electrode Consumed)[b]						EMISSION FACTOR RATING
		Cr	Cr(VI)	Co	Mn	Ni	Pb	
FCAW[f,g] (SCC 3-09-053)	E110 (-06)[y]	0.02	ND	ND	20.2	1.12	ND	D
	E11018 (-08)[z]	9.69	ND	ND	7.04	1.02	ND	C
	E308 (-12)	ND	ND	ND	ND	ND	ND	ND
	E316 (-20)[aa]	9.70	1.40	ND	5.90	0.93	ND	B
	E70T (-54)[bb]	0.04	ND	ND	8.91	0.05	ND	B
	E71T (-55)[cc]	0.02	ND	< 0.01	6.62	0.04	ND	B
SAW[h] (SCC 3-09-054)	EM12K (-10)	ND	ND	ND	ND	ND	ND	ND

[a] References 7-18. SMAW = shielded metal arc welding; GMAW = gas metal arc welding; FCAW = flux cored arc welding; SAW = submerged arc welding. SCC = Source Classification Code. ND = no data.

[b] Mass of pollutant emitted per unit mass of electrode consumed. Cr = chromium. Cr(VI) = chromium +6 valence state. Co = cobalt. Mn = manganese. Ni = nickel. Pb = lead. All HAP emissions are in the PM-10 size range (particles ≤ 10 μm in aerodynamic diameter).

[c] Current = 102 to 225 A; voltage = 21 to 34 V.

[d] Current = 275 to 460 A; voltage = 19 to 32 V.

[e] Type of shielding gas employed will influence emission factors.

[f] Current = 160 to 275 A; voltage = 22 to 34 V.

[g] Current = 450 to 550 A; voltage = 31 to 32 V.

[h] Includes E11018-M

[j] Includes E308-16 and E308L-15

[k] Includes E310-15

[m] Includes E316-15, E316-16, and E316L-16

[n] Includes E410-16

[p] Includes 8018C3

[q] Includes 9018B3

[r] Includes ENiCrMo-3 and ENiCrMo-4

[s] Includes ENi-Cu-2

[t] Includes E308LSi

[u] Includes E70S-3, E70S-5, and E70S-6

[v] Includes ER316I-Si

[w] Includes ERNiCrMo-3 and ERNiCrMo-4

[x] Includes ERNiCu-7

[y] Includes E110TS-K3

[z] Includes E11018-M

[aa] Includes E316LT-3

[bb] Includes E70T-1, E70T-2, E70T-4, E70T-5, E70T-7, and E70T-G

[cc] Includes E71T-1 and E71T-11

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13. MISCELLANEOUS SOURCES

This chapter contains emission factor information on those source categories that differ substantially from, and hence cannot be grouped with, the other "stationary" sources discussed in this publication. Most of these miscellaneous emitters, both natural and manmade, are truly area sources, with their pollutant-generating process(es) dispersed over large land areas. Another characteristic of these sources is the inapplicability, in most cases, of conventional control methods such as wet/dry equipment, fuel switching, process changes, etc. Instead, control of these emissions, where possible at all, may involve such techniques as modification of agricultural burning practices, paving with asphalt or concrete, or stabilization of dirt roads. Finally, miscellaneous sources generally emit pollutants intermittently, compared to most stationary point sources. For example, a wildfire may emit large quantities of particulate and carbon monoxide for several hours or even days. But, when measured against a continuous emitter over a long period of time its emissions may seem relatively minor. Also, effects on air quality may be of relatively short duration.

13.1 Wildfires And Prescribed Burning

13.1.1 General[1]

A wildfire is a large-scale natural combustion process that consumes various ages, sizes, and types of flora growing outdoors in a geographical area. Consequently, wildfires are potential sources of large amounts of air pollutants that should be considered when trying to relate emissions to air quality.

The size and intensity, even the occurrence, of a wildfire depend directly on such variables as meteorological conditions, the species of vegetation involved and their moisture content, and the weight of consumable fuel per acre (available fuel loading). Once a fire begins, the dry combustible material is consumed first. If the energy release is large and of sufficient duration, the drying of green, live material occurs, with subsequent burning of this material as well. Under proper environmental and fuel conditions, this process may initiate a chain reaction that results in a widespread conflagration.

The complete combustion of wildland fuels (forests, grasslands, wetlands) require a heat flux (temperature gradient), adequate oxygen supply, and sufficient burning time. The size and quantity of wildland fuels, meteorological conditions, and topographic features interact to modify the burning behavior as the fire spreads, and the wildfire will attain different degrees of combustion efficiency during its lifetime.

The importance of both fuel type and fuel loading on the fire process cannot be overemphasized. To meet the pressing need for this kind of information, the U. S. Forest Service is developing a model of a nationwide fuel identification system that will provide estimates of fuel loading by size class. Further, the environmental parameters of wind, slope, and expected moisture changes have been superimposed on this fuel model and incorporated into a National Fire Danger Rating System (NFDRS). This system considers five classes of fuel, the components of which are selected on the basis of combustibility, response of dead fuels to moisture, and whether the living fuels are herbaceous (grasses, brush) or woody (trees, shrubs).

Most fuel loading figures are based on values for "available fuel", that is, combustible material that will be consumed in a wildfire under specific weather conditions. Available fuel values must not be confused with corresponding values for either "total fuel" (all the combustible material that would burn under the most severe weather and burning conditions) or "potential fuel" (the larger woody material that remains even after an extremely high intensity wildfire). It must be emphasized, however, that the various methods of fuel identification are of value only when they are related to the existing fuel quantity, the quantity consumed by the fire, and the geographic area and conditions under which the fire occurs.

For the sake of conformity and convenience, estimated fuel loadings estimated for the vegetation in the U. S. Forest Service Regions are presented in Table 13.1-1. Figure 13.1-1 illustrates these areas and regions.

Table 13.1-1 (Metric And English Units). SUMMARY OF ESTIMATED FUEL CONSUMED BY WILDFIRES[a]

National Region[b]	Estimated Average Fuel Loading	
	Mg/hectare	ton/acre
Rocky Mountain	83	37
Region 1: Northern	135	60
Region 2: Rocky Mountain	67	30
Region 3: Southwestern	22	10
Region 4: Intermountain	40	8
Pacific	43	19
Region 5: California	40	18
Region 6: Pacific Northwest	135	60
Region 10: Alaska	36	16
Coastal	135	60
Interior	25	11
Southern	20	9
Region 8: Southern	20	9
Eastern	25	11
North Central	25	11
Region 9: Conifers	22	10
Hardwoods	27	12

[a] Reference 1.

[b] See Figure 13.1-1 for region boundaries.

13.1.2 Emissions And Controls[1]

It has been hypothesized, but not proven, that the nature and amounts of air pollutant emissions are directly related to the intensity and direction (relative to the wind) of the wildfire, and are indirectly related to the rate at which the fire spreads. The factors that affect the rate of spread are (1) weather (wind velocity, ambient temperature, relative humidity); (2) fuels (fuel type, fuel bed array, moisture content, fuel size); and (3) topography (slope and profile). However, logistical problems (such as size of the burning area) and difficulties in safely situating personnel and equipment close to the fire have prevented the collection of any reliable emissions data on actual wildfires, so that it is not possible to verify or disprove the hypothesis. Therefore, until such measurements are made, the only available information is that obtained from burning experiments in the laboratory. These data, for both emissions and emission factors, are contained in Table 13.1-2. It must be emphasized that the factors presented here are adequate for laboratory-scale emissions estimates, but that substantial errors may result if they are used to calculate actual wildfire emissions.

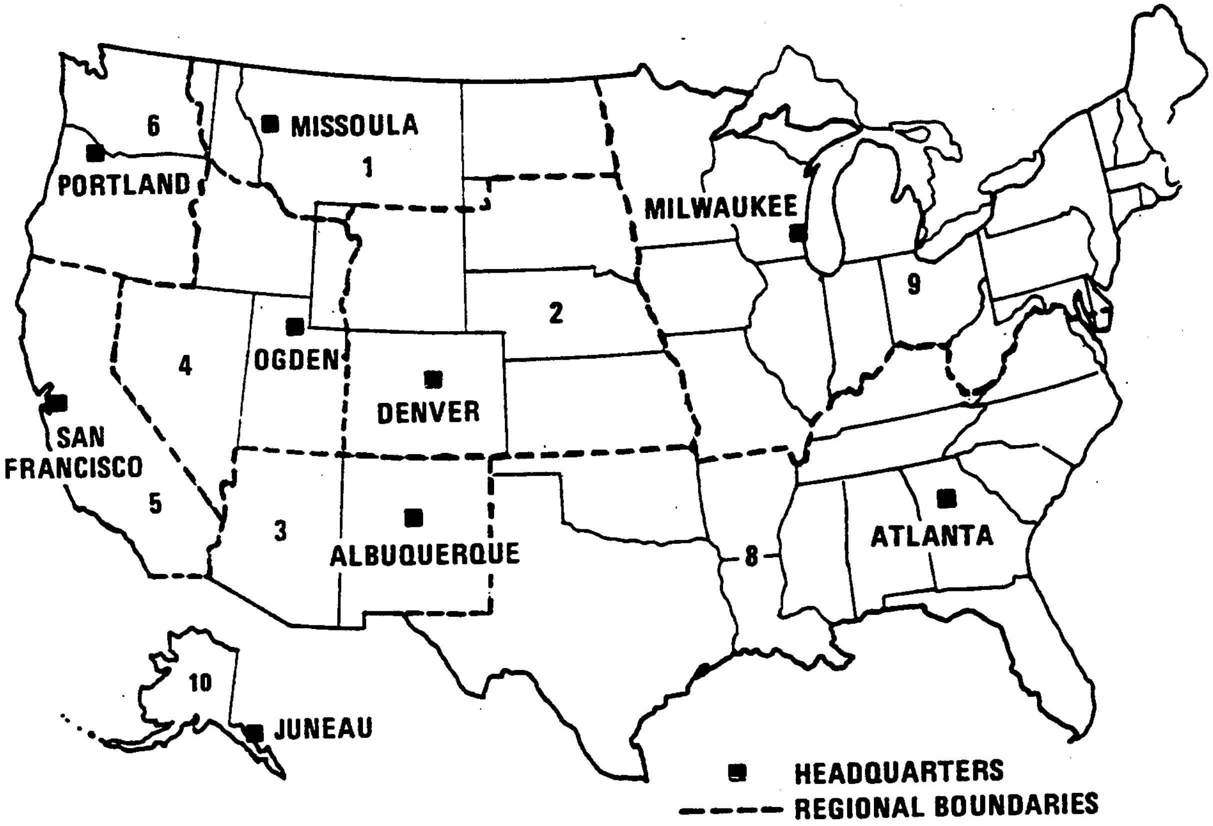

Figure 13.1-1. Forest areas And U. S. Forest Service Regions.

The emissions and emission factors displayed in Table 13.1-2 are calculated using the following formulas:

$$F_i = P_i L \qquad (1)$$

$$E_i = F_i A = P_i L A \qquad (2)$$

where:

F_i = emission factor (mass of pollutant/unit area of forest consumed)
P_i = yield for pollutant "i" (mass of pollutant/unit mass of forest fuel consumed)
= 8.5 kilograms per megagram (kg/Mg) (17 pound per ton [lb/ton]) for total particulate
= 70 kg/Mg (140 lb/ton) for carbon monoxide
= 12 kg/Mg (24 lb/ton) for total hydrocarbon (as CH_4)
= 2 kg/Mg (4 lb/ton) for nitrogen oxides (NO_x)
= negligible for sulfur oxides (SO_x)
L = fuel loading consumed (mass of forest fuel/unit land area burned)
A = land area burned
E_i = total emissions of pollutant "i" (mass pollutant)

Table 13.1-2. EMISSIONS AND EMISSION FACTORS FOR FOREST WILDFIRES

EMISSION FACTOR RATING: D

Geographic Area	Area Consumed By Wildfire[a] (hectares)	Wildfire Fuel Consumption (Mg/hectare)	Emission Factors (kg/Hectare)				Emissions (Mg)			
			Particulate	Carbon Monoxide	Volatile Organics[b]	Nitrogen Oxides	Particulate	Carbon Monoxide	Volatile Organics[b]	Nitrogen Oxides
Rocky Mountain	313,397	83	706	5,810	996	166	220,907	1,819,237	311,869	51,978
Northern (Region 1)	142,276	135	1,144	9,420	1,620	269	162,268	1,339,283	229,592	38,265
Rocky Mountain (Region 2)	65,882	67	572	4,710	808	135	37,654	310,086	53,157	8,860
Southwestern (Region 3)	83,765	22	191	1,570	269	45	15,957	131,417	22,533	3,735
Intermountain (Region 4)	21,475	40	153	1,260	215	36	3,273	26,953	4,620	770
Pacific	469,906	43	362	2,980	512	85	170,090	1,400,738	240,126	40,021
California (Region 5)	18,997	40	343	2,830	485	81	6,514	53,645	9,196	1,533
Alaska (Region 10)	423,530	36	305	2,510	431	72	129,098	1,063,154	182,255	30,376
Pacific Northwest (Region 6)	27,380	135	1,144	9,420	1,620	269	31,296	257,738	44,183	7,363
Southern	806,289	20	172	1,410	242	40	138,244	1,138,484	195,168	35,528
Southern (Region 8)	806,289	20	172	1,410	242	40	138,244	1,138,484	195,168	35,528
North Central and Eastern	94,191	25	210	1,730	296	49	19,739	162,555	27,867	4,644
(Region 9)	141,238	25	210	1,730	296	49	29,598	243,746	41,785	6,964
Eastern Group (With Region 9)	47,046	25	210	1,730	296	49	9,859	81,191	13,918	2,320
Total	1,730,830	38	324	2,670	458	76	560,552	4,616,317	791,369	131,895

[a] Consumption data are for 1971.

[b] Expressed as methane.

For example, suppose that it is necessary to estimate the total particulate emissions from a 10,000-hectare wildfire in the Southern area (Region 8). From Table 13.1-1, it is seen that the average fuel loading is 20 Mg/hectare (9 tons/acre). Further, the pollutant yield for particulates is 8.5 kg/Mg (17 lb/ton). Therefore, the emissions are:

$$E = (8.5 \text{ kg/Mg of fuel}) (20 \text{ Mg of fuel/hectare}) (10{,}000 \text{ hectares})$$

$$E = 1{,}700{,}000 \text{ kg} = 1{,}700 \text{ Mg}$$

The most effective method of controlling wildfire emissions is, of course, to prevent the occurrence of wildfires by various means at the land manager's disposal. A frequently used technique for reducing wildfire occurrence is "prescribed" or "hazard reduction" burning. This type of managed burn involves combustion of litter and underbrush to prevent fuel buildup under controlled conditions, thus reducing the danger of a wildfire. Although some air pollution is generated by this preventive burning, the net amount is believed to be a relatively smaller quantity then that produced by wildfires.

13.1.3 Prescribed Burning[1]

Prescribed burning is a land treatment, used under controlled conditions, to accomplish natural resource management objectives. It is one of several land treatments, used individually or in combination, including chemical and mechanical methods. Prescribed fires are conducted within the limits of a fire plan and prescription that describes both the acceptable range of weather, moisture, fuel, and fire behavior parameters, and the ignition method to achieve the desired effects. Prescribed fire is a cost-effective and ecologically sound tool for forest, range, and wetland management. Its use reduces the potential for destructive wildfires and thus maintains long-term air quality. Also, the practice removes logging residues, controls insects and disease, improves wildlife habitat and forage production, increases water yield, maintains natural succession of plant communities, and reduces the need for pesticides and herbicides. The major air pollutant of concern is the smoke produced.

Smoke from prescribed fires is a complex mixture of carbon, tars, liquids, and different gases. This open combustion source produces particles of widely ranging size, depending to some extent on the rate of energy release of the fire. For example, total particulate and particulate less than 2.5 micrometers (μm) mean mass cutpoint diameters are produced in different proportions, depending on rates of heat release by the fire.[2] This difference is greatest for the highest-intensity fires, and particle volume distribution is bimodal, with peaks near 0.3 μm and exceeding 10 μm.[3] Particles over about 10 μm, probably of ash and partially burned plant matter, are entrained by the turbulent nature of high-intensity fires.

Burning methods differ with fire objectives and with fuel and weather conditions.[4] For example, the various ignition techniques used to burn under standing trees include: (1) heading fire, a line of fire that runs with the wind; (2) backing fire, a line of fire that moves into the wind; (3) spot fires, which burn from a number of fires ignited along a line or in a pattern; and (4) flank fire, a line of fire that is lit into the wind, to spread laterally to the direction of the wind. Methods of igniting the fires depend on forest management objectives and the size of the area. Often, on areas of 50 or more acres, helicopters with aerial ignition devices are used to light broadcast burns. Broadcast fires may involve many lines of fire in a pattern that allows the strips of fire to burn together over a sizeable area.

In discussing prescribed burning, the combustion process is divided into preheating, flaming, glowing, and smoldering phases. The different phases of combustion greatly affect the amount of emissions produced.[5-7] The preheating phase seldom releases significant quantities of material to the atmosphere. Glowing combustion is usually associated with burning of large concentrations of woody fuels such as logging residue piles. The smoldering combustion phase is a very inefficient and incomplete combustion process that emits pollutants at a much higher ratio to the quantity of fuel consumed than does the flaming combustion of similar materials.

The amount of fuel consumed depends on the moisture content of the fuel.[8-9] For most fuel types, consumption during the smoldering phase is greatest when the fuel is driest. When lower layers of the fuel are moist, the fire usually is extinguished rapidly.[10]

The major pollutants from wildland burning are particulate, carbon monoxide, and volatile organics. Nitrogen oxides are emitted at rates of from 1 to 4 g/kg burned, depending on combustion temperatures. Emissions of sulfur oxides are negligible.[11-12]

Particulate emissions depend on the mix of combustion phase, the rate of energy release, and the type of fuel consumed. All of these elements must be considered in selecting the appropriate emission factor for a given fire and fuel situation. In some cases, models developed by the U. S. Forest Service have been used to predict particulate emission factors and source strength.[13] These models address fire behavior, fuel chemistry, and ignition technique, and they predict the mix of combustion products. There is insufficient knowledge at this time to describe the effect of fuel chemistry on emissions.

Table 13.1-3 presents emission factors from various pollutants, by fire and fuel configuration. Table 13.1-4. gives emission factors for prescribed burning, by geographical area within the United States. Estimates of the percent of total fuel consumed by region were compiled by polling experts from the Forest Service. The emission factors are averages and can vary by as much as 50 percent with fuel and fire conditions. To use these factors, multiply the mass of fuel consumed per hectare by the emission factor for the appropriate fuel type. The mass of fuel consumed by a fire is defined as the available fuel. Local forestry officials often compile information on fuel consumption for prescribed fires and have techniques for estimating fuel consumption under local conditions. The *Southern Forestry Smoke Management Guidebook*[5] and the *Prescribed Fire Smoke Management Guide*[15] should be consulted when using these emission factors.

The regional emission factors in Table 13.1-4 should be used only for general planning purposes. Regional averages are based on estimates of the acreage and vegetation type burned and may not reflect prescribed burning activities in a given state. Also, the regions identified are broadly defined, and the mix of vegetation and acres burned within a given state may vary considerably from the regional averages provided. Table 13.1-4 should not be used to develop emission inventories and control strategies.

To develop state emission inventories, the user is strongly urged to contact that state's federal land management agencies and state forestry agencies that conduct prescribed burning to obtain the best information on such activities.

Table 13.1-3 (Metric Units). EMISSION FACTORS FOR PRESCRIBED BURNING[a]

Fire/Fuel Configuration	Phase	Pollutant (g/kg)						Fuel Mix (%)	EMISSION FACTOR RATING
		Particulate			Carbon Monoxide	Volatile Organics			
		PM-2.5	PM-10	Total		Methane	Nonmethane		
Broadcast logging slash									
Hardwood	F	6	7[b]	13	44	2.1	3.8	33	A
	S	13	14[b]	20	146	8.0	7.7	67	A
	Fire	11	12[b]	18	112	6.1	6.4		A
Conifer									
Short needle	F	7	8[c]	12	72	2.3	2.1	33	A
	S	14	15[c]	19	226	7.2	4.2	67	A
	Fire	12	13[c]	17	175	5.6	3.5		A
Long needle	F	6	6[d]	9	45	1.5	1.7	33	B
	S	16	17[d]	25	166	7.7	5.4	67	B
	Fire	13	13[d]	20	126	5.7	4.2		B
Logging slash debris									
Dozer piled conifer									
No mineral soil[d]	F	4	4	5	28	1.0	ND	90	B
	S	6	7	14	116	8.7	ND	10	B
	Fire	4	4	6	37	1.8	ND		B

Table 13.1-3 (cont.).

Fire/Fuel Configuration	Phase	Pollutant (g/kg)						Fuel Mix (%)	EMISSION FACTOR RATING
		Particulate			Carbon Monoxide	Volatile Organics			
		PM-2.5	PM-10	Total		Methane	Nonmethane		
10 to 30% Mineral soil[e]	S	ND	ND	25	200	ND	ND	ND	D
25% Organic soil[e]	S	ND	ND	35	250	ND	ND	ND	D
Range fire									
Juniper slash[f]	F	7	8	11	41	2.0	2.7	8.2	B
	S	12	13	18	125	10.3	7.8	15.6	B
	Fire[g]	9	10	14	82	6.0	5.2	12.5	B
Sagebrush[f]	F	15	16	23	78	3.7	3.4		B
	S	13	15	23	106	6.2	7.3		B
	Fire[g]	13	15	23	103	6.2	6.9		B
Chaparral shrub communities[h]	F	7	8	16	56	1.7	8.2		A
	S	12	13	23	133	6.4	15.6		A
	Fire	10	11	20	101	4.5	12.5		A
Line fire									
Conifer									
Long needle (pine)	Heading[j]	ND	40	50	200	ND	ND		D
	Backing[k]	ND	20	20	125	ND	ND		D
Palmetto/gallberry[j]	Heading	ND	15	17	150	ND	ND		D
	Backing	ND	15	15	100	ND	ND		D
	Fire	ND	8 - 22	ND	ND	ND	ND		D
Chaparral[k]	Heading	8	9	15	62	2.8	3.5		C
Grasslands[j]	Fire	ND	10	10	75	ND	0		D

Table 13.1-3 (cont.).

[a] References 7-8. Unless otherwise noted, determined by field testing of fires ≥ 1 acre size. F = flaming. S = smoldering. Fire = weighted average of F and S. ND = no data.
[b] For PM-10, Reference 7. EMISSION FACTOR RATING: C.
[c] For PM-10, References 3,7. EMISSION FACTOR RATING: D.
[d] For PM-10, References 3,7. EMISSION FACTOR RATING: D.
[e] Reference 12. Determined using laboratory combustion hood.
[f] Reference 16.
[g] Fuel mix uncertain, because of short, intense flaming phase. Use fire average for emission inventory purposes.
[h] References 17-18.
[j] References 13-14. Determined using laboratory combustion hood.
[k] References 13-14.

Table 13.1-4 (Metric Units). EMISSION FACTORS FOR PRESCRIBED BURNING BY U. S. REGION

Regional Configuration And Fuel Type[a]	Percent Of Fuel[b]	Pollutant[c]			
		Particulate (g/kg)			CO
		PM-2.5	PM-10	PM	
Pacific Northwest					
Logging slash					
Piled slash	42	4	5	6	37
Douglas fir/Western hemlock	24	12	13	17	175
Mixed conifer	19	12	13	17	175
Ponderosa pine	6	13	13	20	126
Hardwood	4	11	12	18	112
Underburning pine	5	30	30	35	163
Average for region	100	9.4	10.3	13.3	111.1
Pacific Southwest					
Sagebrush	35		9	15	62
Chaparral	20	8	9	15	62
Pinyon/Juniper	20		13	17	175
Underburning pine	15		30	35	163
Grassland	10		10	10	15
Average for region	100		13.0	17.8	101.0
Southeast					
Palmetto/gallbery	35		15	16	125
Underburning pine	30		30	35	163
Logging slash	20		13	20	126
Grassland	10		10	10	75
Other	5		17	17	175
Average for region	100		18.8	21.9	134

Table 13.1-4 (cont.).

Regional Configuration And Fuel Type[a]	Percent of Fuel[b]	Pollutant[c]			
		Particulate (g/kg)			CO
		PM-2.5	PM-10	PM	
Rocky Mountain					
Logging slash	50		4	6	37
Underburning pine	20		30	35	163
Grassland	20		10	10	75
Other	10		17	17	175
Average for region	100		11.9	13.7	83.4
North Central and Eastern					
Logging slash	50		13	17	175
Grassland	30		10	10	75
Underburning pine	10		30	35	163
Other	10		17	17	175
Average for region	100		14	16.5	143.8

[a] Regional areas are generalized, e. g., the Pacific Northwest includes Oregon, Washington, and parts of Idaho and California. Fuel types generally reflect the ecosystems of a region, but users should seek advice on fuel type mix for a given season of the year. An average factor for Northern California could be more accurately described as chaparral, 25%; underburning pine, 15%; sagebrush, 15%; grassland, 5%; mixed conifer, 25%; and douglas fir/Western hemlock, 15%. Blanks indicate no data.

[b] Based on the judgement of forestry experts.

[c] Adapted from Table 13.1-3 for the dominant fuel types burned.

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13.2 Fugitive Dust Sources

Significant atmospheric dust arises from the mechanical disturbance of granular material exposed to the air. Dust generated from these open sources is termed "fugitive" because it is not discharged to the atmosphere in a confined flow stream. Common sources of fugitive dust include unpaved roads, agricultural tilling operations, aggregate storage piles, and heavy construction operations.

For the above sources of fugitive dust, the dust-generation process is caused by 2 basic physical phenomena:

1. Pulverization and abrasion of surface materials by application of mechanical force through implements (wheels, blades, etc.).
2. Entrainment of dust particles by the action of turbulent air currents, such as wind erosion of an exposed surface by wind speeds over 19 kilometers per hour (km/hr) (12 miles per hour [mph]).

In this section of AP-42, the principal pollutant of interest is PM-10 — particulate matter (PM) no greater than 10 micrometers in aerodynamic diameter (μmA). Because PM-10 is the size basis for the current primary National Ambient Air Quality Standards (NAAQS) for particulate matter, it represents the particle size range of the greatest regulatory interest. Because formal establishment of PM-10 as the primary standard basis occurred in 1987, many earlier emission tests have been referenced to other particle size ranges, such as:

TSP	Total Suspended Particulate, as measured by the standard high-volume ("hi-vol") air sampler, has a relatively coarse size range. TSP was the basis for the previous primary NAAQS for PM and is still the basis of the secondary standard. Wind tunnel studies show that the particle mass capture efficiency curve for the high-volume sampler is very broad, extending from 100 percent capture of particles smaller than 10 μm to a few percent capture of particles as large as 100 μm. Also, the capture efficiency curve varies with wind speed and wind direction, relative to roof ridge orientation. Thus, high-volume samplers do not provide definitive particle size information for emission factors. However, an effective cut point of 30 μm aerodynamic diameter is frequently assigned to the standard high volume sampler.
SP	Suspended Particulate, which is often used as a surrogate for TSP, is defined as PM with an aerodynamic diameter no greater than 30 μm. SP may also be denoted as PM-30.
IP	Inhalable Particulate is defined as PM with an aerodynamic diameter no greater than 15 μm IP also may be denoted as PM-15.
FP	Fine Particulate is defined as PM with an aerodynamic diameter no greater than 2.5 μm. FP may also be denoted as PM-2.5.

The impact of a fugitive dust source on air pollution depends on the quantity and drift potential of the dust particles injected into the atmosphere. In addition to large dust particles that settle out near the source (often creating a local nuisance problem), considerable amounts of fine particles also are emitted and dispersed over much greater distances from the source. PM-10 represents a relatively fine particle size range and, as such, is not overly susceptible to gravitational settling.

The potential drift distance of particles is governed by the initial injection height of the particle, the terminal settling velocity of the particle, and the degree of atmospheric turbulence. Theoretical drift distance, as a function of particle diameter and mean wind speed, has been computed for fugitive dust emissions. Results indicate that, for a typical mean wind speed of 16 km/hr (10 mph), particles larger than about 100 μm are likely to settle out within 6 to 9 meters (20 to 30 feet [ft]) from the edge of the road or other point of emission. Particles that are 30 to 100 μm in diameter are likely to undergo impeded settling. These particles, depending upon the extent of atmospheric turbulence, are likely to settle within a few hundred feet from the road. Smaller particles, particularly IP, PM-10, and FP, have much slower gravitational settling velocities and are much more likely to have their settling rate retarded by atmospheric turbulence.

Control techniques for fugitive dust sources generally involve watering, chemical stabilization, or reduction of surface wind speed with windbreaks or source enclosures. Watering, the most common and, generally, least expensive method, provides only temporary dust control. The use of chemicals to treat exposed surfaces provides longer dust suppression, but may be costly, have adverse effects on plant and animal life, or contaminate the treated material. Windbreaks and source enclosures are often impractical because of the size of fugitive dust sources.

The reduction of source extent and the incorporation of process modifications or adjusted work practices, both of which reduce the amount of dust generation, are preventive techniques for the control of fugitive dust emissions. These techniques could include, for example, the elimination of mud/dirt carryout on paved roads at construction sites. On the other hand, mitigative measures entail the periodic removal of dust-producing material. Examples of mitigative control measures include clean-up of spillage on paved or unpaved travel surfaces and clean-up of material spillage at conveyor transfer points.

13.2.1 Paved Roads

13.2.1.1 General

Particulate emissions occur whenever vehicles travel over a paved surface, such as a road or parking lot. In general terms, particulate emissions from paved roads originate from the loose material present on the surface. In turn, that surface loading, as it is moved or removed, is continuously replenished by other sources. At industrial sites, surface loading is replenished by spillage of material and trackout from unpaved roads and staging areas. Figure 13.2.1-1 illustrates several transfer processes occurring on public streets.

Various field studies have found that public streets and highways, as well as roadways at industrial facilities, can be major sources of the atmospheric particulate matter within an area.[1-8] Of particular interest in many parts of the United States are the increased levels of emissions from public paved roads when the equilibrium between deposition and removal processes is upset. This situation can occur for various reasons, including application of snow and ice controls, carryout from construction activities in the area, and wind and/or water erosion from surrounding unstabilized areas.

13.2.1.2 Emissions And Correction Parameters

Dust emissions from paved roads have been found to vary with what is termed the "silt loading" present on the road surface as well as the average weight of vehicles traveling the road. The term silt loading (sL) refers to the mass of silt-size material (equal to or less than 75 micrometers [μm] in physical diameter) per unit area of the travel surface.[4-5] The total road surface dust loading is that of loose material that can be collected by broom sweeping and vacuuming of the traveled portion of the paved road. The silt fraction is determined by measuring the proportion of the loose dry surface dust that passes through a 200-mesh screen, using the ASTM-C-136 method. Silt loading is the product of the silt fraction and the total loading, and is abbreviated "sL". Additional details on the sampling and analysis of such material are provided in AP-42 Appendices C.1 and C.2.

The surface sL provides a reasonable means of characterizing seasonal variability in a paved road emission inventory.[9] In many areas of the country, road surface loadings are heaviest during the late winter and early spring months when the residual loading from snow/ice controls is greatest.

13.2.1.3 Predictive Emission Factor Equations[9]

The quantity of dust emissions from vehicle traffic on a paved road may be estimated using the following empirical expression:

$$E = k\ (sL/2)^{0.65}\ (W/3)^{1.5} \qquad (1)$$

where:

E = particulate emission factor
k = base emission factor for particle size range and units of interest (see below)
sL = road surface silt loading (grams per square meter) (g/m^2)

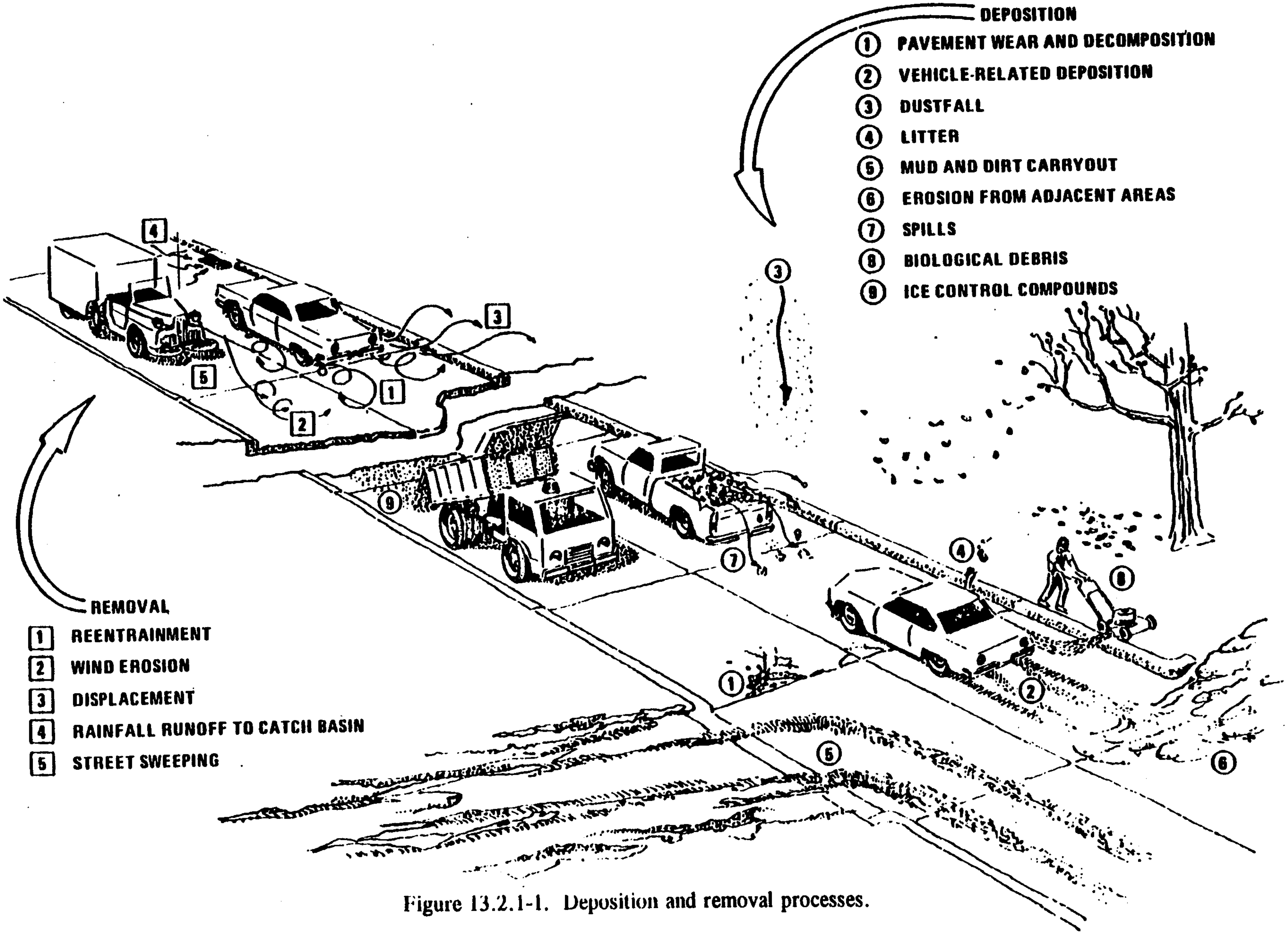

Figure 13.2.1-1. Deposition and removal processes.

The particle size multiplier (k) above varies with aerodynamic size range as follows:

Particle Size Multipliers For Paved Road Equation

Size Range[a]	Multiplier k[b]		
	g/VKT	g/VMT	lb/VMT
PM-2.5	2.1	3.3	0.0073
PM-10	4.6	7.3	0.016
PM-15	5.5	9.0	0.020
PM-30[c]	24	38	0.082

[a] Refers to airborne particulate matter (PM-x) with an aerodynamic diameter equal to or less than x micrometers.

[b] Units shown are grams per vehicle kilometer traveled (g/VKT), grams per vehicle mile traveled (g/VMT), and pounds per vehicle mile traveled (lb/VMT).

[c] PM-30 is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for TSP.

To determine particulate emissions for a specific particle size range, use the appropriate value of k above.

The above equation is based on a regression analysis of numerous emission tests, including 65 tests for PM-10.[9] Sources tested include public paved roads, as well as controlled and uncontrolled industrial paved roads. The equations retain the quality rating of A (B for PM-2.5), if applied within the range of source conditions that were tested in developing the equation as follows:

Silt loading:	0.02 - 400 g/m^2
	0.03 - 570 grains/square foot (ft^2)
Mean vehicle weight:	1.8 - 38 megagrams (Mg)
	2.0 - 42 tons
Mean vehicle speed:	16 - 88 kilometers per hour (kph)
	10 - 55 miles per hour (mph)

To retain the quality rating for the emission factor equation when it is applied to a specific paved road, it is necessary that reliable correction parameter values for the specific road in question be determined. The field and laboratory procedures for determining surface material silt content and surface dust loading are summarized in Appendices C.1 and C.2. In the event that site-specific values cannot be obtained, an appropriate value for an industrial road may be selected from the mean values given in Table 13.2.1-1, but the quality rating of the equation should be reduced by 1 level.

With the exception of limited access roadways, which are difficult to sample, the collection and use of site-specific sL data for public paved road emission inventories are strongly recommended. Although hundreds of public paved road sL measurements have been made since 1980,[7, 13-20] uniformity has been lacking in sampling equipment and analysis techniques, in roadway classification schemes, and in the types of data reported.[9] The assembled data set (described below) does not yield any readily identifiable, coherent relationship between sL and road class, average daily traffic (ADT), etc. Further complicating any analysis is the fact that, in many parts of the country, paved road sL

Table 13.2.1-1 (Metric And English Units). TYPICAL SILT CONTENT AND LOADING VALUES FOR PAVED ROADS AT INDUSTRIAL FACILITIES[a]

Industry	No. Of Sites	No. Of Samples	Silt Content (%)		No. Of Travel Lanes	Total Loading x 10^{-3}			Silt Loading (g/m^2)	
			Range	Mean		Range	Mean	Units[b]	Range	Mean
Copper smelting	1	3	15.4-21.7	19.0	2	12.9-19.5 45.8-69.2	15.9 55.4	kg/km lb/mi	188-400	292
Iron and steel production	9	48	1.1-35.7	12.5	2	0.006-4.77 0.020-16.9	0.495 1.75	kg/km lb/mi	0.09-79	9.7
Asphalt batching	1	3	2.6-4.6	3.3	1	12.1-18.0 43.0-64.0	14.9 52.8	kg/km lb/mi	76-193	120
Concrete batching	1	3	5.2-6.0	5.5	2	1.4-1.8 5.0-6.4	1.7 5.9	kg/km lb/mi	11-12	12
Sand and gravel processing	1	3	6.4-7.9	7.1	1	2.8-5.5 9.9-19.4	3.8 13.3	kg/km lb/mi	53-95	70
Municipal solid waste landfill	2	7	—	—	2	—	—	—	1.1-32.0	7.4
Quarry	1	6	—	—	2	—	—	—	2.4-14	8.2

[a] References 1-2,5-6,10-12. Values represent samples collected from *industrial* roads. Public road silt loading values are presented in Figure 13.2.1-2, Figure 13.2.1-3, Figure 13.2.1-4, Figure 13.2.1-5, Figure 13.2.1-6, and Figure 13.2.1-7, and Tables 13.2.1-2 and 13.2.1-3. Dashes indicate information not available.

[b] Multiply entries by 1000 to obtain stated units; kilograms per kilometer (kg/km) and pounds per mile (lb/mi).

varies greatly over the course of the year. For example, repeated sampling of the same roads over a period of 3 calendar years at 4 Montana municipalities indicated a noticeable annual cycle. Silt loading declines during the first 2 calendar quarters and increases during the fourth quarter.

Figure 13.2.1-2 and Figure 13.2.1-3 present the cumulative frequency distribution for the public paved road sL data base assembled during the preparation of this AP-42 section.[9] The data base includes samples taken from roads that were treated with sand and other snow/ice controls. Roadways are grouped into high- and low-ADT sets, with 5000 vehicles per day being the approximate cutpoint. Figure 13.2.1-2 and Figure 13.2.1-3, respectively, present the cumulative frequency distributions for high- and low-ADT roads.

In the absence of site-specific sL data to serve as input to a public paved road inventory, conservatively high emission estimates can be obtained by using the following values taken from the figures. For annual conditions, the median sL values of 0.4 g/m^2 can be used for high-ADT roads (excluding limited access roads that are discussed below) and 2.5 g/m^2 for low-ADT roads. Worst-case loadings can be estimated for high-ADT (excluding limited access roads) and low-ADT roads, respectively, with the 90th percentile values of 7 and 25 g/m^2. Figure 13.2.1-4, Figure 13.2.1-5, Figure 13.2.1-6, and Figure 13.2.1-7 present similar cumulative frequency distribution information for high- and low-ADT roads, except that the sets were divided based on whether the sample was collected during the first or second half of the year. Information on the 50th and 90th percentile values is summarized in Table 13.2.1-2.

Table 13.2.1-2 (Metric Units). PERCENTILES FOR NONINDUSTRIAL SILT LOADING (g/m^2) DATA BASE

Averaging Period	High-ADT Roads		Low-ADT Roads	
	50th	90th	50th	90th
Annual	0.4	7	2.5	25
January-June	0.5	14	3	30
July-December	0.3	3	1.5	5

In the event that sL values are taken from any of the cumulative frequency distribution figures, the quality ratings for the emission estimates should be downgraded 2 levels.

As an alternative method of selecting sL values in the absence of site-specific data, users can review the public (i. e., nonindustrial) paved road sL data base presented in Table 13.2.1-3 and can select values that are appropriate for the roads and seasons of interest. Table 13.2.1-3 presents paved road surface loading values together with the city, state, road name, collection date (samples collected from the same road during the same month are averaged), road ADT if reported, classification of the roadway, etc. Recommendation of this approach recognizes that end users of AP-42 are capable of identifying roads in the data base that are similar to roads in the area being inventoried. In the event that sL values are developed in this way, and that the selection process is fully described, then the quality ratings for the emission estimates should be downgraded only 1 level.

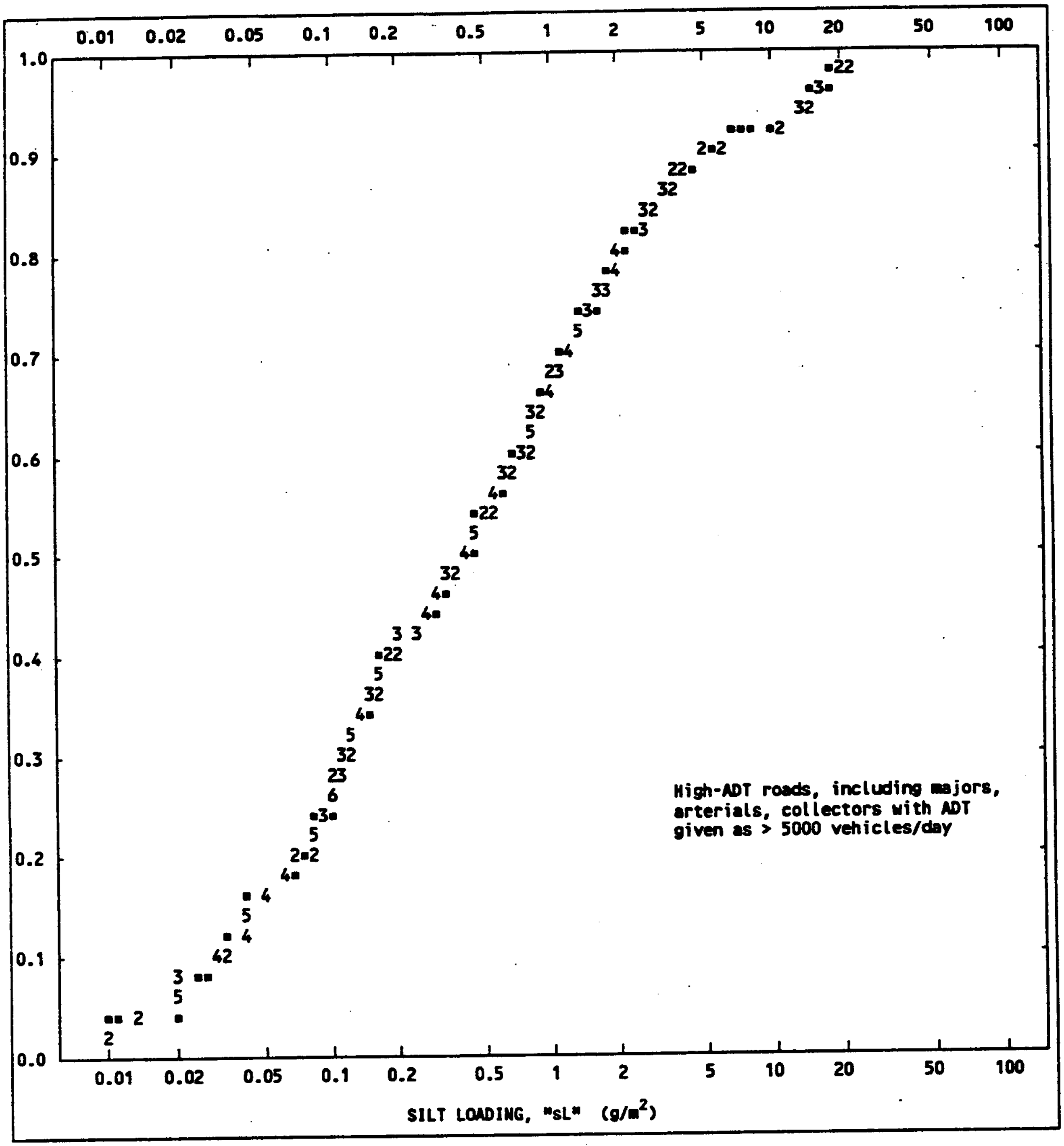

Figure 13.2.1-2. Cumulative frequency distribution for surface silt loading on high-ADT roadways.

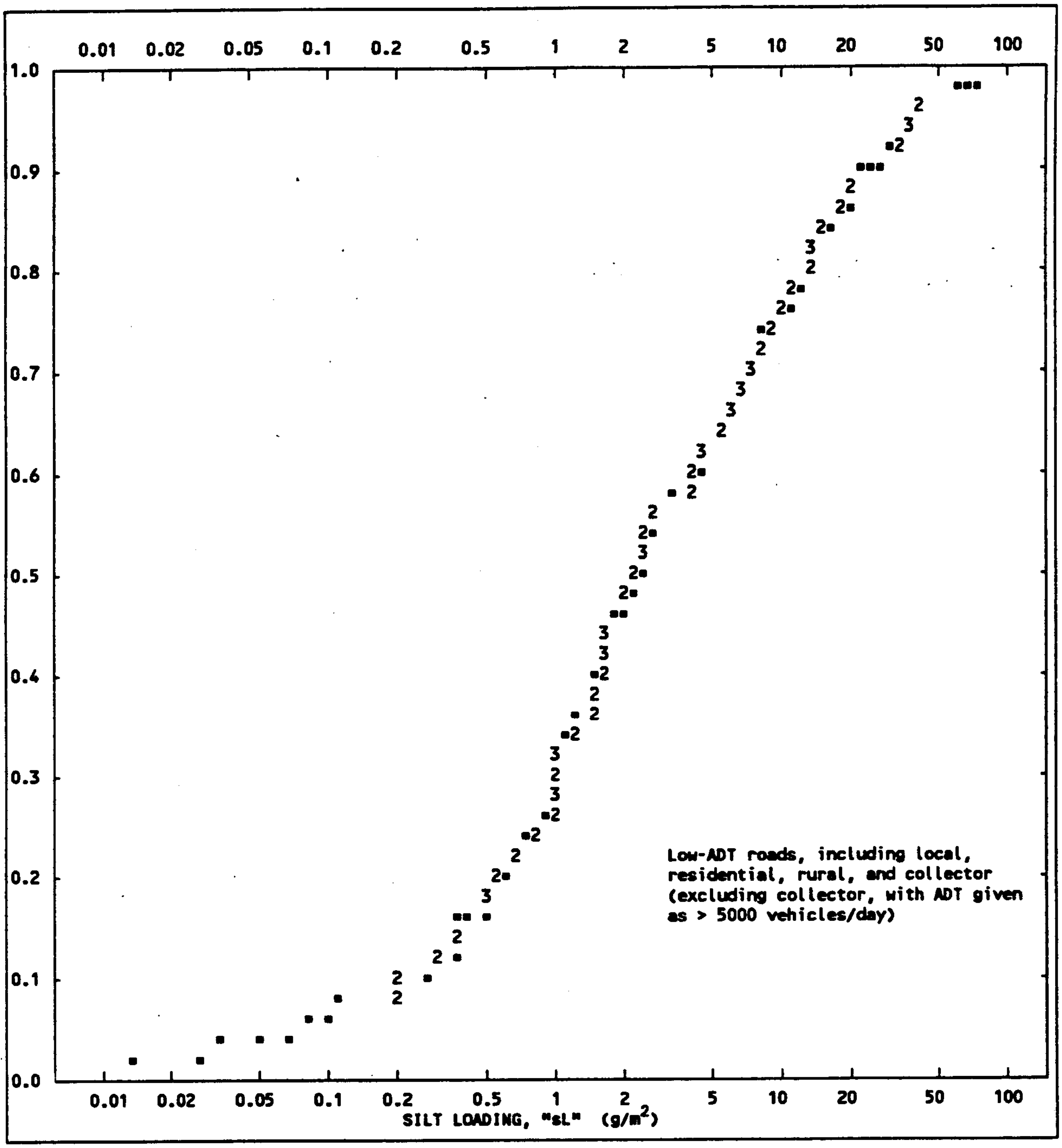

Figure 13.2.1-3. Cumulative frequency distribution for surface silt loading on low-ADT roadways.

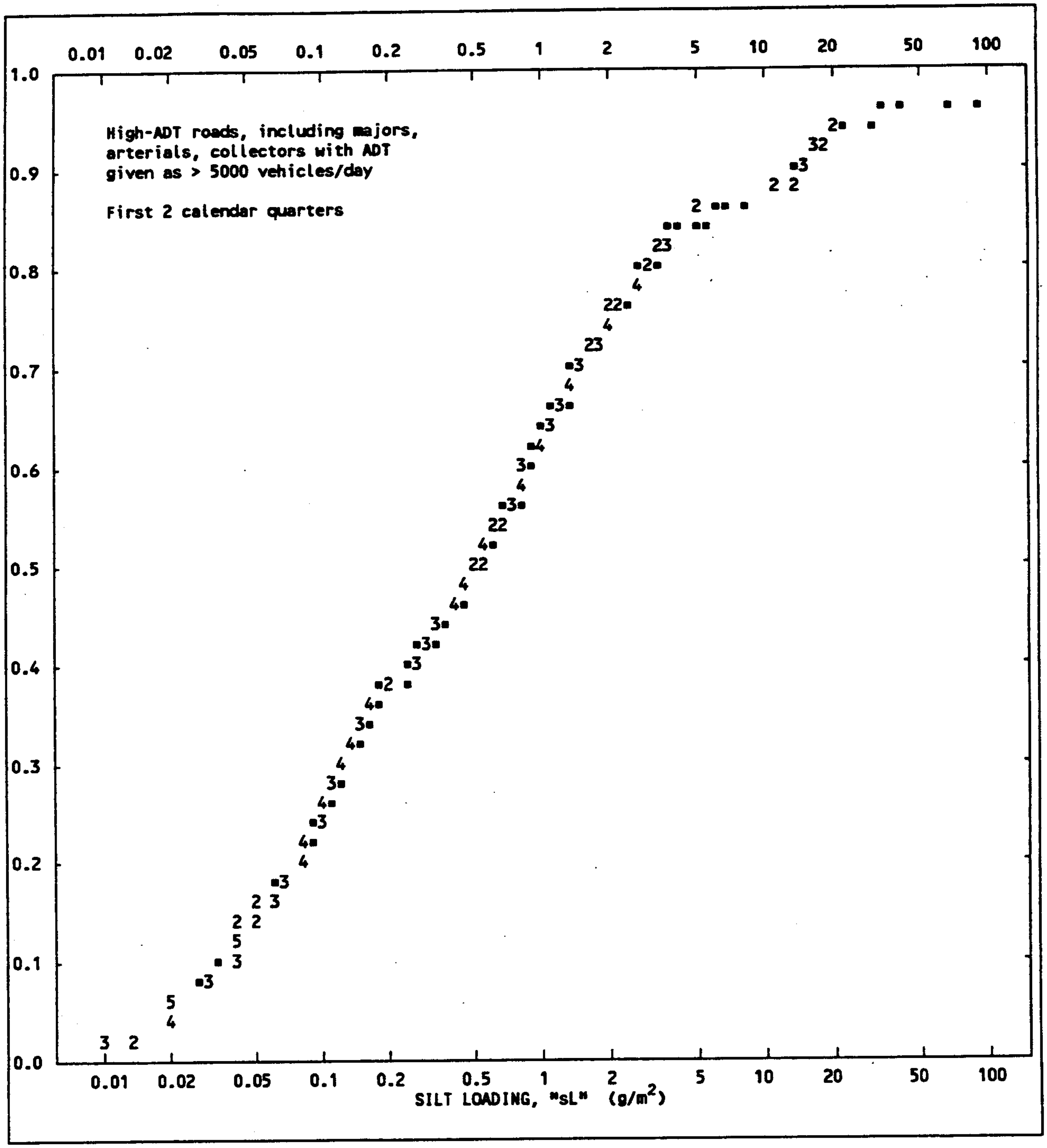

Figure 13.2.1-4. Cumulative frequency distribution for surface silt loading on high-ADT roadways, based on samples during first half of the calendar year.

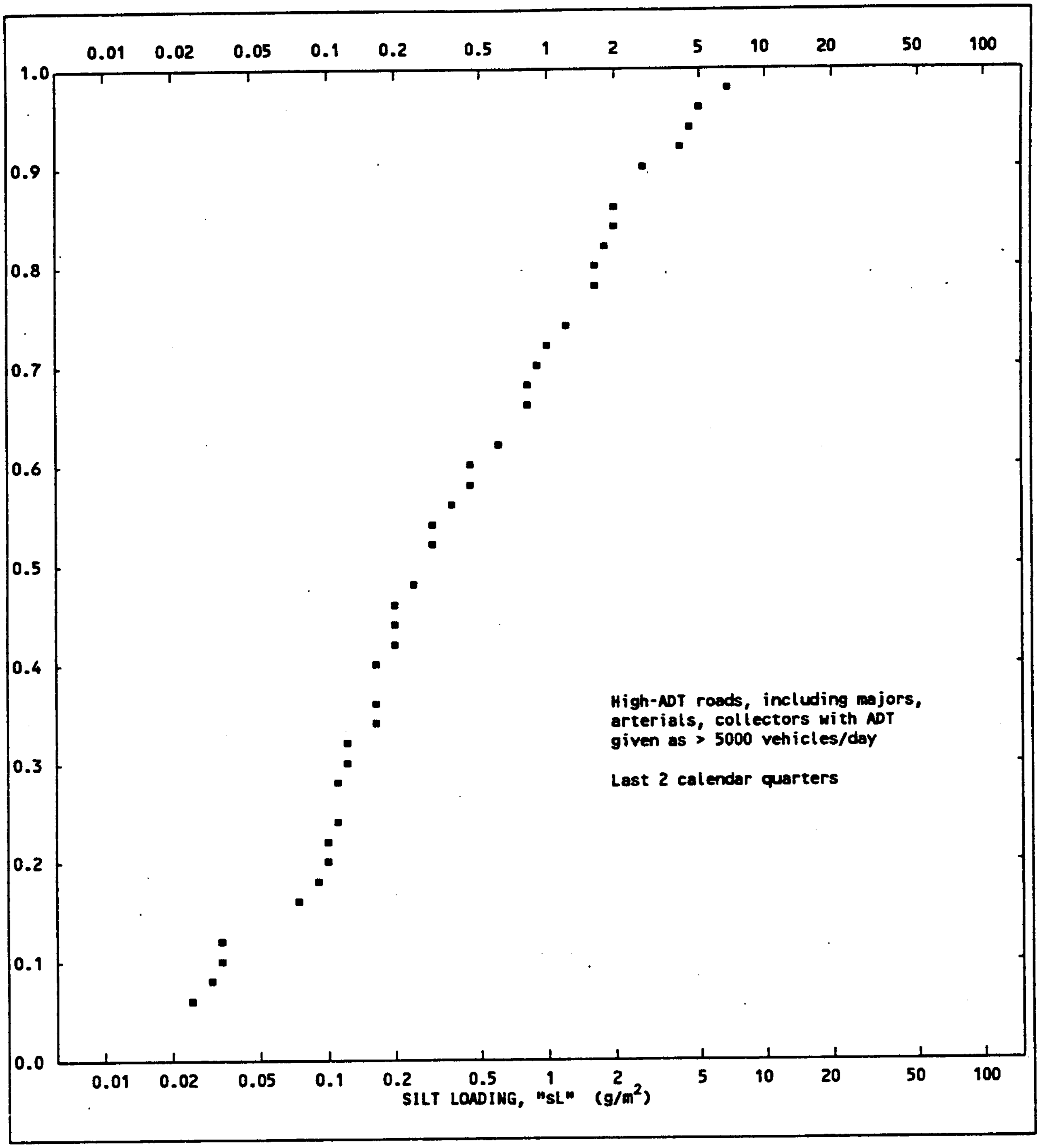

Figure 13.2.1-5. Cumulative frequency distribution for surface silt loading on high-ADT roadways, based on samples during second half of the calendar year.

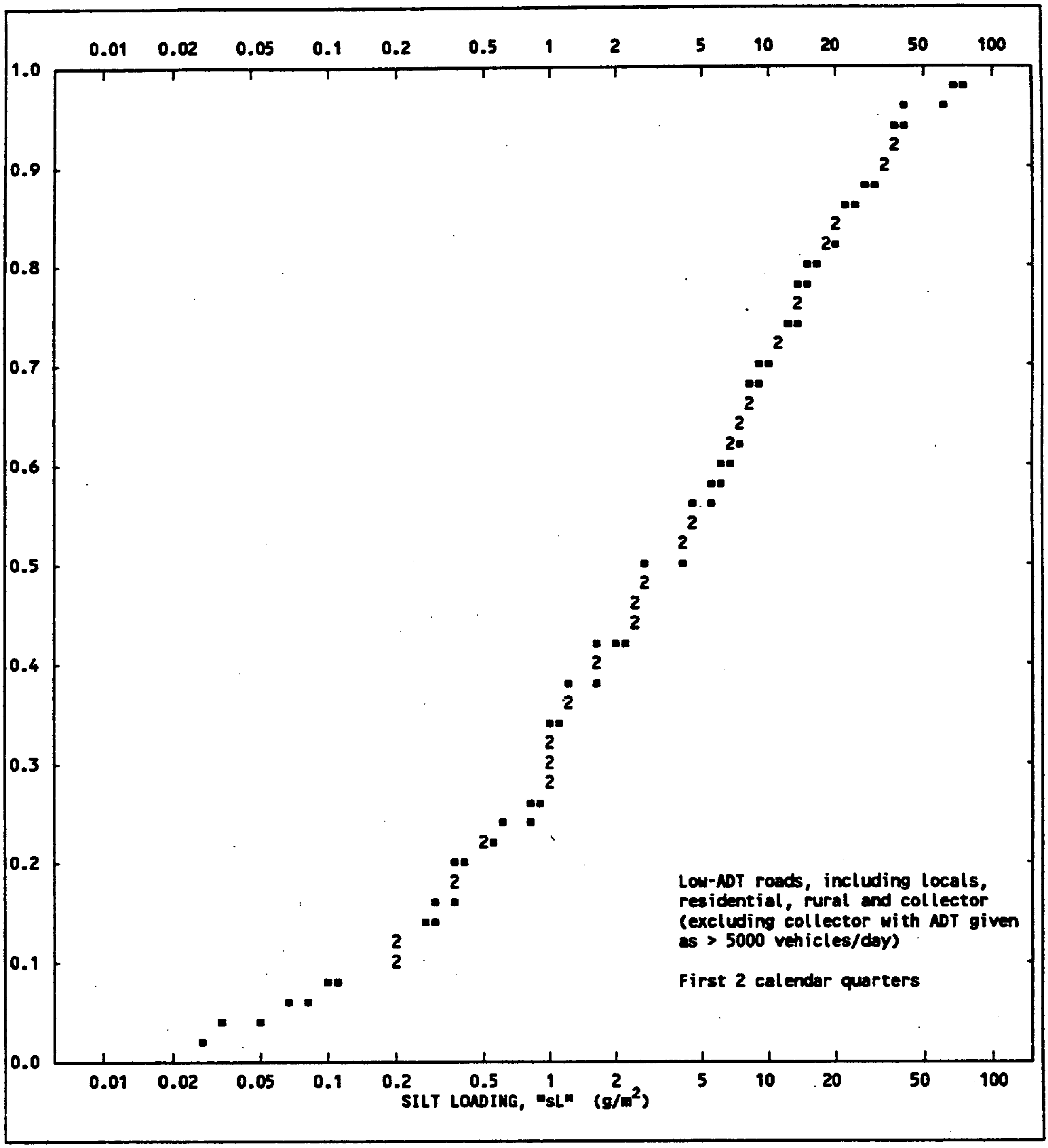

Figure 13.2.1-6. Cumulative frequency distribution for surface silt loading on low-ADT roadways, based on samples during first half of the calendar year.

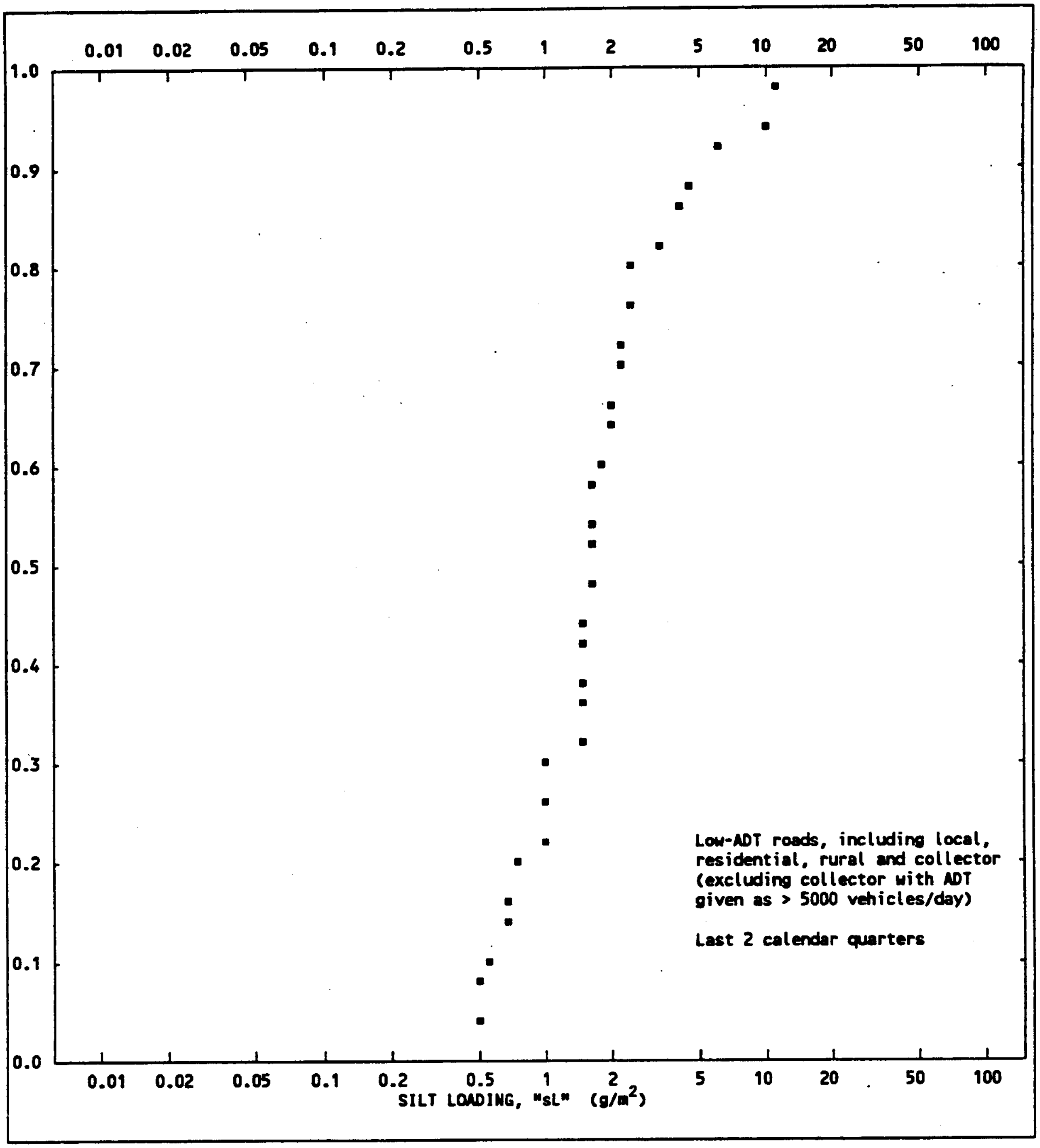

Figure 13.2.1-7. Cumulative frequency distribution for surface silt loading on low-ADT roadways, based on samples during second half of the calendar year.

Limited access roadways pose severe logistical difficulties in terms of surface sampling, and few sL data are available. Nevertheless, the available data do not suggest great variation in sL for limited access roadways from 1 part of the country to another. For annual conditions, a default value of 0.02 g/m^2 is recommended for limited access roadways. Even fewer of the available data correspond to worst-case situations, and elevated loadings are observed to be quickly depleted because of high ADT rates. A default value of 0.1 g/m^2 is recommended for short periods of time following application of snow/ice controls to limited access roads.

13.2.1.4 Controls[6,21]

Because of the importance of the surface loading, control techniques for paved roads attempt either to prevent material from being deposited onto the surface (preventive controls) or to remove from the travel lanes any material that has been deposited (mitigative controls). Regulations requiring the covering of loads in trucks, or the paving of access areas to unpaved lots or construction sites, are preventive measures. Examples of mitigative controls include vacuum sweeping, water flushing, and broom sweeping and flushing.

In general, preventive controls are usually more cost effective than mitigative controls. The cost-effectiveness of mitigative controls falls off dramatically as the size of an area to be treated increases. That is to say, the number and length of public roads within most areas of interest preclude any widespread and routine use of mitigative controls. On the other hand, because of the more limited scope of roads at an industrial site, mitigative measures may be used quite successfully (especially in situations where truck spillage occurs). Note, however, that public agencies could make effective use of mitigative controls to remove sand/salt from roads after the winter ends.

Because available controls will affect the sL, controlled emission factors may be obtained by substituting controlled loading values into the equation. (Emission factors from controlled industrial roads were used in the development of the equation.) The collection of surface loading samples from treated, as well as baseline (untreated), roads provides a means to track effectiveness of the controls over time.

Table 13.2.1-3. NONINDUSTRIAL PAVED ROAD SAMPLING DATA[a]

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Billings	ND	Rural	04/78	50	0.6	18.5	3.4	
MT	Billings	Yellowstone	Residential	04/78	115	0.5	14.3	3.5	
MT	Missoula	Bancroft	Residential	04/78	4000	8.4	33.9	24.9	
MT	Butte	1st St	Residential	04/78	679	24.6	10.6	232.4	
MT	Butte	N Park Pl	Residential	04/78	60	103.7	7	1480.8	
MT	Billings	Grand Ave	Collector	04/78	6453	1.6	19.1	13.05	2 samples, range: 1.0 - 2.2
MT	Billings	4th Ave E	Collector	04/78	3328	7.7	7.7	99.5	
MT	Missoula	6th St	Collector	04/78	3655	26	62.9	6	
MT	Butte	Harrison	Arterial	04/78	22849	1.9	5	37.3	
MT	Missoula	Highway 93	Arterial	04/78	18870	1.9	55.9	3.3	
MT	Butte	Montana	Arterial	04/78	13529	0.8	6.6	11.9	
MT	East Helena	Thurman	Residential	04/83	140	13.1	4.3	305.2	
MT	East Helena	1st St	Local	04/83	780	4	13.6	29	
MT	East Helena	Montana	Collector	04/83	2700	8.2	9.4	86.6	
MT	East Helena	Main St	Collector	04/83	1360	4.7	8.4	55.3	
MT	Libby	6th	Local	03/88	1310	ND	14.8	ND	
MT	Libby	5th	Local	03/88	331	ND	16.5	ND	
MT	Libby	Champion Int So gate	Collector	03/88	800	ND	27.5	ND	
MT	Libby	Mineral Ave	Collector	03/88	5900	7	16	43.5	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Libby	Main Ave btwn 6th &	Collector	03/88	536	61	20.4	299.2	
MT	Libby	California	Collector	03/88	4500	ND	12.1	ND	
MT	Libby	US 2	Arterial	03/88	10850	ND	12.3	ND	
MT	Butte	Garfield Ave	Residential	04/88	562	2.1	10.9	19.3	
MT	Butte	Continental Dr	Arterial	04/88	5272	0.9	10.1	8.8	
MT	Butte	Garfield Ave	Residential	06/89	562	1	8.7	11.2	
MT	Butte	So Park Ave	Residential	06/89	60	2.8	10.9	25.5	
MT	Butte	Continental Dr	Arterial	06/89	5272	7.2	3.6	197.6	
MT	East Helena	Morton St	Local	08/89	250	1.7	6.8	24.6	
MT	East Helena	Main St	Collector	08/89	2316	0.7	4.1	17	
MT	East Helena	US 12	Arterial	08/89	7900	2.1	12.5	16.5	
MT	Columbia Falls	7th St	Residential	03/90	390	ND	9.5	ND	
MT	Columbia Falls	4th St	Residential	03/90	400	18.8	14.3	131.5	
MT	Columbia Falls	3rd Ave	Residential	03/90	50	ND	14.3	ND	
MT	Columbia Falls	4th Ave	Residential	03/90	1720	ND	5.4	ND	
MT	Columbia Falls	CF Forest	Local	03/90	240	ND	16.3	ND	
MT	Columbia Falls	12th Ave	Collector	03/90	1510	ND	8.8	ND	
MT	Columbia Falls	3rd St	Collector	03/90	1945	ND	7	ND	
MT	Columbia Falls	Nucleus	Collector	03/90	4730	15.4	10	153.9	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Columbia Falls	Plum Creek	Collector	03/90	316	ND	6.2	ND	
MT	Columbia Falls	6th Ave	Collector	03/90	1764	ND	4.2	ND	
MT	Columbia Falls	US 2	Arterial	03/90	13110	2.7	18.7	14.6	
MT	East Helena	Morton	Residential	07/90	250	1.6	17	9.3	
MT	East Helena	Main St	Collector	07/90	2316	5.6	10.6	52.5	
MT	East Helena	US 12	Arterial	07/90	7900	3.2	15.4	20.9	
MT	Columbia Falls	4th Ave	Local	08/90	400	1.5	4	37.7	
MT	Libby	Main Ave 4th &	Collector	08/90	530	2.4	17.9	13.2	
MT	Columbia Falls	Nucleus	Collector	08/90	5730	0.8	5.3	16	
MT	Columbia Falls	US 2	Arterial	08/90	13039	0.2	7	2.9	
MT	East Helena	Morton	Local	10/90	250	3.4	10.2	33.6	
MT	East Helena	Main	Collector	10/90	2316	4.5	5.6	81.3	
MT	East Helena	US 12	Arterial	10/90	7900	0.6	13.9	4.3	
MT	Columbia Falls	Nucleus	Collector	11/06/90	5670	5.2	13.5	38	
MT	Columbia Falls	US 2	Arterial	11/06/90	15890	1.7	24.1	7.2	
MT	Libby	US 2	Arterial	12/08/90	10000	21.5	9.6	223.9	
MT	Libby	Main Ave 4th &	Collector	12/09/90	530	13.6	27.1	50.3	
MT	Butte	Texas	Collector	12/13/90	3070	1	15.4	6.4	
MT	East Helena	King	Local	01/91	75	1	3.4	30.6	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	East Helena	Prickly Pear	Local	01/91	425	12	1.8	666.5	
MT	East Helena	Morton	Local	01/91	250	14.1	3.5	402.3	
MT	East Helena	Main St	Collector	01/91	2316	36.7	12.1	303.4	
MT	East Helena	US 12	Arterial	01/91	7900	0.8	14	5.6	
MT	Thompson Falls	Preston	Local	01/23/91	920	9.2	9.9	93	
MT	Thompson Falls	Highway 200	Collector	01/23/91	5000	33.3	27.2	122.2	
MT	East Helena	Seaver Park Rd	Local	02/91	150	21.6	7.1	304.7	
MT	East Helena	New Lake Helena Dr	Collector	02/91	2140	19.2	9	213.4	
MT	East Helena	Porter	Collector	02/91	850	74.4	7.7	966.8	
MT	Libby	Main Ave 4th &	Collector	02/14/91	530	33.3	18.7	178.2	
MT	Libby	US 2	Arterial	02/17/91	10000	69.3	21	330.3	
MT	Butte	Texas	Collector	02/21/91	3070	1.2	11	10.9	
MT	Butte	Harrison	Arterial	02/21/91	22849	2.9	7.9	36.6	
MT	Kalispell	3rd btwn Main & 1st	Collector	02/24/91	2653	30.5	24.8	122.9	
MT	Kalispell	Main	Arterial	02/24/91	14730	17.4	20.4	85.2	
MT	Thompson Falls	Preston	Local	02/25/91	920	35.7	17.9	199.6	
MT	Thompson Falls	Highway 200	Collector	02/25/91	5000	66.8	17.8	375.3	
MT	Helena	Montana	Arterial	03/91	21900	15.4	6.2	248.3	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Kalispell	3rd btwn Main & 1st	Collector	03/09/91	2653	39.1	29.1	134.5	
MT	Columbia Falls	Nucleus	Collector	03/91	5670	30.1	17	174.6	2 samples, range: 0.8 - 0.8
MT	Kalispell	Main	Arterial	03/09/91	14730	17.6	24.7	71.4	
MT	Thompson Falls	Preston	Local	03/91	920	4.4	8.3	51	2 samples, range: 2.8 - 5.9
MT	Thompson Falls	Highway 200	Collector	03/91	5000	4.3	15.5	28.9	2 samples, range: 1.0 - 7.5
MT	Libby	Main Ave 4th &	Collector	03/91	530	14.8	33.1	44.9	2 samples, range: 13.5 - 16.1
MT	Libby	US 2	Arterial	03/91	11963	20	19.5	111.9	3 samples, range: 11.4 - 32.4
MT	East Helena	Morton	Local	04/91	250	4.3	8.8	48.7	
MT	East Helena	US 12	Arterial	04/91	7900	0.5	8.7	5.7	
MT	Thompson Falls	Preston	Local	04/91	920	1.2	15.7	6.3	4 samples, range: 0.3 - 4.0
MT	Thompson Falls	Highway 200	Collector	04/04/91	5000	2	13.4	14.7	2 samples, range: 1.1 - 2.2
MT	Libby	Main Ave 4th &	Collector	04/91	530	3.5	44	7.8	2 samples, range: 2.5 - 4.4
MT	Libby	US 2	Arterial	04/91	12945	11.8	20.5	57.2	4 samples, range: 1.2 - 22.9
MT	Kalispell	3rd btwn Main & 1st	Collector	04/14/91	2653	15.1	37.1	40.9	
MT	Columbia Falls	Nucleus	Collector	04/91	5670	9	19.8	47.6	
MT	Kalispell	Main	Arterial	04/14/91	14730	13	44.5	29.4	
MT	Columbia Falls	Nucleus	Collector	05/91	5670	2.4	17.5	15.9	4 samples, range: 1.3 - 3.8
MT	Columbia Falls	US 2	Arterial	05/91	14712	5.5	20.7	24.8	5 samples, range: 1.5 - 14.2
MT	Libby	Main Ave 4th &	Collector	05/19/91	530	1.7	31	5.7	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Libby	Main Ave 4th &	Collector	06/27/91	530	1.7	24.3	7.1	
MT	Libby	US 2	Arterial	06/27/91	10000	3.8	12.6	30.6	
MT	East Helena	Morton	Local	07/91	250	1.7	11.4	15.3	
MT	East Helena	Main	Collector	07/91	2316	8.8	11	79.7	
MT	Thompson Falls	Preston	Local	07/09/91	920	10.9	11	98.7	
MT	Thompson Falls	Highway 200	Collector	07/09/91	5000	2.1	8.1	25.9	
MT	Helena	Montana	Arterial	07/17/91	21900	0.9	4.7	19.4	
MT	Butte	Texas	Collector	07/26/91	3070	2.5	28.2	8.9	
MT	Butte	Harrison	Arterial	07/26/91	22849	1.6	28.2	5.8	
MT	Kalispell	3rd btwn Main & 1st	Collector	08/03/91	2653	5.8	23	25.3	
MT	Kalispell	Main	Arterial	08/03/91	14730	4	21	19.3	
MT	Columbia Falls	US 2	Arterial	08/11/91	15890	0.1	5.6	2.3	
MT	Missoula	Russel btwn 4th & 5th	Road	08/30/91	5270	1.6	8.3	19.3	
MT	East Helena	US 12	Arterial	08/30/91	7900	7	20.5	34.3	
MT	Butte	Texas	Collector	10/03/91	3070	1	17.7	5.4	
MT	Butte	Harrison	Arterial	10/03/91	22849	2.1	23.1	9.1	
MT	Kalispell	3rd btwn Main & 1st	Collector	10/06/91	2653	10	31.3	31.9	
MT	Kalispell	Main	Arterial	10/06/91	14730	4.3	27.7	15.7	
MT	East Helena	Morton	Local	10/16/91	250	1.8	31	5.9	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m²)	Silt Content (%)	Total Loading (g/m²)	Comments
MT	East Helena	Main St	Collector	10/16/91	2316	1.6	20.5	7.7	
MT	East Helena	US 12	Arterial	10/16/91	7900	1	6.7	14.9	
MT	Columbia Falls	Nucleus	Collector	10/20/91	5670	1.9	13.9	13.3	
MT	Columbia Falls	US 2	Arterial	10/20/91	15890	1.2	11.3	10.2	
MT	Kalispell	3rd btwn Main & 1st	Collector	11/06/91	2653	2.2	12.3	17.8	
MT	Kalispell	Main	Arterial	11/28/91	14730	2.7	8.6	30.8	
MT	Thompson Falls	Preston	Local	12/17/91	920	4	18.1	22.5	
MT	Thompson Falls	Highway 200	Collector	12/17/91	5000	1.5	13.2	11.6	
MT	Butte	Texas	Collector	02/02/92	3070	19.1	11.6	164.5	
MT	Butte	Harrison	Arterial	02/02/92	22849	8.3	12	69.3	
MT	East Helena	Morton	Local	02/03/92	250	78.3	9.5	824.7	
MT	Libby	W 4th St	Local	02/03/92	350	36.3	56.3	64.5	
MT	Libby	Main Ave 4th &	Collector	02/03/92	530	10.7	49.9	21.4	
MT	East Helena	Main St	Collector	02/03/92	2316	57.9	14.8	391	
MT	Columbia Falls	Nucleus	Collector	02/03/92	5670	29.2	20.1	145.4	
MT	Columbia Falls	US 2	Arterial	02/92	12945	51.3	32.2	143.1	2 samples, range: 13.0 - 89.5
MT	East Helena	US 12	Arterial	02/03/92	7900	2.9	14.3	20.7	
MT	Thompson Falls	Preston	Local	02/22/92	920	0.5	18	2.6	
MT	Thompson Falls	Highway 200	Collector	02/22/92	5000	1.2	14.6	8.1	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Kalispell	3rd btwn Main & 1st	Collector	03/15/92	2653	81.1	37.3	217.3	
MT	Kalispell	Main	Arterial	03/15/92	14730	16.5	32.1	51.3	
MT	Thompson Falls	Preston	Local	04/92	920	0.43	14.9	3.2	
MT	Thompson Falls	Highway 200	Collector	04/92	5000	0.8	18.2	4.7	3 samples, range: 0.4 - 1.0
MT	Kalispell	3rd btwn 2nd & 3rd	Local	04/26/92	450	20.9	45.8	45.5	
MT	Kalispell	3rd btwn Main & 1st	Collector	04/26/92	2653	19.2	50.9	37.7	
MT	Kalispell	Main	Arterial	04/26/92	14730	10.7	33.5	32.1	
MT	Kalispell	3rd btwn 2nd & 3rd	Local	05/92	450	8.3	35.6	23.5	3 samples, range: 6.6 - 10.3
MT	Kalispell	3rd btwn Main & 1st	Collector	05/92	2653	8.5	32.4	25.8	3 samples, range: 6.3 - 11.4
MT	Kalispell	Main	Arterial	05/92	14730	5.1	23.6	21.7	3 samples, range: 3.8 - 5.9
MT	Libby	W 4th St	Local	05/11/92	350	13.4	56.5	23.7	
MT	Libby	Main Ave 4th &	Collector	05/11/92	530	5.6	58.9	9.4	
MT	Libby	US 2	Arterial	05/92	12945	10.4	25.6	29.4	
MT	East Helena	Morton	Local	05/15/92	250	6.9	6.7	103	
MT	East Helena	Main St	Collector	05/15/92	2316	6.4	10.2	62.8	
MT	East Helena	US 12	Arterial	05/15/92	7900	1.2	6.9	17	
MT	Columbia Falls	Nucleus	Collector	05/25/92	5670	1	21.7	4.5	
MT	Missoula	Inez btwn 4th & 5th	Local	06/04/92	500	1	17.4	5.6	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
MT	Missoula	Russel btwn 3rd & 4th	Collector	06/04/92	5270	15.2	14	108.4	
MT	Missoula	3rd btwn Prince & In	Arterial	06/04/92	12000	2	13.1	15.7	
CO	Denver	E. Colfax	Princ. Arterial[b]	03/89	1994[c]	0.21	2	19.9	4 samples, range: 0.04 - 0.47
CO	Denver	E. Colfax	Princ. Arterial[b]	04/89	2228[c]	0.73	1.7	106.7	18 samples, range: 0.08 - 1.76
CO	Denver	York St	Princ. Arterial[b]	04/89	780[c]	0.86	1.2	74.8	2 samples, range: 0.83 - 0.89
CO	Denver	E. Belleview	Princ. Arterial[b]	04/89	ND	0.07	4.2	2	3 samples, range: 0.03 - 0.09
CO	Denver	I-225	Expressway[b]	04/89	4731[c]	0.02	3.6	0.4	3 samples, range: 0.01 - 0.02
CO	Denver	W. Evans	Princ. Arterial[b]	05/89	1905[c]	0.76	1.9	74	11 samples, range: 0.03 - 2.24
CO	Denver	W. Evans	Princ. Arterial[b]	06/89	1655[c]	0.71	1.2	66.1	12 samples, range: 0.07 - 3.34
CO	Denver	E. Louisiana	Minor Arterial[b]	06/89	515[c]	0.14	4.66	3.5	5 samples, range: 0.08 - 0.24
CO	Denver	E. Louisiana	Minor Arterial[b]	01/90	ND	1.44[d]	ND	ND	6 samples, range: 0.12 - 2.8
CO	Denver	E. Jewell Ave	Collector[b]	01/24/90	ND	2.24[d]	ND	ND	
CO	Denver	State Highway 36	Expressway[b]	01/30/90	ND	0.56[d]	ND	ND	2 samples, range: 0.56 - 0.56

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
CO	Denver	State Highway 36	Expressway[b]	02/01/90	ND	1.92[d]	ND	ND	4 samples, range: 1.92 - 1.92
CO	Denver	W. Evans Ave	Princ. Arterial[b]	02/03/90	ND	1.64[d]	ND	ND	2 samples, range: 1.64 - 1.64
CO	Denver	E. Mexico St	Local[b]	02/07/90	ND	2.58[d]	ND	ND	3 samples, range: 2.58 - 2.58
CO	Denver	E. Colfax Ave	Princ. Arterial[b]	02/90	ND	0.09[d]	ND	ND	16 samples, range: 0.02 - 0.17
CO	Denver	State Highway 36	Expressway[b]	03/90	ND	ND	ND	ND	7 samples
CO	Denver	E. Louisiana Ave	Minor Arterial[b]	03/10/90	ND	ND	ND	ND	3 samples
CO	Denver	W. Evans Ave	Princ. Arterial[b]	03/90	ND	1.27[d]	ND	ND	5 samples, range: 0.07 - 3.38
CO	Denver	W. Colfax Ave	Princ. Arterial[b]	03/90	ND	0.41[d]	ND	ND	21 samples, range: 0.04 - 2.61
CO	Denver	Parker Rd	Local[b]	04/90	ND	0.05[d]	ND	ND	6 samples, range: 0.01 - 0.11
CO	Denver	W. Byron Pl	Princ. Arterial[b]	04/90	ND	0.3[d]	ND	ND	6 samples, range: 0.21 - 0.35
CO	Denver	E. Colfax Ave	Princ. Arterial[b]	04/18/90	ND	0.21[d]	ND	ND	
UT	Salt Lake County	700 East	Arterial	—[e]	42340	0.137	11.5	1.187	4 samples, range: 0.107 - 0.162

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
UT	Salt Lake County	State St	Collector	—[e]	27140	0.288	17	1.692	4 samples, range: 0.212 - 0.357
UT	Salt Lake County	I-80	Freeway	—[e]	77040	0.023	21.4	0.1	5 samples, range: 0.011 - 0.034
UT	Salt Lake County	I-15	Freeway	—[e]	146180	0.096	23.5	0.419	6 samples, range: 0.078 - 0.126
UT	Salt Lake County	400 East	Local	—[e]	5000	1.967	4.07	46.043	14 samples, range: 0.177 - 5.772
NV	Las Vegas	Lake Mead	Major	07/15/87	ND	0.81	12.4	6.51	
NV	Las Vegas	Perliter	Local	07/15/87	ND	2.23	31.2	7.14	
NV	Las Vegas	Bruce	Collector	07/15/87	ND	1.64	26.1	6.3	
NV	Las Vegas	Stewart	Major	09/29/87	ND	0.38	24	1.63	3 samples, range: 0.24 - 0.46
NV	Las Vegas	Ambler	Local	09/29/87	ND	1.38	23	6.32	3 samples, range: 0.64 - 2.00
NV	Las Vegas	28th St	Collector	09/29/87	ND	0.52	15.8	3.4	3 samples, range: 0.51 - 0.54
NV	Las Vegas	Lake Mead	Major	10/07/87	ND	0.19	14.9	1.26	2 samples, range: 0.17 - 0.20
NV	Las Vegas	Perliter	Local	10/07/87	ND	1.5	31.9	4.76	2 samples, range: 1.48 - 1.52
NV	Las Vegas	Bruce	Collector	10/07/87	ND	0.9	24.1	3.74	2 samples, range: 0.76 - 1.03
AZ	Phoenix	Broadway	Arterial	—[f]	ND	0.127	12.2	1.071	
AZ	Phoenix	South Central	Arterial	—[f]	ND	0.085	5	1.726	
AZ	Phoenix	Indian School & 28th	Arterial	—[f]	ND	0.035	3.1	1.021	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
AZ	Glendale	43rd & Vista	Arterial	—[f]	ND	0.042	3.9	1.049	
AZ	Glendale	59th & Peoria	Arterial	—[f]	ND	0.099	8.2	1.183	
AZ	Mesa	Mesa Drive	Arterial	—[f]	ND	0.099	8.9	1.085	
AZ	Mesa	E. McKellips & Olive	Arterial	—[f]	ND	0.014	17	0.092	
AZ	Phoenix	17th & Highland	Collector	—[f]	ND	0.028	13.4	0.232	
AZ	Mesa	3rd & Miller	Collector	—[f]	ND	0.07	11.8	0.627	
AZ	Phoenix	Avalon & 25th	Collector	—[f]	ND	0.528	11.1	4.79	
AZ	Phoenix	Apache	Collector	—[f]	ND	0.282	6.4	4.367	
AZ	Phoenix	N. 28th St & E. Glenrosa	Collector	—[f]	ND	0.035	2.3	1.479	
AZ	Pima County	6th Ave	Collector	—[f]	ND	1.282	6.417	19.961	
AZ	Pima County	Speedway Blvd	Arterial	—[f]	ND	0.401	8.117	4.937	
AZ	Pima County	22nd St	Arterial	—[f]	ND	0.028	16.529	0.176	
AZ	Pima County	Amklam Rd	Collector	—[f]	ND	0.014	5.506	0.197	
AZ	Pima County	Fort Lowel Rd	Arterial	—[f]	ND	0.113	3.509	3.268	
AZ	Pima County	Oracle Rd	Arterial	—[f]	ND	0.014	1.556	0.725	
AZ	Pima County	Inn Rd	Arterial	—[f]	ND	0.021	18.756	0.127	
AZ	Pima County	Orange Grove	Arterial	—[f]	ND	0.162	21.989	0.725	
AZ	Pima County	La Canada	Arterial	—[f]	ND	0.106	3.975	2.571	

Table 13.2.1-3 (cont.).

ST	City	Sampling Location, Street, Road Name	Class[a]	Date	ADT[a]	Silt Loading (g/m^2)	Silt Content (%)	Total Loading (g/m^2)	Comments
KS	Kansas City	7th	Arterial	02/80	ND	0.29	6.8	4.2	3 samples, range: 0.15 - 0.46
MO	Kansas City	Volker	Arterial	02/80	ND	0.67	20.1	3.5	3 samples, range: 0.43 -1.00
MO	Kansas City	Rockhill	Arterial	02/80	ND	0.68	21.7	3.3	
KS	Tonganoxie	4th	Collector	03/80	ND	2.5	14.5	17.1	
KS	Kansas City	7th	Arterial	03/80	ND	0.29	12.2	2.4	
MO	St. Louis	I-44	Expressway	05/80	ND	0.02	ND	ND	4 samples
MO	St. Louis	Kingshighway	Collector	05/80	ND	0.08	10.9	0.7	3 samples, range: 0.05 - 0.11
IL	Granite City	24th	Arterial	05/80	ND	0.78	6.4	12.3	2 samples, range: 0.7 - 0.83
IL	Granite City	Benton	Collector	05/80	ND	0.93	8.6	10.8	
MN	Duluth	US 53 (northbound lanes)	Highway	03/19/92	5000	0.23	28	1.94	8 samples, range: 0.04 - 0.77
MN	Duluth	US 53 (southbound lanes)	Highway	02/26/92	5000	0.24	13.4	2.3	5 samples, range: 0.05 - 0.37

[a] References 7,13-20. Classifications and values as given in reference, except as noted. ADT = average daily traffic. ND = no data.

[b] Reference 16.

[c] Value given is the hourly traffic rate observed during testing. ADT values not reported.

[d] Samples are said to wet sieved. Wet sieving results are not directly comparable to those for the dry sieving described in AP-42 Appendix C.2.

[e] No specific date given for sampling. Samples are said to be "post storm".

[f] No specific date given for sampling.

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13.2.2 Unpaved Roads

13.2.2.1 General

Dust plumes trailing behind vehicles traveling on unpaved roads are a familiar sight in rural areas of the United States. When a vehicle travels an unpaved road, the force of the wheels on the road surface causes pulverization of surface material. Particles are lifted and dropped from the rolling wheels, and the road surface is exposed to strong air currents in turbulent shear with the surface. The turbulent wake behind the vehicle continues to act on the road surface after the vehicle has passed.

13.2.2.2 Emissions Calculation And Correction Parameters

The quantity of dust emissions from a given segment of unpaved road varies linearly with the volume of traffic. Field investigations also have shown that emissions depend on correction parameters (average vehicle speed, average vehicle weight, average number of wheels per vehicle, road surface texture, and road surface moisture) that characterize the condition of a particular road and the associated vehicle traffic.[1-4]

Dust emissions from unpaved roads have been found to vary in direct proportion to the fraction of silt (particles smaller than 75 micrometers [μm] in diameter) in the road surface materials.[1] The silt fraction is determined by measuring the proportion of loose dry surface dust that passes a 200-mesh screen, using the ASTM-C-136 method. Table 13.2.2-1 summarizes measured silt values for industrial and rural unpaved roads.

Since the silt content of a rural dirt road will vary with location, it should be measured for use in projecting emissions. As a conservative approximation, the silt content of the parent soil in the area can be used. Tests, however, show that road silt content is normally lower than in the surrounding parent soil, because the fines are continually removed by the vehicle traffic, leaving a higher percentage of coarse particles.

Unpaved roads have a hard, generally nonporous surface that usually dries quickly after a rainfall. The temporary reduction in emissions caused by precipitation may be accounted for by not considering emissions on "wet" days (more than 0.254 millimeters [mm] [0.01 inches (in.)] of precipitation).

The following empirical expression may be used to estimate the quantity of size-specific particulate emissions from an unpaved road, per vehicle kilometer traveled (VKT) or vehicle mile traveled (VMT):

$$E = k(1.7) \left[\frac{s}{12}\right] \left[\frac{S}{48}\right] \left[\frac{W}{2.7}\right]^{0.7} \left[\frac{w}{4}\right]^{0.5} \left[\frac{365-p}{365}\right] \quad \text{(kilograms [kg]/VKT)}$$

$$E = k(5.9) \left[\frac{s}{12}\right] \left[\frac{S}{30}\right] \left[\frac{W}{3}\right]^{0.7} \left[\frac{w}{4}\right]^{0.5} \left[\frac{365-p}{365}\right] \quad \text{(pounds [lb]/VMT)} \qquad (1)$$

Table 13.2.2-1. TYPICAL SILT CONTENT VALUES OF SURFACE MATERIAL ON INDUSTRIAL AND RURAL UNPAVED ROADS[a]

Industry	Road Use Or Surface Material	Plant Sites	No. Of Samples	Silt Content (%)	
				Range	Mean
Copper smelting	Plant road	1	3	16 - 19	17
Iron and steel production	Plant road	19	135	0.2 - 19	6.0
Sand and gravel processing	Plant road	1	3	4.1 - 6.0	4.8
Stone quarrying and processing	Plant road	2	10	2.4 - 16	10
	Haul road	1	10	5.0 - 15	9.6
Taconite mining and processing	Service road	1	8	2.4 - 7.1	4.3
	Haul road	1	12	3.9 - 9.7	5.8
Western surface coal mining	Haul road	3	21	2.8 - 18	8.4
	Access road	2	2	4.9 - 5.3	5.1
	Scraper route	3	10	7.2 - 25	17
	Haul road (freshly graded)	2	5	18 - 29	24
Rural roads	Gravel/crushed limestone	3	9	5.0 - 13	8.9
	Dirt	7	32	1.6 - 68	12
Municipal roads	Unspecified	3	26	0.4 - 13	5.7
Municipal solid waste landfills	Disposal routes	4	20	2.2 - 21	6.4

[a] References 1,5-16.

where:

E = emission factor
k = particle size multiplier (dimensionless)
s = silt content of road surface material (%)
S = mean vehicle speed, kilometers per hour (km/hr) (miles per hour [mph])
W = mean vehicle weight, megagrams (Mg) (ton)
w = mean number of wheels
p = number of days with at least 0.254 mm (0.01 in.) of precipitation per year (see discussion below about the effect of precipitation.)

The particle size multiplier in the equation, k, varies with aerodynamic particle size range as follows:

Aerodynamic Particle Size Multiplier (k) For Equation 1					
≤30 μm[a]	≤30 μm	≤15 μm	≤10 μm	≤5 μm	≤2.5 μm
1.0	0.80	0.50	0.36	0.20	0.095

[a] Stokes diameter.

The number of wet days per year, p, for the geographical area of interest should be determined from local climatic data. Figure 13.2.2-1 gives the geographical distribution of the mean annual number of wet days per year in the United States.[17] The equation is rated "A" for dry conditions ($p = 0$) and "B" for annual or seasonal conditions ($p > 0$). The lower rating is applied because extrapolation to seasonal or annual conditions assumes that emissions occur at the estimated rate on days without measurable precipitation and, conversely, are absent on days with measurable precipitation. Clearly, natural mitigation depends not only on how much precipitation falls, but also on other factors affecting the evaporation rate, such as ambient air temperature, wind speed, and humidity. Persons in dry, arid portions of the country may wish to base p (the number of wet days) on a greater amount of precipitation than 0.254 mm (0.01 in.). In addition, Reference 18 contains procedures to estimate the emission reduction achieved by the application of water to an unpaved road surface.

The equation retains the assigned quality rating, if applied within the ranges of source conditions that were tested in developing the equation, as follows:

Ranges Of Source Conditions For Equation					
Road Silt Content (wt %)	Mean Vehicle Weight		Mean Vehicle Speed		Mean No. Of Wheels
	Mg	ton	km/hr	mph	
4.3 - 20	2.7 - 142	3 - 157	21 - 64	13 - 40	4 - 13

Moreover, to retain the quality rating of the equation when addressing a specific unpaved road, it is necessary that reliable correction parameter values be determined for the road in question. The field and laboratory procedures for determining road surface silt content are given in AP-42 Appendices C.1 and C.2. In the event that site-specific values for correction parameters cannot be obtained, the appropriate mean values from Table 13.2.2-1 may be used, but the quality rating of the equation is reduced by 1 letter.

For calculating annual average emissions, the equation is to be multiplied by annual vehicle distance traveled (VDT). Annual average values for each of the correction parameters are to be substituted for the equation. Worst-case emissions, corresponding to dry road conditions, may be calculated by setting $p = 0$ in the equation (equivalent to dropping the last term from the equation). A separate set of nonclimatic correction parameters and a higher than normal VDT value may also be justified for the worst-case average period (usually 24 hours). Similarly, in using the equation to

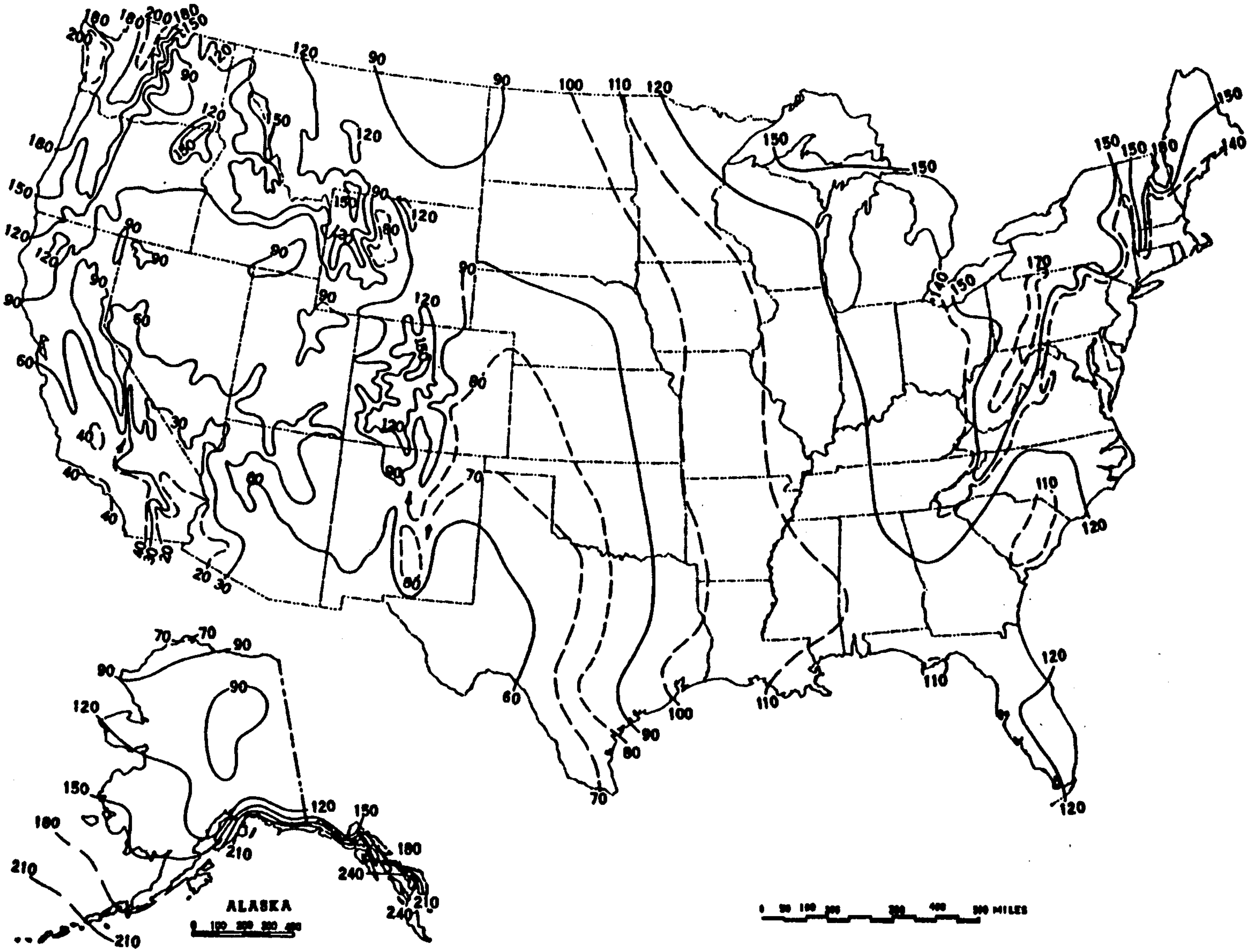

Figure 13.2.2-1. Mean number of days with 0.01 inch or more of precipitation in United States.

calculate emissions for a 91-day season of the year, replace the term (365-p)/365 with the term (91-p)/91, and set p equal to the number of wet days in the 91-day period. Use appropriate seasonal values for the nonclimatic correction parameters and for VDT.

13.2.2.3 Controls[18-21]

Common control techniques for unpaved roads are paving, surface treating with penetration chemicals, working stabilization chemicals into the roadbed, watering, and traffic control regulations. Chemical stabilizers work either by binding the surface material or by enhancing moisture retention. Paving, as a control technique, is often not economically practical. Surface chemical treatment and watering can be accomplished at moderate to low costs, but frequent treatments are required. Traffic controls, such as speed limits and traffic volume restrictions, provide moderate emission reductions, but may be difficult to enforce. The control efficiency obtained by speed reduction can be calculated using the predictive emission factor equation given above.

The control efficiencies achievable by paving can be estimated by comparing emission factors for unpaved and paved road conditions, relative to airborne particle size range of interest. The predictive emission factor equation for paved roads, given in Section 13.2.4, requires estimation of the silt loading on the traveled portion of the paved surface, which in turn depends on whether the pavement is periodically cleaned. Unless curbing is to be installed, the effects of vehicle excursion onto shoulders (berms) also must be taken into account in estimating control efficiency.

The control efficiencies afforded by the periodic use of road stabilization chemicals are much more difficult to estimate. The application parameters that determine control efficiency include dilution ratio, application intensity, mass of diluted chemical per road area, and application frequency. Other factors that affect the performance of chemical stabilizers include vehicle characteristics (e. g., traffic volume, average weight) and road characteristics (e. g., bearing strength).

Besides water, petroleum resin products historically have been the dust suppressants most widely used on industrial unpaved roads. Figure 13.2.2-2 presents a method to estimate average control efficiencies associated with petroleum resins applied to unpaved roads.[19] Several items should be noted:

1. The term "ground inventory" represents the total volume (per unit area) of petroleum resin concentrate (*not solution*) applied since the start of the dust control season.

2. Because petroleum resin products must be periodically reapplied to unpaved roads, the use of a time-averaged control efficiency value is appropriate. Figure 13.2.2-2 presents control efficiency values averaged over 2 common application intervals, 2 weeks and 1 month. Other application intervals will require interpolation.

3. Note that zero efficiency is assigned until the ground inventory reaches 0.2 liter per square meter (L/m^2) (0.05 gallon per square yard [gal/yd^2]).

As an example of the application of Figure 13.2.2-2, suppose that the equation was used to estimate an emission factor of 2.0 kg/VKT for PM-10 from a particular road. Also, suppose that, starting on May 1, the road is treated with 1 L/m^2 of a solution (1 part petroleum resin to 5 parts water) on the first of each month through September. Then, the following average controlled emission factors are found:

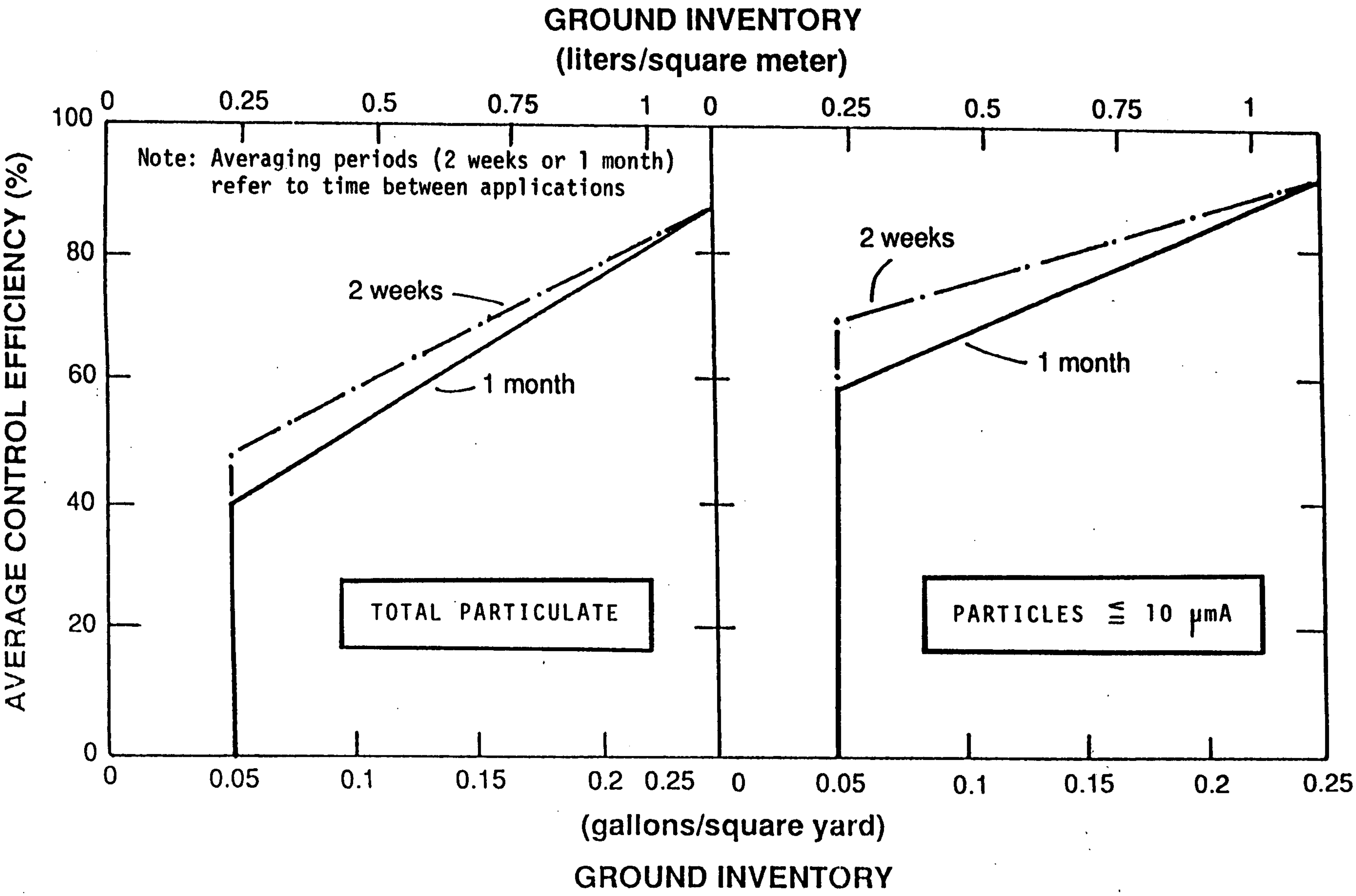

Figure 13.2.2-2. Average control efficiencies over common application intervals.

Period	Ground Inventory (L/m^2)	Average Control Efficiency[a] (%)	Average Controlled Emission Factor (kg/VKT)
May	0.17	0	2.0
June	0.33	62	0.76
July	0.50	68	0.64
August	0.67	74	0.52
September	0.83	80	0.40

[a] From Figure 13.2.2-2, ≤ 10 μm. Zero efficiency assigned if ground inventory is less than 0.2 L/m^2 (0.05 gal/yd^2).

Newer dust suppressants are successful in controlling emissions from unpaved roads. Specific test results for those chemicals, as well as for petroleum resins and watering, are provided in References 18 through 21.

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13.2.3 Heavy Construction Operations

13.2.3.1 General

Heavy construction is a source of dust emissions that may have substantial temporary impact on local air quality. Building and road construction are 2 examples of construction activities with high emissions potential. Emissions during the construction of a building or road can be associated with land clearing, drilling and blasting, ground excavation, cut and fill operations (i.e., earth moving), and construction of a particular facility itself. Dust emissions often vary substantially from day to day, depending on the level of activity, the specific operations, and the prevailing meteorological conditions. A large portion of the emissions results from equipment traffic over temporary roads at the construction site.

The temporary nature of construction differentiates it from other fugitive dust sources as to estimation and control of emissions. Construction consists of a series of different operations, each with its own duration and potential for dust generation. In other words, emissions from any single construction site can be expected (1) to have a definable beginning and an end and (2) to vary substantially over different phases of the construction process. This is in contrast to most other fugitive dust sources, where emissions are either relatively steady or follow a discernable annual cycle. Furthermore, there is often a need to estimate areawide construction emissions, without regard to the actual plans of any individual construction project. For these reasons, following are methods by which either areawide or site-specific emissions may be estimated.

13.2.3.2 Emissions And Correction Parameters

The quantity of dust emissions from construction operations is proportional to the area of land being worked and to the level of construction activity. By analogy to the parameter dependence observed for other similar fugitive dust sources,[1] one can expect emissions from heavy construction operations to be positively correlated with the silt content of the soil (that is, particles smaller than 75 micrometers [μm] in diameter), as well as with the speed and weight of the average vehicle, and to be negatively correlated with the soil moisture content.

13.2.3.3 Emission Factors

Only 1 set of field studies has been performed that attempts to relate the emissions from construction directly to an emission factor.[1-2] Based on field measurements of total suspended particulate (TSP) concentrations surrounding apartment and shopping center construction projects, the approximate emission factors for construction activity operations are:

E = 2.69 megagrams (Mg)/hectare/month of activity
E = 1.2 tons/acre/month of activity

These values are most useful for developing estimates of overall emissions from construction scattered throughout a geographical area. The value is most applicable to construction operations with: (1) medium activity level, (2) moderate silt contents, and (3) semiarid climate. Test data were not sufficient to derive the specific dependence of dust emissions on correction parameters. Because the above emission factor is referenced to TSP, use of this factor to estimate particulate matter (PM) no greater than 10 μm in aerodynamic diameter (PM-10) emissions will result in conservatively high estimates. Also, because derivation of the factor assumes that construction activity occurs 30 days per month, the above estimate is somewhat conservatively high for TSP as well.

Although the equation above represents a relatively straightforward means of preparing an areawide emission inventory, at least 2 features limit its usefulness for specific construction sites. First, the conservative nature of the emission factor may result in too high an estimate for PM-10 to be of much use for a specific site under consideration. Second, the equation provides neither information about which particular construction activities have the greatest emission potential nor guidance for developing an effective dust control plan.

For these reasons, it is strongly recommended that when emissions are to be estimated for a particular construction site, the construction process be broken down into component operations. (Note that many general contractors typically employ planning and scheduling tools, such as critical path method [CPM], that make use of different sequential operations to allocate resources.) This approach to emission estimation uses a unit or phase method to consider the more basic dust sources of vehicle travel and material handling. That is to say, the construction project is viewed as consisting of several operations, each involving traffic and material movements, and emission factors from other AP-42 sections are used to generate estimates. Table 13.2.3-1 displays the dust sources involved with construction, along with the recommended emission factors.[3]

In addition to the on-site activities shown in Table 13.2.3-1, substantial emissions are possible because of material tracked out from the site and deposited on adjacent paved streets. Because all traffic passing the site (i. e., not just that associated with the construction) can resuspend the deposited material, this "secondary" source of emissions may be far more important than all the dust sources actually within the construction site. Furthermore, this secondary source will be present during all construction operations. Persons developing construction site emission estimates must consider the potential for increased adjacent emissions from off-site paved roadways (see Section 13.2.1, "Paved Roads"). High wind events also can lead to emissions from cleared land and material stockpiles. Section 13.2.5, "Industrial Wind Erosion", presents an estimation methodology that can be used for such sources at construction sites.

13.2.3.4 Control Measures[4]

Because of the relatively short-term nature of construction activities, some control measures are more cost effective than others. Wet suppression and wind speed reduction are 2 common methods used to control open dust sources at construction sites, because a source of water and material for wind barriers tend to be readily available on a construction site. However, several other forms of dust control are available.

Table 13.2.3-2 displays each of the preferred control measures, by dust source.[3-4] Because most of the controls listed in the table modify independent variables in the emission factor models, the effectiveness can be calculated by comparing controlled and uncontrolled emission estimates from Table 13.2.3-1. Additional guidance on controls is provided in the AP-42 sections from which the recommended emission factors were taken, as well as in other documents, such as Reference 4.

Table 13.2.3-1. RECOMMENDED EMISSION FACTORS FOR CONSTRUCTION OPERATIONS[a]

Construction Phase	Dust-generating Activities	Recommended Emission Factor	Comments	Rating Adjustment[b]
I. Demolition and debris removal	1. Demolition of buildings or other (natural) obstacles such as trees, boulders, etc.			
	a. Mechanical dismemberment ("headache ball") of existing structures	NA		—
	b. Implosion of existing structures	NA		—
	c. Drilling and blasting of soil	Drilling factor in Table 11.9-4		-1
		Blasting factor NA	Blasting factor in Tables 11.9-1 and 11.9-2 not considered appropriate for general construction activities	NA
	d. General land clearing	Dozer equation (overburden) in Tables 11.9-1 and 11.9-2		-1/-2[c]
	2. Loading of debris into trucks	Material handling factor in Section 13.2.2		-0/-1[c]
	3. Truck transport of debris	Unpaved road emission factor in Section 13.2.2, or paved road emission factor in Section 13.2.1		-0/-1[c]
	4. Truck unloading of debris	Material handling factor in Section 13.2.2	May occur offsite	-0/-1[c]

Table 13.2.3-1 (cont.).

Construction Phase	Dust-generating Activities	Recommended Emission Factor	Comments	Rating Adjustment^b
II. Site Preparation (earth moving)	1. Bulldozing	Dozer equation (overburden) in Tables 11.9-1 and 11.9-2		-1/-2^c
	2. Scrapers unloading topsoil	Scraper unloading factor in Table 11.9-4		-1
	3. Scrapers in travel	Scraper (travel mode) expression in Tables 11.9-1 and 11.9-2		-0/-1^c
	4. Scrapers removing topsoil	5.7 kg/vehicle kilometer traveled (VKT) (20.2 lb/vehicle mile traveled [VMT])		E^d
	5. Loading of excavated material into trucks	Material handling factor in Section 13.2.2		-0/-1^c
	6. Truck dumping of fill material, road base, or other materials	Material handling factor in Section 13.2.2	May occur offsite	-0/-1^c
	7. Compacting	Dozer equation in Tables 11.9-1 and 11.9-2	Emission factor downgraded because of differences in operating equipment	-1/-2^c
	8. Motor grading	Grading equation in Tables 11.9-1 and 11.9-2		-1/-2^c

Table 13.2.3-1 (cont.).

Construction Phase	Dust-generating Activities	Recommended Emission Factor	Comments	Rating Adjustment[b]
III. General Construction	1. Vehicular traffic	Unpaved road emission factor in Section 13.2.2, or paved road emission factor in Section 13.2.1		-0/-1[c] -0/-1[c]
	2. Portable plants			
	a. Crushing	Factors for similar material/operations in Chapter 11 of this document		-1/-2[c]
	b. Screening	Factors for similar material/operations in Chapter 11 of this document		-1/-2[c]
	c. Material transfers	Material handling factor in Section 13.2.2		-0/-1[c]
	3. Other operations	Factors for similar material/operations in Chapter 11 of this document		—

[a] NA = not applicable.

[b] Refers to how many additional letters the emission factor should be downrated (beyond the guidance given in the other sections of AP-42) for application to construction activities. For example, "-2" means that an A-rated factor should be considered of C quality in estimating construction emissions. All emission factors assumed to have site-specific input values; otherwise, additional downgrading of one letter should be employed. Note that no rating can be lower than E.

[c] First value for cases with independent variables within range given in AP-42 section; second value for cases with at least 1 variable outside the range.

[d] Rating for emission factor given. Reference 5.

[e] In the event that individual operations cannot be identified, one may very conservatively overestimate PM-10 emissions by using Equation 1.

Table 13.2.3-2. CONTROL OPTIONS FOR GENERAL CONSTRUCTION OPEN SOURCES OF PM-10

Emission Source	Recommended Control Method(s)
Debris handling	Wind speed reduction Wet suppression[a]
Truck transport[b]	Wet suppression Paving Chemical stabilization[c]
Bulldozers	Wet suppression[d]
Pan scrapers	Wet suppression of travel routes
Cut/fill material handling	Wind speed reduction Wet suppression
Cut/fill haulage	Wet suppression Paving Chemical stabilization
General construction	Wind speed reduction Wet suppression Early paving of permanent roads

[a] Dust control plans should contain precautions against watering programs that confound trackout problems.

[b] Loads could be covered to avoid loss of material in transport, especially if material is transported offsite.

[c] Chemical stabilization usually cost-effective for relatively long-term or semipermanent unpaved roads.

[d] Excavated materials may already be moist and not require additional wetting. Furthermore, most soils are associated with an "optimum moisture" for compaction.

References For Section 13.2.3

1. C. Cowherd, Jr., *et al.*, *Development Of Emissions Factors For Fugitive Dust Sources*, EPA-450/3-74-03, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

2. G. A. Jutze, *et al.*, *Investigation Of Fugitive Dust Sources Emissions And Control*, EPA-450/3-74-036a, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

3. *Background Documentation For AP-42 Section 11.2.4, Heavy Construction Operations*, EPA Contract No. 69-D0-0123, Midwest Research Institute, Kansas City, MO, April 1993.

4. C. Cowherd, *et al.*, *Control Of Open Fugitive Dust Sources*, EPA-450/3-88-008, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1988.

5. M. A. Grelinger, *et al.*, *Gap Filling PM-10 Emission Factors For Open Area Fugitive Dust Sources*, EPA-450/4-88-003, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1988.

13.2.4 Aggregate Handling And Storage Piles

13.2.4.1 General

Inherent in operations that use minerals in aggregate form is the maintenance of outdoor storage piles. Storage piles are usually left uncovered, partially because of the need for frequent material transfer into or out of storage.

Dust emissions occur at several points in the storage cycle, such as material loading onto the pile, disturbances by strong wind currents, and loadout from the pile. The movement of trucks and loading equipment in the storage pile area is also a substantial source of dust.

13.2.4.2 Emissions And Correction Parameters

The quantity of dust emissions from aggregate storage operations varies with the volume of aggregate passing through the storage cycle. Emissions also depend on 3 parameters of the condition of a particular storage pile: age of the pile, moisture content, and proportion of aggregate fines.

When freshly processed aggregate is loaded onto a storage pile, the potential for dust emissions is at a maximum. Fines are easily disaggregated and released to the atmosphere upon exposure to air currents, either from aggregate transfer itself or from high winds. As the aggregate pile weathers, however, potential for dust emissions is greatly reduced. Moisture causes aggregation and cementation of fines to the surfaces of larger particles. Any significant rainfall soaks the interior of the pile, and then the drying process is very slow.

Silt (particles equal to or less than 75 micrometers [μm] in diameter) content is determined by measuring the portion of dry aggregate material that passes through a 200-mesh screen, using ASTM-C-136 method.[1] Table 13.2.4-1 summarizes measured silt and moisture values for industrial aggregate materials.

13.2.4.3 Predictive Emission Factor Equations

Total dust emissions from aggregate storage piles result from several distinct source activities within the storage cycle:

1. Loading of aggregate onto storage piles (batch or continuous drop operations).
2. Equipment traffic in storage area.
3. Wind erosion of pile surfaces and ground areas around piles.
4. Loadout of aggregate for shipment or for return to the process stream (batch or continuous drop operations).

Either adding aggregate material to a storage pile or removing it usually involves dropping the material onto a receiving surface. Truck dumping on the pile or loading out from the pile to a truck with a front-end loader are examples of batch drop operations. Adding material to the pile by a conveyor stacker is an example of a continuous drop operation.

Table 13.2.4-1. TYPICAL SILT AND MOISTURE CONTENTS OF MATERIALS AT VARIOUS INDUSTRIES[a]

Industry	No. Of Facilities	Material	Silt Content (%)			Moisture Content (%)		
			No. Of Samples	Range	Mean	No. Of Samples	Range	Mean
Iron and steel production	9	Pellet ore	13	1.3 - 13	4.3	11	0.64 - 4.0	2.2
		Lump ore	9	2.8 - 19	9.5	6	1.6 - 8.0	5.4
		Coal	12	2.0 - 7.7	4.6	11	2.8 - 11	4.8
		Slag	3	3.0 - 7.3	5.3	3	0.25 - 2.0	0.92
		Flue dust	3	2.7 - 23	13	1	—	7
		Coke breeze	2	4.4 - 5.4	4.9	2	6.4 - 9.2	7.8
		Blended ore	1	—	15	1	—	6.6
		Sinter	1	—	0.7	0	—	—
		Limestone	3	0.4 - 2.3	1.0	2	ND	0.2
Stone quarrying and processing	2	Crushed limestone	2	1.3 - 1.9	1.6	2	0.3 - 1.1	0.7
		Various limestone products	8	0.8 - 14	3.9	8	0.46 - 5.0	2.1
Taconite mining and processing	1	Pellets	9	2.2 - 5.4	3.4	7	0.05 - 2.0	0.9
		Tailings	2	ND	11	1	—	0.4
Western surface coal mining	4	Coal	15	3.4 - 16	6.2	7	2.8 - 20	6.9
		Overburden	15	3.8 - 15	7.5	0	—	—
		Exposed ground	3	5.1 - 21	15	3	0.8 - 6.4	3.4
Coal-fired power plant	1	Coal (as received)	60	0.6 - 4.8	2.2	59	2.7 - 7.4	4.5
Municipal solid waste landfills	4	Sand	1	—	2.6	1	—	7.4
		Slag	2	3.0 - 4.7	3.8	2	2.3 - 4.9	3.6
		Cover	5	5.0 - 16	9.0	5	8.9 - 16	12
		Clay/dirt mix	1	—	9.2	1	—	14
		Clay	2	4.5 - 7.4	6.0	2	8.9 - 11	10
		Fly ash	4	78 - 81	80	4	26 - 29	27
		Misc. fill materials	1	—	12	1	—	11

[a] References 1-10. ND = no data.

The quantity of particulate emissions generated by either type of drop operation, per kilogram (kg) (ton) of material transferred, may be estimated, with a rating of A, using the following empirical expression:[11]

$$E = k(0.0016) \frac{\left(\frac{U}{2.2}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}} \text{ (kg/megagram [Mg])} \tag{1}$$

$$E = k(0.0032) \frac{\left(\frac{U}{5}\right)^{1.3}}{\left(\frac{M}{2}\right)^{1.4}} \text{ (pound [lb]/ton)}$$

where:

E = emission factor
k = particle size multiplier (dimensionless)
U = mean wind speed, meters per second (m/s) (miles per hour [mph])
M = material moisture content (%)

The particle size multiplier in the equation, k, varies with aerodynamic particle size range, as follows:

Aerodynamic Particle Size Multiplier (k) For Equation 1				
< 30 μm	< 15 μm	< 10 μm	< 5 μm	< 2.5 μm
0.74	0.48	0.35	0.20	0.11

The equation retains the assigned quality rating if applied within the ranges of source conditions that were tested in developing the equation, as follows. Note that silt content is included, even though silt content does not appear as a correction parameter in the equation. While it is reasonable to expect that silt content and emission factors are interrelated, no significant correlation between the 2 was found during the derivation of the equation, probably because most tests with high silt contents were conducted under lower winds, and vice versa. It is recommended that estimates from the equation be reduced 1 quality rating level if the silt content used in a particular application falls outside the range given:

Ranges Of Source Conditions For Equation 1			
Silt Content (%)	Moisture Content (%)	Wind Speed	
		m/s	mph
0.44 - 19	0.25 - 4.8	0.6 - 6.7	1.3 - 15

To retain the quality rating of the equation when it is applied to a specific facility, reliable correction parameters must be determined for specific sources of interest. The field and laboratory procedures for aggregate sampling are given in Reference 3. In the event that site-specific values for correction parameters cannot be obtained, the appropriate mean from Table 13.2.4-1 may be used, but the quality rating of the equation is reduced by 1 letter.

For emissions from equipment traffic (trucks, front-end loaders, dozers, etc.) traveling between or on piles, it is recommended that the equations for vehicle traffic on unpaved surfaces be used (see Section 13.2.2). For vehicle travel between storage piles, the silt value(s) for the areas among the piles (which may differ from the silt values for the stored materials) should be used.

Worst-case emissions from storage pile areas occur under dry, windy conditions. Worst-case emissions from materials-handling operations may be calculated by substituting into the equation appropriate values for aggregate material moisture content and for anticipated wind speeds during the worst case averaging period, usually 24 hours. The treatment of dry conditions for Section 13.2.2, vehicle traffic, "Unpaved Roads", follows the methodology described in that section centering on parameter p. A separate set of nonclimatic correction parameters and source extent values corresponding to higher than normal storage pile activity also may be justified for the worst-case averaging period.

13.2.4.4 Controls[12-13]

Watering and the use of chemical wetting agents are the principal means for control of aggregate storage pile emissions. Enclosure or covering of inactive piles to reduce wind erosion can also reduce emissions. Watering is useful mainly to reduce emissions from vehicle traffic in the storage pile area. Watering of the storage piles themselves typically has only a very temporary slight effect on total emissions. A much more effective technique is to apply chemical agents (such as surfactants) that permit more extensive wetting. Continuous chemical treating of material loaded onto piles, coupled with watering or treatment of roadways, can reduce total particulate emissions from aggregate storage operations by up to 90 percent.[12]

References For Section 13.2.4

1. C. Cowherd, Jr., *et al.*, *Development Of Emission Factors For Fugitive Dust Sources*, EPA-450/3-74-037, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

2. R. Bohn, *et al.*, *Fugitive Emissions From Integrated Iron And Steel Plants*, EPA-600/2-78-050, U. S. Environmental Protection Agency, Cincinnati, OH, March 1978.

3. C. Cowherd, Jr., *et al.*, *Iron And Steel Plant Open Dust Source Fugitive Emission Evaluation*, EPA-600/2-79-103, U. S. Environmental Protection Agency, Cincinnati, OH, May 1979.

4. *Evaluation Of Open Dust Sources In The Vicinity Of Buffalo, New York*, EPA Contract No. 68-02-2545, Midwest Research Institute, Kansas City, MO, March 1979.

5. C. Cowherd, Jr., and T. Cuscino, Jr., *Fugitive Emissions Evaluation*, MRI-4343-L, Midwest Research Institute, Kansas City, MO, February 1977.

6. T. Cuscino, Jr., *et al.*, *Taconite Mining Fugitive Emissions Study*, Minnesota Pollution Control Agency, Roseville, MN, June 1979.

7. *Improved Emission Factors For Fugitive Dust From Western Surface Coal Mining Sources*, 2 Volumes, EPA Contract No. 68-03-2924, PEDCo Environmental, Kansas City, MO, and Midwest Research Institute, Kansas City, MO, July 1981.

8. *Determination Of Fugitive Coal Dust Emissions From Rotary Railcar Dumping*, TRC, Hartford, CT, May 1984.

9. *PM-10 Emission Inventory Of Landfills In the Lake Calumet Area*, EPA Contract No. 68-02-3891, Midwest Research Institute, Kansas City, MO, September 1987.

10. *Chicago Area Particulate Matter Emission Inventory — Sampling And Analysis*, EPA Contract No. 68-02-4395, Midwest Research Institute, Kansas City, MO, May 1988.

11. *Update Of Fugitive Dust Emission Factors In AP-42 Section 11.2*, EPA Contract No. 68-02-3891, Midwest Research Institute, Kansas City, MO, July 1987.

12. G. A. Jutze, *et al.*, *Investigation Of Fugitive Dust Sources Emissions And Control*, EPA-450/3-74-036a, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1974.

13. C. Cowherd, Jr., *et al.*, *Control Of Open Fugitive Dust Sources*, EPA-450/3-88-008, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1988.

13.2.5 Industrial Wind Erosion

13.2.5.1 General[1-3]

Dust emissions may be generated by wind erosion of open aggregate storage piles and exposed areas within an industrial facility. These sources typically are characterized by nonhomogeneous surfaces impregnated with nonerodible elements (particles larger than approximately 1 centimeter [cm] in diameter). Field testing of coal piles and other exposed materials using a portable wind tunnel has shown that (a) threshold wind speeds exceed 5 meters per second (m/s) (11 miles per hour [mph]) at 15 cm above the surface or 10 m/s (22 mph) at 7 m above the surface, and (b) particulate emission rates tend to decay rapidly (half-life of a few minutes) during an erosion event. In other words, these aggregate material surfaces are characterized by finite availability of erodible material (mass/area) referred to as the erosion potential. Any natural crusting of the surface binds the erodible material, thereby reducing the erosion potential.

13.2.5.2 Emissions And Correction Parameters

If typical values for threshold wind speed at 15 cm are corrected to typical wind sensor height (7 - 10 m), the resulting values exceed the upper extremes of hourly mean wind speeds observed in most areas of the country. In other words, mean atmospheric wind speeds are not sufficient to sustain wind erosion from flat surfaces of the type tested. However, wind gusts may quickly deplete a substantial portion of the erosion potential. Because erosion potential has been found to increase rapidly with increasing wind speed, estimated emissions should be related to the gusts of highest magnitude.

The routinely measured meteorological variable that best reflects the magnitude of wind gusts is the fastest mile. This quantity represents the wind speed corresponding to the whole mile of wind movement that has passed by the 1 mile contact anemometer in the least amount of time. Daily measurements of the fastest mile are presented in the monthly Local Climatological Data (LCD) summaries. The duration of the fastest mile, typically about 2 minutes (for a fastest mile of 30 mph), matches well with the half-life of the erosion process, which ranges between 1 and 4 minutes. It should be noted, however, that peak winds can significantly exceed the daily fastest mile.

The wind speed profile in the surface boundary layer is found to follow a logarithmic distribution:

$$u(z) = \frac{u^*}{0.4} \ln \frac{z}{z_0} \qquad (z > z_0) \tag{1}$$

where:

u = wind speed, cm/s
u^* = friction velocity, cm/s
z = height above test surface, cm
z_0 = roughness height, cm
0.4 = von Karman's constant, dimensionless

The friction velocity (u^*) is a measure of wind shear stress on the erodible surface, as determined from the slope of the logarithmic velocity profile. The roughness height (z_o) is a measure of the roughness of the exposed surface as determined from the y intercept of the velocity profile, i. e., the height at which the wind speed is zero. These parameters are illustrated in Figure 13.2.5-1 for a roughness height of 0.1 cm.

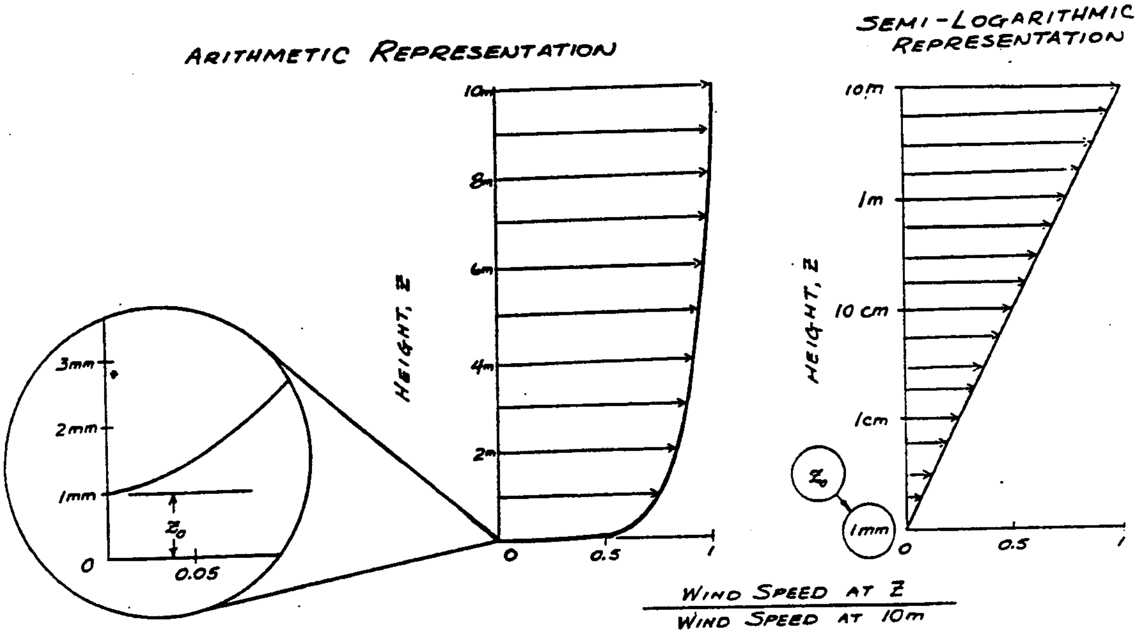


Figure 13.2.5-1. Illustration of logarithmic velocity profile.

Emissions generated by wind erosion are also dependent on the frequency of disturbance of the erodible surface because each time that a surface is disturbed, its erosion potential is restored. A disturbance is defined as an action that results in the exposure of fresh surface material. On a storage pile, this would occur whenever aggregate material is either added to or removed from the old surface. A disturbance of an exposed area may also result from the turning of surface material to a depth exceeding the size of the largest pieces of material present.

13.2.5.3 Predictive Emission Factor Equation[4]

The emission factor for wind-generated particulate emissions from mixtures of erodible and nonerodible surface material subject to disturbance may be expressed in units of grams per square meter (g/m^2) per year as follows:

$$\text{Emission factor} = k \sum_{i=1}^{N} P_i \qquad (2)$$

where:

k = particle size multiplier
N = number of disturbances per year
P_i = erosion potential corresponding to the observed (or probable) fastest mile of wind for the ith period between disturbances, g/m^2

The particle size multiplier (k) for Equation 2 varies with aerodynamic particle size, as follows:

Aerodynamic Particle Size Multipliers For Equation 2			
30 µm	<15 µm	<10 µm	<2.5 µm
1.0	0.6	0.5	0.2

This distribution of particle size within the under 30 micrometer (µm) fraction is comparable to the distributions reported for other fugitive dust sources where wind speed is a factor. This is illustrated, for example, in the distributions for batch and continuous drop operations encompassing a number of test aggregate materials (see Section 13.2.4).

In calculating emission factors, each area of an erodible surface that is subject to a different frequency of disturbance should be treated separately. For a surface disturbed daily, N = 365 per year, and for a surface disturbance once every 6 months, N = 2 per year.

The erosion potential function for a dry, exposed surface is:

$$\begin{aligned} P &= 58\,(u^* - u_t^*)^2 + 25\,(u^* - u_t^*) \\ P &= 0 \text{ for } u^* \le u_t^* \end{aligned} \tag{3}$$

where:

u^* = friction velocity (m/s)
u_t = threshold friction velocity (m/s)

Because of the nonlinear form of the erosion potential function, each erosion event must be treated separately.

Equations 2 and 3 apply only to dry, exposed materials with limited erosion potential. The resulting calculation is valid only for a time period as long or longer than the period between disturbances. Calculated emissions represent intermittent events and should not be input directly into dispersion models that assume steady-state emission rates.

For uncrusted surfaces, the threshold friction velocity is best estimated from the dry aggregate structure of the soil. A simple hand sieving test of surface soil can be used to determine the mode of the surface aggregate size distribution by inspection of relative sieve catch amounts, following the procedure described below.

FIELD PROCEDURE FOR DETERMINATION OF THRESHOLD FRICTION VELOCITY
(from a 1952 laboratory procedure published by W. S. Chepil):

1. Prepare a nest of sieves with the following openings: 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.25 mm. Place a collector pan below the bottom (0.25 mm) sieve.
2. Collect a sample representing the surface layer of loose particles (approximately 1 cm in depth, for an encrusted surface), removing any rocks larger than about 1 cm in average physical diameter. The area to be sampled should be not less than 30 cm by 30 cm.
3. Pour the sample into the top sieve (4-mm opening), and place a lid on the top.
4. Move the covered sieve/pan unit by hand, using a broad circular arm motion in the horizontal plane. Complete 20 circular movements at a speed just necessary to achieve some relative horizontal motion between the sieve and the particles.
5. Inspect the relative quantities of catch within each sieve, and determine where the mode in the aggregate size distribution lies, i. e., between the opening size of the sieve with the largest catch and the opening size of the next largest sieve.
6. Determine the threshold friction velocity from Table 13.2.5-1.

The results of the sieving can be interpreted using Table 13.2.5-1. Alternatively, the threshold friction velocity for erosion can be determined from the mode of the aggregate size distribution using the graphical relationship described by Gillette.[5-6] If the surface material contains nonerodible elements that are too large to include in the sieving (i. e., greater than about 1 cm in diameter), the effect of the elements must be taken into account by increasing the threshold friction velocity.[10]

Table 13.2.5-1 (Metric Units). FIELD PROCEDURE FOR DETERMINATION OF THRESHOLD FRICTION VELOCITY

Tyler Sieve No.	Opening (mm)	Midpoint (mm)	u_t^* (cm/s)
5	4		
9	2	3	100
16	1	1.5	76
32	0.5	0.75	58
60	0.25	0.375	43

Threshold friction velocities for several surface types have been determined by field measurements with a portable wind tunnel. These values are presented in Table 13.2.5-2.

Table 13.2.5-2 (Metric Units). THRESHOLD FRICTION VELOCITIES

Material	Threshold Friction Velocity (m/s)	Roughness Height (cm)	Threshold Wind Velocity At 10 m (m/s)	
			z_0 = Act	z_0 = 0.5 cm
Overburden[a]	1.02	0.3	21	19
Scoria (roadbed material)[a]	1.33	0.3	27	25
Ground coal (surrounding coal pile)[a]	0.55	0.01	16	10
Uncrusted coal pile[a]	1.12	0.3	23	21
Scraper tracks on coal pile[a,b]	0.62	0.06	15	12
Fine coal dust on concrete pad[c]	0.54	0.2	11	10

[a] Western surface coal mine. Reference 2.
[b] Lightly crusted.
[c] Eastern power plant. Reference 3.

The fastest mile of wind for the periods between disturbances may be obtained from the monthly LCD summaries for the nearest reporting weather station that is representative of the site in question.[7] These summaries report actual fastest mile values for each day of a given month. Because the erosion potential is a highly nonlinear function of the fastest mile, mean values of the fastest mile are inappropriate. The anemometer heights of reporting weather stations are found in Reference 8, and should be corrected to a 10-m reference height using Equation 1.

To convert the fastest mile of wind (u^+) from a reference anemometer height of 10 m to the equivalent friction velocity (u^*), the logarithmic wind speed profile may be used to yield the following equation:

$$u^* = 0.053\, u_{10}^+ \qquad (4)$$

where:

u^* = friction velocity (m/s)

u_{10}^+ = fastest mile of reference anemometer for period between disturbances (m/s)

This assumes a typical roughness height of 0.5 cm for open terrain. Equation 4 is restricted to large relatively flat piles or exposed areas with little penetration into the surface wind layer.

If the pile significantly penetrates the surface wind layer (i. e., with a height-to-base ratio exceeding 0.2), it is necessary to divide the pile area into subareas representing different degrees of exposure to wind. The results of physical modeling show that the frontal face of an elevated pile is exposed to wind speeds of the same order as the approach wind speed at the top of the pile.

For 2 representative pile shapes (conical and oval with flattop, 37-degree side slope), the ratios of surface wind speed (u_s) to approach wind speed (u_r) have been derived from wind tunnel studies.[9] The results are shown in Figure 13.2.5-2 corresponding to an actual pile height of 11 m, a reference (upwind) anemometer height of 10 m, and a pile surface roughness height (z_o) of 0.5 cm. The measured surface winds correspond to a height of 25 cm above the surface. The area fraction within each contour pair is specified in Table 13.2.5-3.

Table 13.2.5-3. SUBAREA DISTRIBUTION FOR REGIMES OF u_s/u_r[a]

Pile Subarea	Percent Of Pile Surface Area			
	Pile A	Pile B1	Pile B2	Pile B3
0.2a	5	5	3	3
0.2b	35	2	28	25
0.2c	NA	29	NA	NA
0.6a	48	26	29	28
0.6b	NA	24	22	26
0.9	12	14	15	14
1.1	NA	NA	3	4

[a] NA = not applicable.

The profiles of u_s/u_r in Figure 13.2.5-2 can be used to estimate the surface friction velocity distribution around similarly shaped piles, using the following procedure:

1. Correct the fastest mile value (u^+) for the period of interest from the anemometer height (z) to a reference height of 10 m u^+_{10} using a variation of Equation 1:

$$u^+_{10} = u^+ \frac{\ln (10/0.005)}{\ln (z/0.005)} \qquad (5)$$

where a typical roughness height of 0.5 cm (0.005 m) has been assumed. If a site-specific roughness height is available, it should be used.

2. Use the appropriate part of Figure 13.2.5-2 based on the pile shape and orientation to the fastest mile of wind, to obtain the corresponding surface wind speed distribution (u^+_s)

$$u^+_s = \frac{(u_s)}{u_r} \quad u^+_{10} \qquad (6)$$

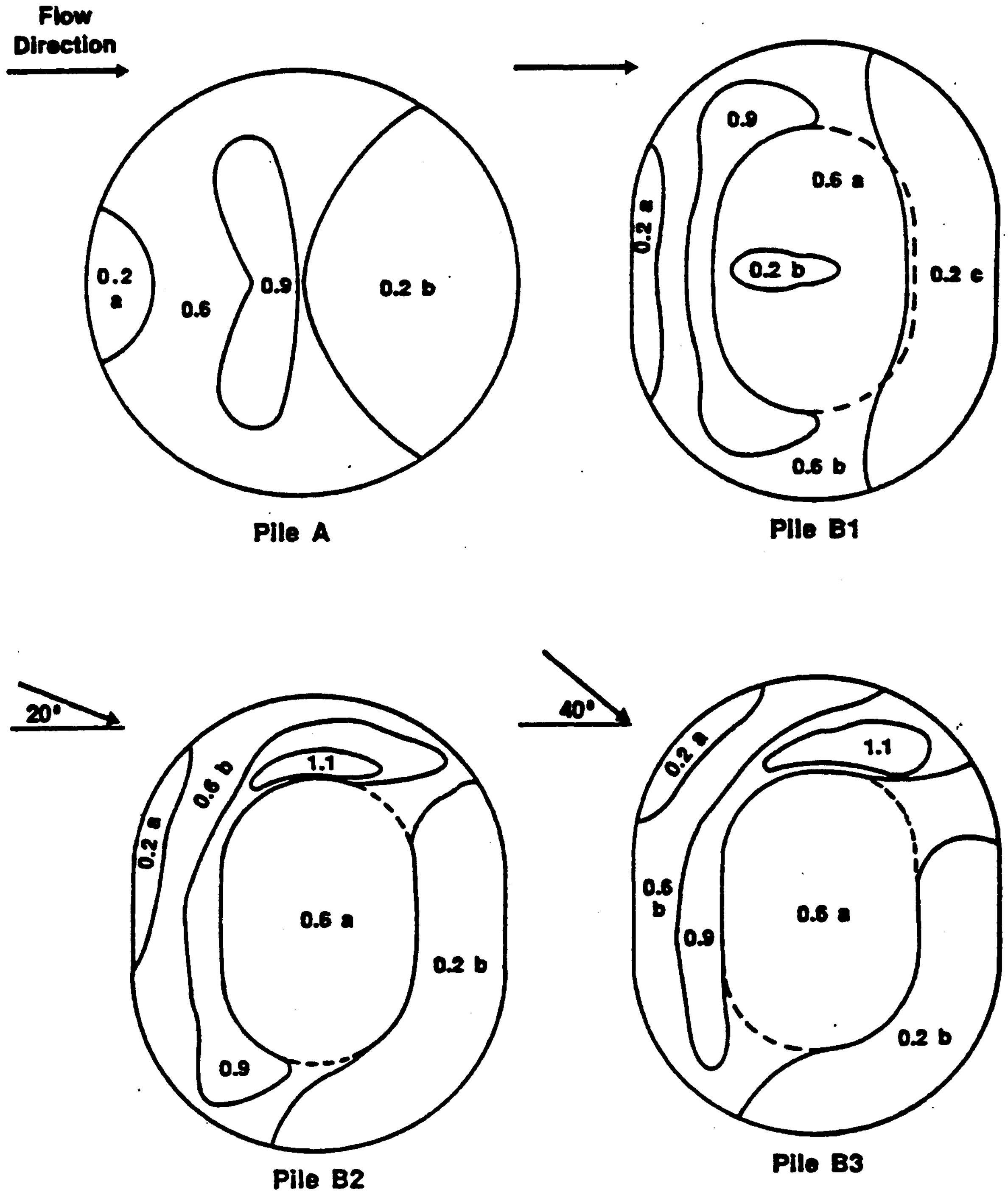


Figure 13.2.5-2. Contours of normalized surface windspeeds, u_s/u_r.

3. For any subarea of the pile surface having a narrow range of surface wind speed, use a variation of Equation 1 to calculate the equivalent friction velocity (u^*):

$$u^* = \frac{0.4u_s^+}{\frac{25}{\ln 0.5}} = 0.10u_s^+ \qquad (7)$$

From this point on, the procedure is identical to that used for a flat pile, as described above.

Implementation of the above procedure is carried out in the following steps:

1. Determine threshold friction velocity for erodible material of interest (see Table 13.2.5-2 or determine from mode of aggregate size distribution).

2. Divide the exposed surface area into subareas of constant frequency of disturbance (N).

3. Tabulate fastest mile values (u^+) for each frequency of disturbance and correct them to 10 m (u_{10}^+) using Equation 5.5

4. Convert fastest mile values (u_{10}) to equivalent friction velocities (u^*), taking into account (a) the uniform wind exposure of nonelevated surfaces, using Equation 4, or (b) the nonuniform wind exposure of elevated surfaces (piles), using Equations 6 and 7.

5. For elevated surfaces (piles), subdivide areas of constant N into subareas of constant u^* (i. e., within the isopleth values of u_s/u_r in Figure 13.2.5-2 and Table 13.2.5-3) and determine the size of each subarea.

6. Treating each subarea (of constant N and u^*) as a separate source, calculate the erosion potential (P_i) for each period between disturbances using Equation 3 and the emission factor using Equation 2.

7. Multiply the resulting emission factor for each subarea by the size of the subarea, and add the emission contributions of all subareas. Note that the highest 24-hour (hr) emissions would be expected to occur on the windiest day of the year. Maximum emissions are calculated assuming a single event with the highest fastest mile value for the annual period.

The recommended emission factor equation presented above assumes that all of the erosion potential corresponding to the fastest mile of wind is lost during the period between disturbances. Because the fastest mile event typically lasts only about 2 minutes, which corresponds roughly to the half-life for the decay of actual erosion potential, it could be argued that the emission factor overestimates particulate emissions. However, there are other aspects of the wind erosion process that offset this apparent conservatism:

1. The fastest mile event contains peak winds that substantially exceed the mean value for the event.

2. Whenever the fastest mile event occurs, there are usually a number of periods of slightly lower mean wind speed that contain peak gusts of the same order as the fastest mile wind speed.

Of greater concern is the likelihood of overprediction of wind erosion emissions in the case of surfaces disturbed infrequently in comparison to the rate of crust formation.

13.2.5.4 Example 1: Calculation for wind erosion emissions from conically shaped coal pile

A coal burning facility maintains a conically shaped surge pile 11 m in height and 29.2 m in base diameter, containing about 2000 megagrams (Mg) of coal, with a bulk density of 800 kilograms per cubic meter (kg/m^3) (50 pounds per cubic feet [lb/ft^3]). The total exposed surface area of the pile is calculated as follows:

$$S = \pi r (r^2 + h^2)$$

$$= 3.14(14.6)\ (14.6)^2 + (11.0)^2$$

$$= 838\ m^2$$

Coal is added to the pile by means of a fixed stacker and reclaimed by front-end loaders operating at the base of the pile on the downwind side. In addition, every 3 days 250 Mg (12.5 percent of the stored capacity of coal) is added back to the pile by a topping off operation, thereby restoring the full capacity of the pile. It is assumed that (a) the reclaiming operation disturbs only a limited portion of the surface area where the daily activity is occurring, such that the remainder of the pile surface remains intact, and (b) the topping off operation creates a fresh surface on the entire pile while restoring its original shape in the area depleted by daily reclaiming activity.

Because of the high frequency of disturbance of the pile, a large number of calculations must be made to determine each contribution to the total annual wind erosion emissions. This illustration will use a single month as an example.

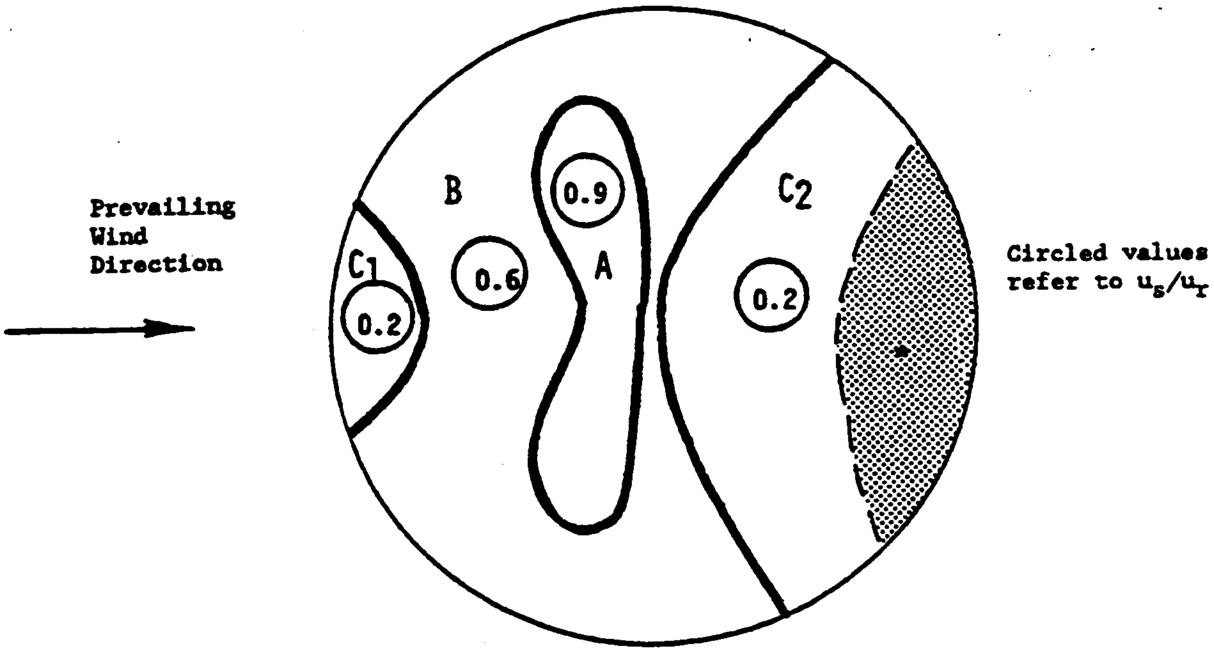
Step 1: In the absence of field data for estimating the threshold friction velocity, a value of 1.12 m/s is obtained from Table 13.2.5-2.

Step 2: Except for a small area near the base of the pile (see Figure 13.2.5-3), the entire pile surface is disturbed every 3 days, corresponding to a value of N = 120 per year. It will be shown that the contribution of the area where daily activity occurs is negligible so that it does not need to be treated separately in the calculations.

Step 3: The calculation procedure involves determination of the fastest mile for each period of disturbance. Figure 13.2.5-4 shows a representative set of values (for a 1-month period) that are assumed to be applicable to the geographic area of the pile location. The values have been separated into 3-day periods, and the highest value in each period is indicated. In this example, the anemometer height is 7 m, so that a height correction to 10 m is needed for the fastest mile values. From Equation 5,

$$u_{10}^{+} = u_7^{+} \left[\frac{\ln(10/0.005)}{\ln(7/0.005)} \right]$$

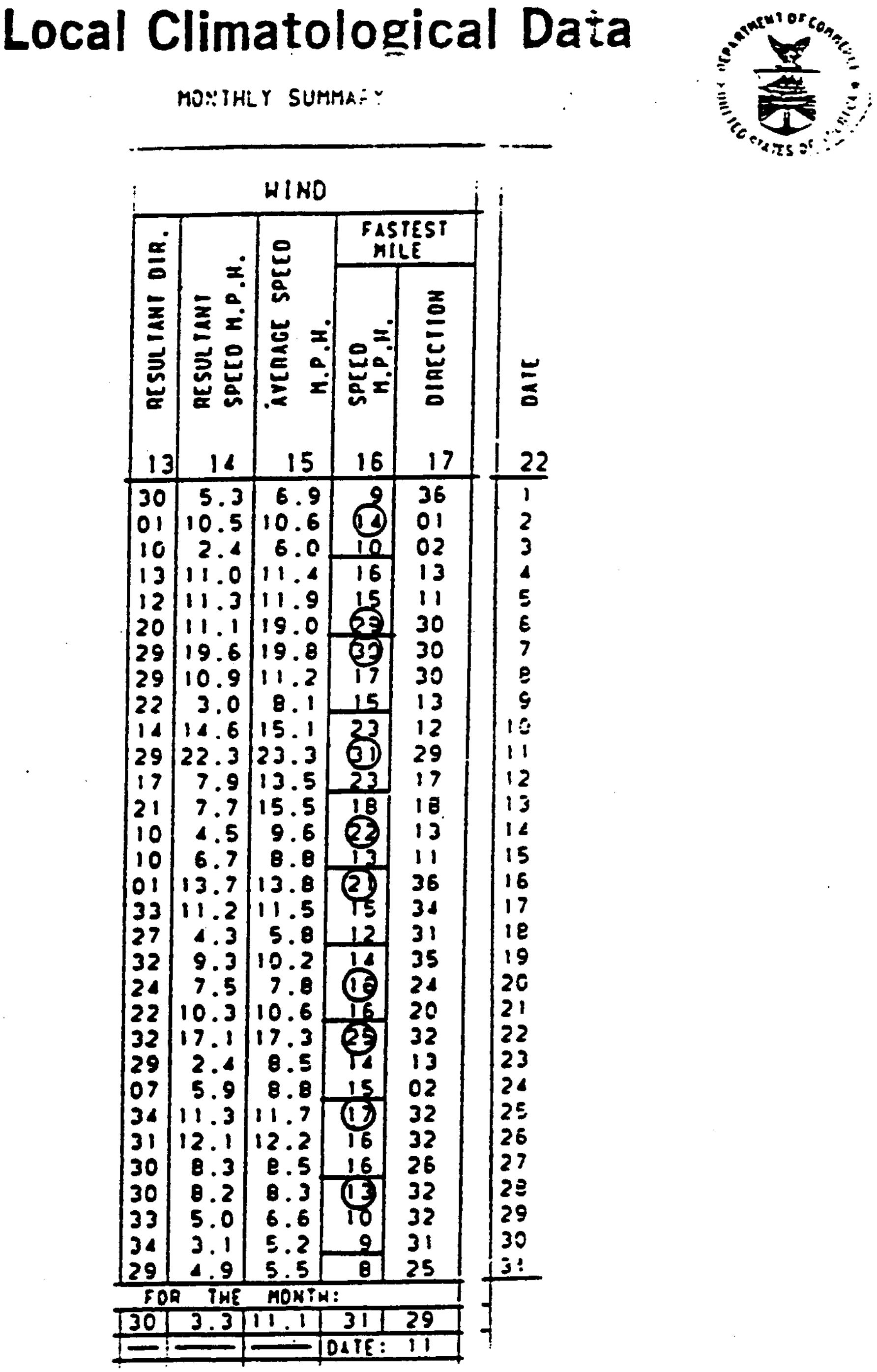
$$u_{10}^{+} = 1.05\ u_7^{+}$$



* A portion of C_2 is disturbed daily by reclaiming activities.

Area ID	$\frac{u_s}{u_r}$	Pile Surface %	Pile Surface Area (m^2)
A	0.9	12	101
B	0.6	48	402
$C_1 + C_2$	0.2	40	335
		Total	838

Figure 13.2.5-3. Example 1: Pile surface areas within each wind speed regime.



Local Climatological Data

MONTHLY SUMMARY

WIND					
			FASTEST MILE		
RESULTANT DIR. 13	RESULTANT SPEED M.P.H. 14	AVERAGE SPEED M.P.H. 15	SPEED M.P.H. 16	DIRECTION 17	DATE 22
30	5.3	6.9	9	36	1
01	10.5	10.6	14	01	2
10	2.4	6.0	10	02	3
13	11.0	11.4	16	13	4
12	11.3	11.9	15	11	5
20	11.1	19.0	23	30	6
29	19.6	19.8	30	30	7
29	10.9	11.2	17	30	8
22	3.0	8.1	15	13	9
14	14.6	15.1	23	12	10
29	22.3	23.3	31	29	11
17	7.9	13.5	23	17	12
21	7.7	15.5	18	18	13
10	4.5	9.6	22	13	14
10	6.7	8.8	13	11	15
01	13.7	13.8	21	36	16
33	11.2	11.5	15	34	17
27	4.3	5.8	12	31	18
32	9.3	10.2	14	35	19
24	7.5	7.8	16	24	20
22	10.3	10.6	16	20	21
32	17.1	17.3	25	32	22
29	2.4	8.5	14	13	23
07	5.9	8.8	15	02	24
34	11.3	11.7	17	32	25
31	12.1	12.2	16	32	26
30	8.3	8.5	16	26	27
30	8.2	8.3	13	32	28
33	5.0	6.6	10	32	29
34	3.1	5.2	9	31	30
29	4.9	5.5	8	25	31
FOR THE MONTH:					
30	3.3	11.1	31	29	
—	—	—	DATE: 11		

Figure 13.2.5-4. Example daily fastest miles wind for periods of interest.

Step 4: The next step is to convert the fastest mile value for each 3-day period into the equivalent friction velocities for each surface wind regime (i. e., u_s/u_r ratio) of the pile, using Equations 6 and 7. Figure 13.2.5-3 shows the surface wind speed pattern (expressed as a fraction of the approach wind speed at a height of 10 m). The surface areas lying within each wind speed regime are tabulated below the figure.

The calculated friction velocities are presented in Table 13.2.5-4. As indicated, only 3 of the periods contain a friction velocity which exceeds the threshold value of 1.12 m/s for an uncrusted coal pile. These 3 values all occur within the $u_s/u_r = 0.9$ regime of the pile surface.

Table 13.2.5-4 (Metric And English Units). EXAMPLE 1:
CALCULATION OF FRICTION VELOCITIES

3-Day Period	u_7^+		u_{10}^+		$u^* = 0.1u_s^+$ (m/s)		
	mph	m/s	mph	m/s	u_s/u_r: 0.2	u_s/u_r: 0.6	u_s/u_r: 0.9
1	14	6.3	15	6.6	0.13	0.40	0.59
2	29	13.0	31	13.7	0.27	0.82	1.23
3	30	13.4	32	14.1	0.28	0.84	1.27
4	31	13.9	33	14.6	0.29	0.88	1.31
5	22	9.8	23	10.3	0.21	0.62	0.93
6	21	9.4	22	9.9	0.20	0.59	0.89
7	16	7.2	17	7.6	0.15	0.46	0.68
8	25	11.2	26	11.8	0.24	0.71	1.06
9	17	7.6	18	8.0	0.16	0.48	0.72
10	13	5.8	14	6.1	0.12	0.37	0.55

Step 5: This step is not necessary because there is only 1 frequency of disturbance used in the calculations. It is clear that the small area of daily disturbance (which lies entirely within the $u_s/u_r = 0.2$ regime) is never subject to wind speeds exceeding the threshold value.

Steps 6 and 7: The final set of calculations (shown in Table 13.2.5-5) involves the tabulation and summation of emissions for each disturbance period and for the affected subarea. The erosion potential (P) is calculated from Equation 3.

For example, the calculation for the second 3-day period is:

$$P = 58(u^* - u_t^*)^2 + 25(u^* - u_t^*)$$

$$P_2 = 58(1.23 - 1.12)^2 + 25(1.23 - 1.12)$$

$$= 0.70 + 2.75 = 3.45 \text{ g/m}^2$$

Table 13.2.5-5 (Metric Units). EXAMPLE 1: CALCULATION OF PM-10 EMISSIONS[a]

3-Day Period	u^* (m/s)	$u^* - u_t^*$ (m/s)	P (g/m^2)	ID	Pile Surface Area (m^2)	kPA (g)
2	1.23	0.11	3.45	A	101	170
3	1.27	0.15	5.06	A	101	260
4	1.31	0.19	6.84	A	101	350
TOTAL						780

[a] Where $u_t^* = 1.12$ m/s for uncrusted coal and k = 0.5 for PM-10.

The emissions of particulate matter greater than 10 μm (PM-10) generated by each event are found as the product of the PM-10 multiplier (k = 0.5), the erosion potential (P), and the affected area of the pile (A).

As shown in Table 13.2.5-5, the results of these calculations indicate a monthly PM-10 emission total of 780 g.

13.2.5.5 Example 2: Calculation for wind erosion from flat area covered with coal dust

A flat circular area 29.2 m in diameter is covered with coal dust left over from the total reclaiming of a conical coal pile described in the example above. The total exposed surface area is calculated as follows:

$$s = \frac{\pi}{4} d^2 = 0.785\ (29.2)^2 = 670\ \text{m}^2$$

This area will remain exposed for a period of 1 month when a new pile will be formed.

Step 1: In the absence of field data for estimating the threshold friction velocity, a value of 0.54 m/s is obtained from Table 13.2.5-2.

Step 2: The entire surface area is exposed for a period of 1 month after removal of a pile and N = 1/yr.

Step 3: From Figure 13.2.5-4, the highest value of fastest mile for the 30-day period (31 mph) occurs on the 11th day of the period. In this example, the reference anemometer height is 7 m, so that a height correction is needed for the fastest mile value. From Step 3 of the previous example, $u_{10}^+ = 1.05\ u_7^+$, so that $u_{10}^+ = 33$ mph.

Step 4: Equation 4 is used to convert the fastest mile value of 14.6 m/s (33 mph) to an equivalent friction velocity of 0.77 m/s. This value exceeds the threshold friction velocity from Step 1 so that erosion does occur.

Step 5: This step is not necessary, because there is only 1 frequency of disturbance for the entire source area.

Steps 6 and 7: The PM-10 emissions generated by the erosion event are calculated as the product of the PM-10 multiplier (k = 0.5), the erosion potential (P) and the source area (A). The erosion potential is calculated from Equation 3 as follows:

$$P = 58(u^* - u_t^*)^2 + 25(u^* - u_t^*)$$

$$\begin{aligned} P &= 58(0.77 - 0.54)^2 + 25(0.77 - 0.54) \\ &= 3.07 + 5.75 \\ &= 8.82 \text{ g/m}^2 \end{aligned}$$

Thus the PM-10 emissions for the 1-month period are found to be:

$$\begin{aligned} E &= (0.5)(8.82 \text{ g/m}^2)(670 \text{ m}^2) \\ &= 3.0 \text{ kg} \end{aligned}$$

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13.4 Wet Cooling Towers

13.4.1 General[1]

Cooling towers are heat exchangers that are used to dissipate large heat loads to the atmosphere. They are used as an important component in many industrial and commercial processes needing to dissipate heat. Cooling towers may range in size from less than 5.3(10)^6 kilojoules (kJ) (5[10]^6 British thermal units per hour [Btu/hr]) for small air conditioning cooling towers to over 5275(10)^6 kJ/hr (5000[10^6] Btu/hr) for large power plant cooling towers.

When water is used as the heat transfer medium, wet, or evaporative, cooling towers may be used. Wet cooling towers rely on the latent heat of water evaporation to exchange heat between the process and the air passing through the cooling tower. The cooling water may be an integral part of the process or may provide cooling via heat exchangers.

Although cooling towers can be classified several ways, the primary classification is into dry towers or wet towers, and some hybrid wet-dry combinations exist. Subclassifications can include the draft type and/or the location of the draft relative to the heat transfer medium, the type of heat transfer medium, the relative direction of air movement, and the type of water distribution system.

In wet cooling towers, heat transfer is measured by the decrease in the process temperature and a corresponding increase in both the moisture content and the wet bulb temperature of the air passing through the cooling tower. (There also may be a change in the sensible, or dry bulb, temperature, but its contribution to the heat transfer process is very small and is typically ignored when designing wet cooling towers.) Wet cooling towers typically contain a wetted medium called "fill" to promote evaporation by providing a large surface area and/or by creating many water drops with a large cumulative surface area.

Cooling towers can be categorized by the type of heat transfer; the type of draft and location of the draft, relative to the heat transfer medium; the type of heat transfer medium; the relative direction of air and water contact; and the type of water distribution system. Since wet, or evaporative, cooling towers are the dominant type, and they also generate air pollutants, this section will address only that type of tower. Diagrams of the various tower configurations are shown in Figure 13.4-1 and Figure 13.4-2.

13.4.2 Emissions And Controls[1]

Because wet cooling towers provide direct contact between the cooling water and the air passing through the tower, some of the liquid water may be entrained in the air stream and be carried out of the tower as "drift" droplets. Therefore, the particulate matter constituent of the drift droplets may be classified as an emission.

The magnitude of drift loss is influenced by the number and size of droplets produced within the cooling tower, which in turn are determined by the fill design, the air and water patterns, and other interrelated factors. Tower maintenance and operation levels also can influence the formation of drift droplets. For example, excessive water flow, excessive airflow, and water bypassing the tower drift eliminators can promote and/or increase drift emissions.

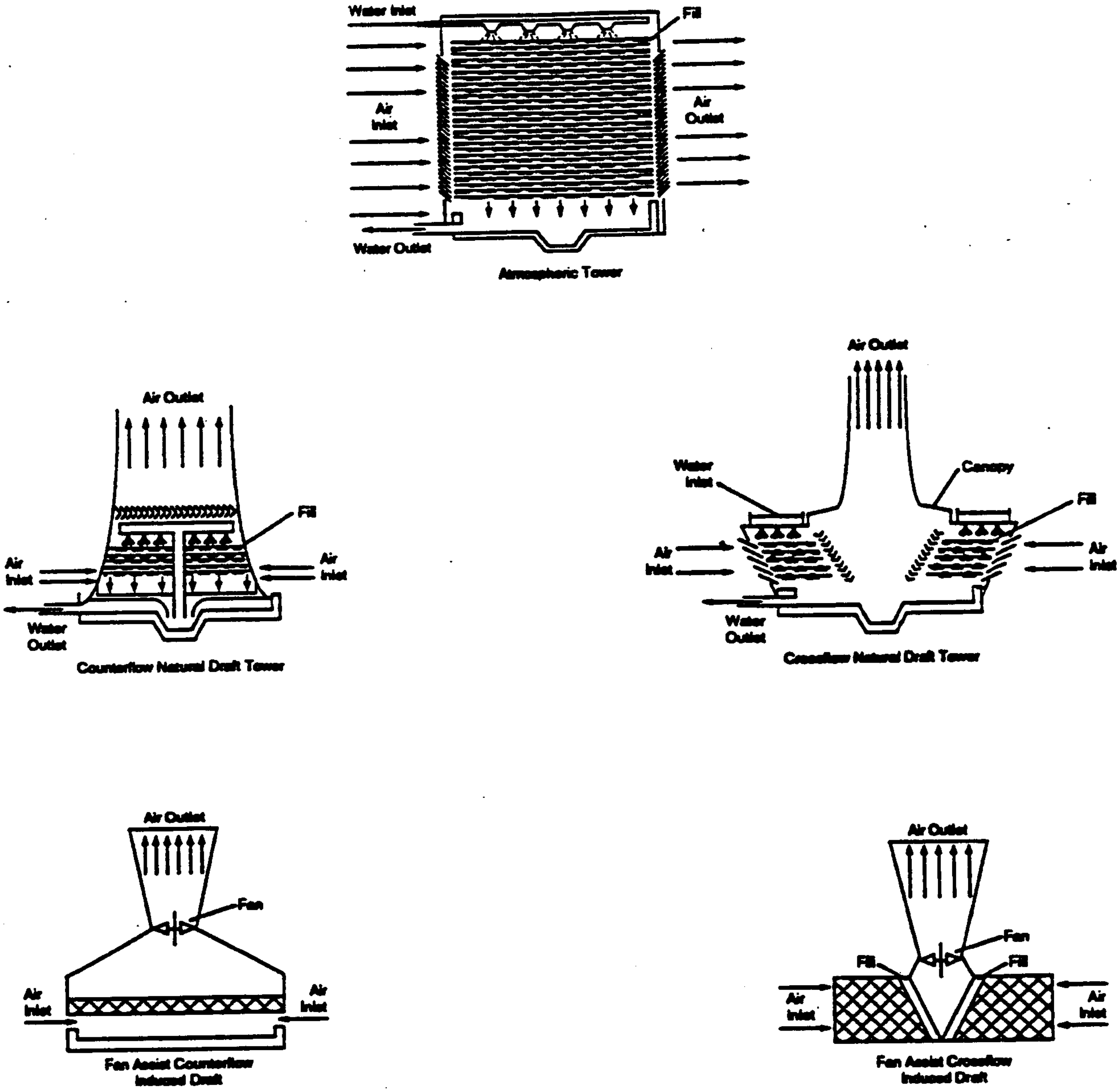
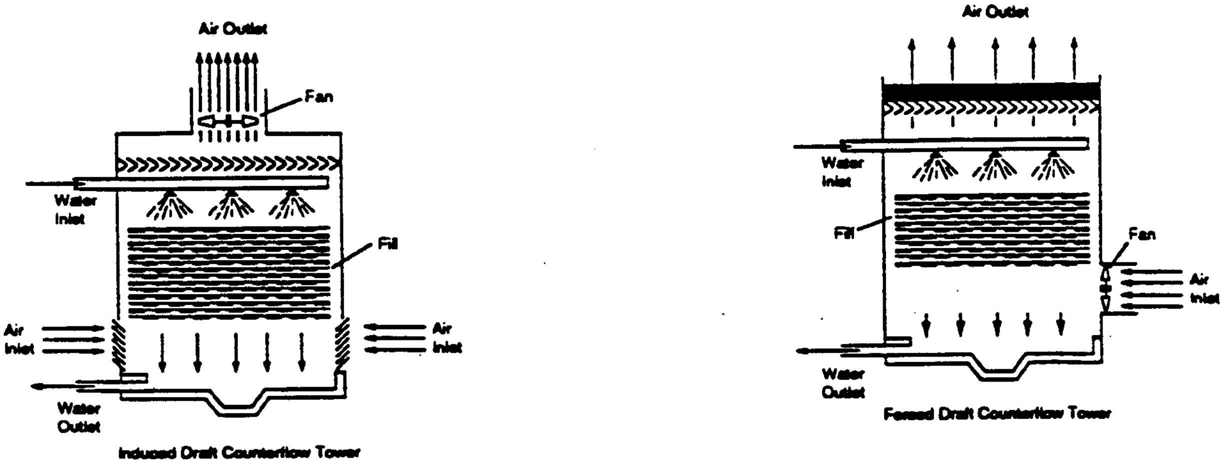


Figure 13.4-1 Atmospheric and natural draft cooling towers.

Because the drift droplets generally contain the same chemical impurities as the water circulating through the tower, these impurities can be converted to airborne emissions. Large drift droplets settle out of the tower exhaust air stream and deposit near the tower. This process can lead to wetting, icing, salt deposition, and related problems such as damage to equipment or to vegetation. Other drift droplets may evaporate before being deposited in the area surrounding the tower, and they also can produce PM-10 emissions. PM-10 is generated when the drift droplets evaporate and leave fine particulate matter formed by crystallization of dissolved solids. Dissolved solids found in cooling tower drift can consist of mineral matter, chemicals for corrosion inhibition, etc.



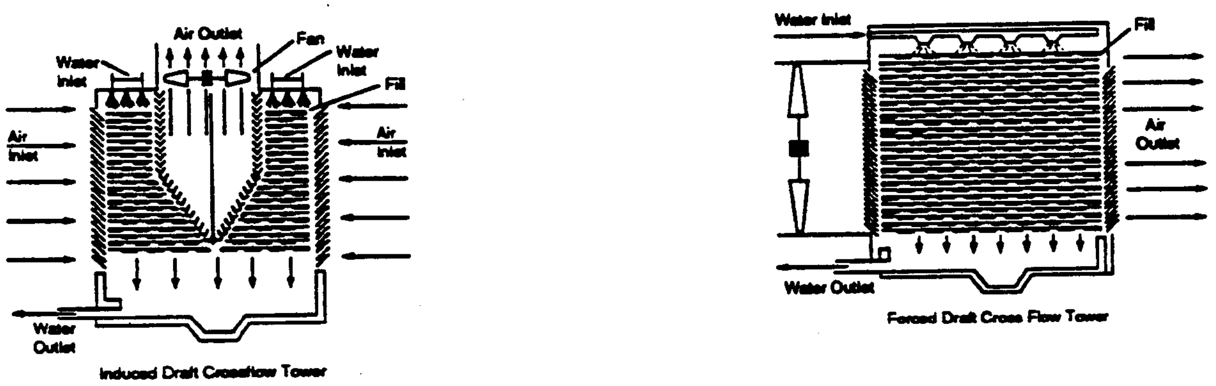


Figure 13.4-2. Mechanical draft cooling towers.

To reduce the drift from cooling towers, drift eliminators are usually incorporated into the tower design to remove as many droplets as practical from the air stream before exiting the tower. The drift eliminators used in cooling towers rely on inertial separation caused by direction changes while passing through the eliminators. Types of drift eliminator configurations include herringbone (blade-type), wave form, and cellular (or honeycomb) designs. The cellular units generally are the most efficient. Drift eliminators may include various materials, such as ceramics, fiber reinforced cement, fiberglass, metal, plastic, and wood installed or formed into closely spaced slats, sheets, honeycomb assemblies, or tiles. The materials may include other features, such as corrugations and water removal channels, to enhance the drift removal further.

Table 13.4-1 provides available particulate emission factors for wet cooling towers. Separate emission factors are given for induced draft and natural draft cooling towers. Several features in Table 13.4-1 should be noted. First, a *conservatively high* PM-10 emission factor can be obtained by (a) multiplying the total liquid drift factor by the total dissolved solids (TDS) fraction in the circulating water and (b) assuming that, once the water evaporates, all remaining solid particles are within the PM-10 size range.

Second, if TDS data for the cooling tower are not available, a source-specific TDS content can be estimated by obtaining the TDS data for the make-up water and multiplying them by the cooling tower cycles of concentration. The cycles of concentration ratio is the ratio of a measured

Table 13.4-1 (Metric And English Units). PARTICULATE EMISSIONS FACTORS FOR WET COOLING TOWERS[a]

Tower Type[d]	Total Liquid Drift[b]				PM-10[c]		
	Circulating Water Flow[b]	g/daL	lb/10^3 gal	EMISSION FACTOR RATING	g/daL[e]	lb/10^3 gal	EMISSION FACTOR RATING
Induced Draft (SCC 3-85-001-01, 3-85-001-20, 3-85-002-01)	0.020	2.0	1.7	D	0.023	0.019	E
Natural Draft (SCC 3-85-001-02, 3-85-002-02)	0.00088	0.088	0.073	E	ND	ND	—

[a] References 1-17. Numbers are given to 2 significant digits. ND = no data. SCC = Source Classification Code.

[b] References 2,5-7,9-10,12-13,15-16. Total liquid drift is water droplets entrained in the cooling tower exit air stream. Factors are for % of circulating water flow (10^{-2} L drift/L [10^{-2} gal drift/gal] water flow) and g drift/daL (lb drift/10^3 gal) circulating water flow. 0.12 g/daL = 0.1 lb/10^3 gal; 1 daL = 10^1 L.

[c] See discussion in text on how to use the table to obtain PM-10 emission estimates. Values shown above are the arithmetic average of test results from References 2,4,8, and 11-14, and they imply an effective TDS content of approximately 12,000 parts per million (ppm) in the circulating water.

[d] See Figure 13.4-1 and Figure 13.4-2. Additional SCCs for wet cooling towers of unspecified draft type are 3-85-001-10 and 3-85-002-10.

[e] Expressed as g PM-10/daL (lb PM-10/10^3 gal) circulating water flow.

parameter for the cooling tower water (such as conductivity, calcium, chlorides, or phosphate) to that parameter for the make-up water. This estimated cooling tower TDS can be used to calculate the PM-10 emission factor as above. If neither of these methods can be used, the arithmetic average PM-10 factor given in Table 13.4-1 can be used. Table 13.4-1 presents the arithmetic average PM-10 factor calculated from the test data in References 2, 4, 8, and 11 - 14. Note that this average corresponds to an effective cooling tower recirculating water TDS content of approximately 11,500 ppm for induced draft towers. (This can be found by dividing the total liquid drift factor into the PM-10 factor.)

As an alternative approach, if TDS data are unavailable for an induced draft tower, a value may be selected from Table 13.4-2 and then be combined with the total liquid drift factor in Table 13.4-1 to determine an apparent PM-10 factor.

As shown in Table 13.4-2, available data do not suggest that there is any significant difference between TDS levels in counter and cross flow towers. Data for natural draft towers are not available.

Table 13.4-2. SUMMARY STATISTICS FOR TOTAL DISSOLVED SOLIDS (TDS) CONTENT IN CIRCULATING WATER[a]

Type Of Draft	No. Of Cases	Range Of TDS Values (ppm)	Geometric Mean TDS Value (ppm)
Counter Flow	10	3700 - 55,000	18,500
Cross Flow	7	380 - 91,000	24,000
Overall[b]	17	380 - 91,000	20,600

[a] References 2,4,8,11-14.

[b] Data unavailable for natural draft towers.

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13.5 Industrial Flares

13.5.1 General

Flaring is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons, of waste gases from industrial operations. Natural gas, propane, ethylene, propylene, butadiene and butane constitute over 95 percent of the waste gases flared. In combustion, gaseous hydrocarbons react with atmospheric oxygen to form carbon dioxide (CO_2) and water. In some waste gases, carbon monoxide (CO) is the major combustible component. Presented below, as an example, is the combustion reaction of propane.

$$C_3H_8 + 5\ O_2 \longrightarrow 3\ CO_2 + 4\ H_2O$$

During a combustion reaction, several intermediate products are formed, and eventually, most are converted to CO_2 and water. Some quantities of stable intermediate products such as carbon monoxide, hydrogen, and hydrocarbons will escape as emissions.

Flares are used extensively to dispose of (1) purged and wasted products from refineries, (2) unrecoverable gases emerging with oil from oil wells, (3) vented gases from blast furnaces, (4) unused gases from coke ovens, and (5) gaseous wastes from chemical industries. Gases flared from refineries, petroleum production, chemical industries, and to some extent, from coke ovens, are composed largely of low molecular weight hydrocarbons with high heating value. Blast furnace flare gases are largely of inert species and CO, with low heating value. Flares are also used for burning waste gases generated by sewage digesters, coal gasification, rocket engine testing, nuclear power plants with sodium/water heat exchangers, heavy water plants, and ammonia fertilizer plants.

There are two types of flares, elevated and ground flares. Elevated flares, the more common type, have larger capacities than ground flares. In elevated flares, a waste gas stream is fed through a stack anywhere from 10 to over 100 meters tall and is combusted at the tip of the stack. The flame is exposed to atmospheric disturbances such as wind and precipitation. In ground flares, combustion takes place at ground level. Ground flares vary in complexity, and they may consist either of conventional flare burners discharging horizontally with no enclosures or of multiple burners in refractory-lined steel enclosures.

The typical flare system consists of (1) a gas collection header and piping for collecting gases from processing units, (2) a knockout drum (disentrainment drum) to remove and store condensables and entrained liquids, (3) a proprietary seal, water seal, or purge gas supply to prevent flash-back, (4) a single- or multiple-burner unit and a flare stack, (5) gas pilots and an ignitor to ignite the mixture of waste gas and air, and, if required, (6) a provision for external momentum force (steam injection or forced air) for smokeless flaring. Natural gas, fuel gas, inert gas, or nitrogen can be used as purge gas. Figure 13.5-1 is a diagram of a typical steam-assisted elevated smokeless flare system.

Complete combustion requires sufficient combustion air and proper mixing of air and waste gas. Smoking may result from combustion, depending upon waste gas components and the quantity and distribution of combustion air. Waste gases containing methane, hydrogen, CO, and ammonia usually burn without smoke. Waste gases containing heavy hydrocarbons such as paraffins above methane, olefins, and aromatics, cause smoke. An external momentum force, such as steam injection

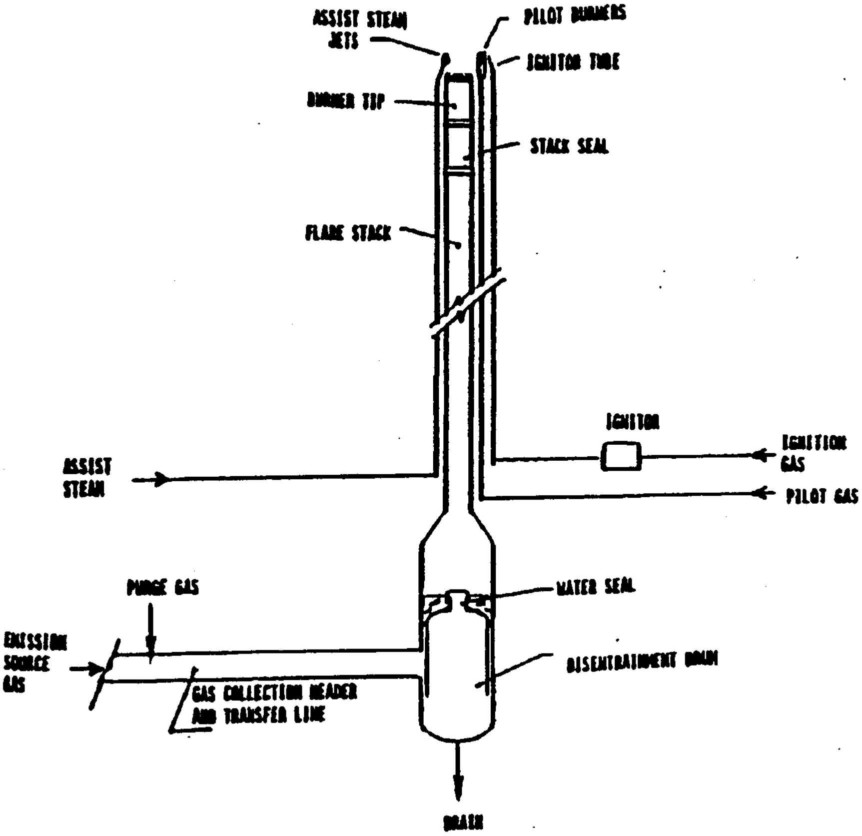

Figure 13.5-1. Diagram of a typical steam-assisted smokeless elevated flare.

or blowing air, is used for efficient air/waste gas mixing and turbulence, which promotes smokeless flaring of heavy hydrocarbon waste gas. Other external forces may be used for this purpose, including water spray, high velocity vortex action, or natural gas. External momentum force is rarely required in ground flares.

Steam injection is accomplished either by nozzles on an external ring around the top of the flare tip or by a single nozzle located concentrically within the tip. At installations where waste gas flow varies, both are used. The internal nozzle provides steam at low waste gas flow rates, and the external jets are used with large waste gas flow rates. Several other special-purpose flare tips are commercially available, one of which is for injecting both steam and air. Typical steam usage ratio varies from 7:1 to 2:1, by weight.

Waste gases to be flared must have a fuel value of at least 7500 to 9300 kilojoules per cubic meter kJ/m^3 (200 to 250 British thermal units per cubic foot [Btu/ft^3]) for complete combustion; otherwise fuel must be added. Flares providing supplemental fuel to waste gas are known as fired, or endothermic, flares. In some cases, even flaring waste gases having the necessary heat content will also require supplemental heat. If fuel-bound nitrogen is present, flaring ammonia with a heating value of 13,600 kJ/m^3 (365 Btu/ft^3) will require higher heat to minimize nitrogen oxides (NO_x) formation.

At many locations, flares normally used to dispose of low-volume continuous emissions are designed to handle large quantities of waste gases that may be intermittently generated during plant emergencies. Flare gas volumes can vary from a few cubic meters per hour during regular operations up to several thousand cubic meters per hour during major upsets. Flow rates at a refinery could be from 45 to 90 kilograms per hour (kg/hr) (100 - 200 pounds per hour [lb/hr]) for relief valve leakage but could reach a full plant emergency rate of 700 megagrams per hour (Mg/hr) (750 tons/hr). Normal process blowdowns may release 450 to 900 kg/hr (1000 - 2000 lb/hr), and unit maintenance or minor failures may release 25 to 35 Mg/hr (27 - 39 tons/hr). A 40 molecular weight gas typically of 0.012 cubic nanometers per second (nm^3/s) (25 standard cubic feet per minute [scfm]) may rise to as high as 115 nm^3/s (241,000 scfm). The required flare turndown ratio for this typical case is over 15,000 to 1.

Many flare systems have 2 flares, in parallel or in series. In the former, 1 flare can be shut down for maintenance while the other serves the system. In systems of flares in series, 1 flare, usually a low-level ground flare, is intended to handle regular gas volumes, and the other, an elevated flare, to handle excess gas flows from emergencies.

13.5.2 Emissions

Noise and heat are the most apparent undesirable effects of flare operation. Flares are usually located away from populated areas or are sufficiently isolated, thus minimizing their effects on populations.

Emissions from flaring include carbon particles (soot), unburned hydrocarbons, CO, and other partially burned and altered hydrocarbons. Also emitted are NO_x and, if sulfur-containing material such as hydrogen sulfide or mercaptans is flared, sulfur dioxide (SO_2). The quantities of hydrocarbon emissions generated relate to the degree of combustion. The degree of combustion depends largely on the rate and extent of fuel-air mixing and on the flame temperatures achieved and maintained. Properly operated flares achieve at least 98 percent combustion efficiency in the flare plume, meaning that hydrocarbon and CO emmissions amount to less than 2 percent of hydrocarbons in the gas stream.

The tendency of a fuel to smoke or make soot is influenced by fuel characteristics and by the amount and distribution of oxygen in the combustion zone. For complete combustion, at least the stoichiometric amount of oxygen must be provided in the combustion zone. The theoretical amount of oxygen required increases with the molecular weight of the gas burned. The oxygen supplied as air ranges from 9.6 units of air per unit of methane to 38.3 units of air per unit of pentane, by volume. Air is supplied to the flame as primary air and secondary air. Primary air is mixed with the gas before combustion, whereas secondary air is drawn into the flame. For smokeless combustion, sufficient primary air must be supplied, this varying from about 20 percent of stoichiometric air for a paraffin to about 30 percent for an olefin. If the amount of primary air is insufficient, the gases entering the base of the flame are preheated by the combustion zone, and larger hydrocarbon molecules crack to form hydrogen, unsaturated hydrocarbons, and carbon. The carbon particles may escape further combustion and cool down to form soot or smoke. Olefins and other unsaturated hydrocarbons may polymerize to form larger molecules which crack, in turn forming more carbon.

The fuel characteristics influencing soot formation include the carbon-to-hydrogen (C-to-H) ratio and the molecular structure of the gases to be burned. All hydrocarbons above methane, i. e., those with a C-to-H ratio of greater than 0.33, tend to soot. Branched chain paraffins smoke more readily than corresponding normal isomers. The more highly branched the paraffin, the greater the tendency to smoke. Unsaturated hydrocarbons tend more toward soot formation than do saturated ones. Soot is eliminated by adding steam or air; hence, most industrial flares are steam-assisted and some are air-assisted. Flare gas composition is a critical factor in determining the amount of steam necessary.

Since flares do not lend themselves to conventional emission testing techniques, only a few attempts have been made to characterize flare emissions. Recent EPA tests using propylene as flare gas indicated that efficiencies of 98 percent can be achieved when burning an offgas with at least 11,200 kJ/m^3 (300 Btu/ft^3). The tests conducted on steam-assisted flares at velocities as low as 39.6 meters per minute (m/min) (130 ft/min) to 1140 m/min (3750 ft/min), and on air-assisted flares at velocities of 180 m/min (617 ft/min) to 3960 m/min (13,087 ft/min) indicated that variations in incoming gas flow rates have no effect on the combustion efficiency. Flare gases with less than 16,770 kJ/m^3 (450 Btu/ft^3) do not smoke.

Table 13.5-1 presents flare emission factors, and Table 13.5-2 presents emission composition data obtained from the EPA tests.[1] Crude propylene was used as flare gas during the tests. Methane was a major fraction of hydrocarbons in the flare emissions, and acetylene was the dominant intermediate hydrocarbon species. Many other reports on flares indicate that acetylene is always formed as a stable intermediate product. The acetylene formed in the combustion reactions may react further with hydrocarbon radicals to form polyacetylenes followed by polycyclic hydrocarbons.[2]

In flaring waste gases containing no nitrogen compounds, NO is formed either by the fixation of atmospheric nitrogen (N) with oxygen (O) or by the reaction between the hydrocarbon radicals present in the combustion products and atmospheric nitrogen, by way of the intermediate stages, HCN, CN, and OCN.[2] Sulfur compounds contained in a flare gas stream are converted to SO_2 when burned. The amount of SO_2 emitted depends directly on the quantity of sulfur in the flared gases.

Table 13.5-1 (English Units). EMISSION FACTORS FOR FLARE OPERATIONS[a]

EMISSION FACTOR RATING: B

Component	Emission Factor ($lb/10^6$ Btu)
Total hydrocarbons[b]	0.14
Carbon monoxide	0.37
Nitrogen oxides	0.068
Soot[c]	0 - 274

[a] Reference 1. Based on tests using crude propylene containing 80% propylene and 20% propane.

[b] Measured as methane equivalent.

[c] Soot in concentration values: nonsmoking flares, 0 micrograms per liter ($\mu g/L$); lightly smoking flares, 40 $\mu g/L$; average smoking flares, 177 $\mu g/L$; and heavily smoking flares, 274 $\mu g/L$.

Table 13.5-2. HYDROCARBON COMPOSITION OF FLARE EMISSION[a]

Composition	Volume %	
	Average	Range
Methane	55	14 - 83
Ethane/Ethylene	8	1 - 14
Acetylene	5	0.3 - 23
Propane	7	0 - 16
Propylene	25	1 - 65

[a] Reference 1. The composition presented is an average of a number of test results obtained under the following sets of test conditions: steam-assisted flare using high-Btu-content feed; steam-assisted using low-Btu-content feed; air-assisted flare using high-Btu-content feed; and air-assisted flare using low-Btu-content feed. In all tests, "waste" gas was a synthetic gas consisting of a mixture of propylene and propane.

References For Section 13.5

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APPENDIX A

MISCELLANEOUS DATA AND CONVERSION FACTORS

SOME USEFUL WEIGHTS AND MEASURES

Unit Of Measure	Equivalent	
grain	0.002	ounces
gram	0.04	ounces
ounce	28.35	grams
kilogram	2.21	pounds
pound	0.45	kilograms
pound (troy)	12	ounces
ton (short)	2000	pounds
ton (long)	2240	pounds
ton (metric)	2200	pounds
ton (shipping)	40	$feet^3$
centimeter	0.39	inches
inch	2.54	centimeters
foot	30.48	centimeters
meter	1.09	yards
yard	0.91	meters
mile	1.61	kilometers
$centimeter^2$	0.16	$inches^2$
$inch^2$	6.45	$centimeters^2$
$foot^2$	0.09	$meters^2$
$meter^2$	1.2	$yards^2$
$yard^2$	0.84	$meters^2$
$mile^2$	2.59	$kilometers^2$
$centimeter^3$	0.061	$inches^3$
$inch^3$	16.39	$centimeters^3$
$foot^3$	283.17	$centimeters^3$
$foot^3$	1728	$inches^3$

SOME USEFUL WEIGHTS AND MEASURES (cont.)

Unit Of Measure	Equivalent	
meter^3	1.31	yeads^3
yard^3	0.77	meters^3
cord	128	feet^3
cord	4	meters^3
peck	8	quarts
bushel (dry)	4	pecks
bushel	2150.4	inches^3
gallon (U. S.)	231	inches^3
barrel	31.5	gallons
hogshead	2	barrels
township	36	miles^2
hectare	2.5	acres

MISCELLANEOUS DATA

One cubic foot of anthracite coal weighs about 53 pounds.

One cubic foot of bituminous coal weighs from 47 to 50 pounds.

One ton of coal is equivalent to two cords of wood for steam purposes.

A gallon of water (U. S. Standard) weighs 8.33 pounds and contains 231 cubic inches.

There are 9 square feet of heating surface to each square foot of grate surface.

A cubic foot of water contains 7.5 gallons and 1728 cubic inches, and weighs 62.5 lbs..

Each nominal horsepower of a boiler requires 30 to 35 pounds of water per hour.

A horsepower is equivalent to raising 33,000 pounds one foot per minute, or 550 pounds one foot per second.

To find the pressure in pounds per square inch of a column of water, multiply the height of the column in feet by 0.434.

TYPICAL PARAMETERS OF VARIOUS FUELS[a]

Type Of Fuel	Heating Value		Sulfur % (by weight)	Ash % (by weight)
	kcal	Btu		
Solid Fuels				
Bituminous Coal	7,200/kg	13,000/lb	0.6-5.4	4-20
Anthracite Coal	6,810/kg	12,300/lb	0.5-1.0	7.0-16.0
Lignite (@ 35% moisture)	3,990/kg	7,200/lb	0.7	6.2
Wood (@ 40% moisture)	2,880/kg	5,200/lb	N	1-3
Bagasse (@ 50% moisture)	2,220/kg	4,000/lb	N	1-2
Bark (@ 50% moisture)	2,492/kg	4,500/lb	N	1-3[b]
Coke, Byproduct	7,380/kg	13,300/lb	0.5-1.0	0.5-5.0
Liquid Fuels				
Residual Oil	$9.98 \times 10^6/m^3$	150,000/gal	0.5-4.0	0.05-0.1
Distillate Oil	$9.30 \times 10^6/m^3$	140,000/gal	0.2-1.0	N
Diesel	$9.12 \times 10^6/m^3$	137,000/gal	0.4	N
Gasoline	$8.62 \times 10^6/m^3$	130,000/gal	0.03-0.04	N
Kerosene	$8.32 \times 10^6/m^3$	135,000/gal	0.02-0.05	N
Liquid Petroleum Gas	$6.25 \times 10^6/m^3$	94,000/gal	N	N
Gaseous Fuels				
Natural Gas	$9{,}341/m^3$	1,050/SCF	N	N
Coke Oven Gas	$5{,}249/m^3$	590/SCF	0.5-2.0	N
Blast Furnace Gas	$890/m^3$	100/SCF	N	N

[a] N = negligible.

[b] Ash content may be considerably higher when sand, dirt, etc., are present.

THERMAL EQUIVALENTS FOR VARIOUS FUELS

Type Of Fuel	kcal	Btu (gross)
Solid fuels		
Bituminous coal	$(5.8$ to $7.8) \times 10^6$/Mg	$(21.0$ to $28.0) \times 10^6$/ton
Anthracite coal	7.03×10^6/Mg	25.3×10^6/ton
Lignite	4.45×10^6/Mg	16.0×10^6/ton
Wood	$1.47 \times 10^6/m^3$	21.0×10^6/cord
Liquid fuels		
Residual fuel oil	10×10^3/liter	6.3×10^6/bbl
Distillate fuel oil	9.35×10^3/liter	5.9×10^6/bbl
Gaseous fuels		
Natural gas	$9{,}350/m^3$	$1{,}050/ft^3$
Liquefied petroleum gas		
Butane	6,480/liter	97,400/gal
Propane	6,030/liter	90,500/gal

WEIGHTS OF SELECTED SUBSTANCES

Type Of Substance	g/liter	lb/gal
Asphalt	1030	8.57
Butane, liquid at 60°F	579	4.84
Crude oil	850	7.08
Distillate oil	845	7.05
Gasoline	739	6.17
Propane, liquid at 60°F	507	4.24
Residual oil	944	7.88
Water	1000	8.4

DENSITIES OF SELECTED SUBSTANCES

Substance	Density	
Fuels		
Crude Oil	874 kg/m^3	7.3 lb/gal
Residual Oil	944 kg/m^3	7.88 lb/gal
Distillate Oil	845 kg/m^3	7.05 lb/gal
Gasoline	739 kg/m^3	6.17 lb/gal
Natural Gas	673 kg/m^3	1 lb/23.8 ft^3
Butane	579 kg/m^3	4.84 lb/gal (liquid)
Propane	507 kg/m^3	4.24 lb/gal (liquid)
Wood (Air dried)		
Elm	561 kg/m^3	35 lb/ft^3
Fir, Douglas	513 kg/m^3	32 lb/ft^3
Fir, Balsam	400 kg/m^3	25 lb/ft^3
Hemlock	465 kg/m^3	29 lb/ft^3
Hickory	769 kg/m^3	48 lb/ft^3
Maple, Sugar	689 kg/m^3	43 lb/ft^3
Maple, White	529 kg/m^3	33 lb/ft^3
Oak, Red	673 kg/m^3	42 lb/ft^3
Oak, White	769 kg/m^3	48 lb/ft^3
Pine, Southern	641 kg/m^3	40 lb/ft^3
Agricultural Products		
Corn	25.4 kg/bu	56 lb/bu
Milo	25.4 kg/bu	56 lb/bu
Oats	14.5 kg/bu	32 lb/bu
Barley	21.8 kg/bu	48 lb/bu
Wheat	27.2 kg/bu	60 lb/bu
Cotton	226 kg/bale	500 lb/bale
Mineral Products		
Brick	2.95 kg/brick	6.5 lb/brick
Cement	170 kg/bbl	375 lb/bbl
Cement	1483 kg/m^3	2500 lb/yd^3

DENSITIES OF SELECTED SUBSTANCES (cont.).

Substance	Density	
Concrete	2373 kg/m^3	4000 lb/yd^3
Glass, Common	2595 kg/m^3	162 lb/ft^3
Gravel, Dry Packed	1600 - 1920 kg/m^3	100 - 120 lb/ft^3
Gravel, Wet	2020 kg/m^3	126 lb/ft^3
Gypsum, Calcined	880 - 960 kg/m^3	55 - 60 lb/ft^3
Lime, Pebble	850 - 1025 kg/m^3	53 - 64 lb/ft^3
Sand, Gravel (Dry, loose)	1440 - 1680 kg/m^3	90 - 105 lb/ft^3

CONVERSION FACTORS

The table of conversion factors on the following pages contains factors for converting English to metric units and metric to English units as well as factors to manipulate units within the same system. The factors are arranged alphabetically by unit within the following property groups.

- Area
- Density
- Energy
- Force
- Length
- Mass
- Pressure
- Velocity
- Volume
- Volumetric Rate

To convert a number from one unit to another:

1. Locate the unit in which the number is currently expressed in the left-hand column of the table;

2. Find the desired unit in the center column; and

3. Multiply the number by the corresponding conversion factor in the right-hand column.

CONVERSION FACTORS[a]

To Convert From	To	Multiply By
Area		
Acres	Sq feet	4.356×10^4
Acres	Sq kilometers	4.0469×10^{-3}
Acres	Sq meters	4.0469×10^3
Acres	Sq miles (statute)	1.5625×10^{-3}
Acres	Sq yards	4.84×10^3
Sq feet	Acres	2.2957×10^{-5}
Sq feet	Sq cm	929.03
Sq feet	Sq inches	144.0
Sq feet	Sq meters	0.092903
Sq feet	Sq miles	3.587×10^{-8}
Sq feet	Sq yards	0.111111
Sq inches	Sq feet	6.9444×10^{-3}
Sq inches	Sq meters	6.4516×10^{-4}
Sq inches	Sq mm	645.16
Sq kilometers	Acres	247.1
Sq kilometers	Sq feet	1.0764×10^7
Sq kilometers	Sq meters	1.0×10^6
Sq kilometers	Sq miles	0.386102
Sq kilometers	Sq yards	1.196×10^6
Sq meters	Sq cm	1.0×10^4
Sq meters	Sq feet	10.764
Sq meters	Sq inches	1.55×10^3
Sq meters	Sq kilometers	1.0×10^{-6}
Sq meters	Sq miles	3.861×10^{-7}
Sq meters	Sq mm	1.0×10^6
Sq meters	Sq yards	1.196
Sq miles	Acres	640.0
Sq miles	Sq feet	2.7878×10^7
Sq miles	Sq kilometers	2.590

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Sq miles	Sq meters	2.59×10^6
Sq miles	Sq yards	3.0976×10^6
Sq yards	Acres	2.0661×10^{-4}
Sq yards	Sq cm	8.3613×10^3
Sq yards	Sq ft	9.0
Sq yards	Sq inches	1.296×10^3
Sq yards	Sq meters	0.83613
Sq yards	Sq miles	3.2283×10^{-7}
Density		
Dynes/cu cm	Grams/cu cm	1.0197×10^{-3}
Grains/cu foot	Grams/cu meter	2.28835
Grams/cu cm	Dynes/cu cm	980.665
Grams/cu cm	Grains/milliliter	15.433
Grams/cu cm	Grams/milliliter	1.0
Grams/cu cm	Pounds/cu inch	1.162
Grams/cu cm	Pounds/cu foot	62.428
Grams/cu cm	Pounds/cu inch	0.036127
Grams/cu cm	Pounds/gal (Brit.)	10.022
Grams/cu cm	Pounds/gal (U. S., dry)	9.7111
Grams/cu cm	Pounds/gal (U. S., liq.)	8.3454
Grams/cu meter	Grains/cu foot	0.4370
Grams/liter	Pounds/gal (U. S.)	8.345×10^{-3}
Kilograms/cu meter	Grams/cu cm	0.001
Kilograms/cu meter	Pounds/cu ft	0.0624
Kilograms/cu meter	Pounds/cu in	3.613×10^{-5}
Pounds/cu foot	Grams/cu cm	0.016018
Pounds/cu foot	kg/cu meter	16.018
Pounds/cu inch	Grams/cu cm	27.68
Pounds/cu inch	Grams/liter	27.681
Pounds/cu inch	kg/cu meter	2.768×10^4

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Pounds/gal (U. S., liq.)	Grams/cu cm	0.1198
Pounds/gal (U. S., liq.)	Pounds/cu ft	7.4805
Energy		
Btu	Cal. gm (IST.)	251.83
Btu	Ergs	1.05435×10^{10}
Btu	Foot-pounds	777.65
Btu	Hp-hours	3.9275×10^{-4}
Btu	Joules (Int.)	1054.2
Btu	kg-meters	107.51
Btu	kW-hours (Int.)	2.9283×10^{-4}
Btu/hr	Cal. kg/hr	0.252
Btu/hr	Ergs/sec	2.929×10^{6}
Btu/hr	Foot-pounds/hr	777.65
Btu/hr	Horsepower (mechanical)	3.9275×10^{-4}
Btu/hr	Horsepower (boiler)	2.9856×10^{-5}
Btu/hr	Horsepower (electric)	3.926×10^{-4}
Btu/hr	Horsepower (metric)	3.982×10^{-4}
Btu/hr	Kilowatts	2.929×10^{-4}
Btu/lb	Foot-pounds/lb	777.65
Btu/lb	Hp-hr/lb	3.9275×10^{-4}
Btu/lb	Joules/gram	2.3244
Calories, kg (mean)	Btu (IST.)	3.9714
Calories, kg (mean)	Ergs	4.190×10^{10}
Calories, kg (mean)	Foot-pounds	3.0904×10^{3}
Calories, kg (mean)	Hp-hours	1.561×10^{-3}
Calories, kg (mean)	Joules	4.190×10^{3}
Calories, kg (mean)	kg-meters	427.26
Calories, kg (mean)	kW-hours (Int.)	1.1637×10^{-3}
Ergs	Btu	9.4845×10^{-11}
Ergs	Foot-poundals	2.373×10^{-6}

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Ergs	Foot-pounds	7.3756×10^{-8}
Ergs	Joules (Int.)	9.99835×10^{-8}
Ergs	kW-hours	2.7778×10^{-14}
Ergs	kg-meters	1.0197×10^{-8}
Foot-pounds	Btu (IST.)	1.2851×10^{-3}
Foot-pounds	Cal. kg (IST.)	3.2384×10^{-4}
Foot-pounds	Ergs	1.3558×10^{7}
Foot-pounds	Foot-poundals	32.174
Foot-pounds	Hp-hours	5.0505×10^{-7}
Foot-pounds	Joules	1.3558
Foot-pounds	kg-meters	0.138255
Foot-pounds	kW-hours (Int.)	3.76554×10^{-7}
Foot-pounds	Newton-meters	1.3558
Foot-pounds/hr	Btu/min	2.1432×10^{-5}
Foot-pounds/hr	Ergs/min	2.2597×10^{5}
Foot-pounds/hr	Horsepower (mechanical)	5.0505×10^{-7}
Foot-pounds/hr	Horsepower (metric)	5.121×10^{-7}
Foot-pounds/hr	Kilowatts	3.766×10^{-7}
Horsepower (mechanical)	Btu (mean)/hr	2.5425×10^{3}
Horsepower (mechanical)	Ergs/sec	7.457×10^{9}
Horsepower (mechanical)	Foot-pounds/hr	1.980×10^{6}
Horsepower (mechanical)	Horsepower (boiler)	0.07602
Horsepower (mechanical)	Horsepower (electric)	0.9996
Horsepower (mechanical)	Horsepower (metric)	1.0139
Horsepower (mechanical)	Joules/sec	745.70
Horsepower (mechanical)	Kilowatts (Int.)	0.74558
Horsepower (boiler)	Btu (mean)/hr	3.3446×10^{4}
Horsepower (boiler)	Ergs/sec	9.8095×10^{10}
Horsepower (boiler)	Foot-pounds/min	4.341×10^{5}
Horsepower (boiler)	Horsepower (mechanical)	13.155

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Horsepower (boiler)	Horsepower (electric)	13.15
Horsepower (boiler)	Horsepower (metric)	13.337
Horsepower (boiler)	Joules/sec	9.8095×10^3
Horsepower (boiler)	Kilowatts	9.8095
Horsepower (electric)	Btu (mean)/hr	2.5435×10^3
Horsepower (electric)	Cal. kg/hr	641.87
Horsepower (electric)	Ergs/sec	7.46×10^9
Horsepower (electric)	Foot-pounds/min	3.3013×10^4
Horsepower (electric)	Horsepower (boiler)	0.07605
Horsepower (electric)	Horsepower (metric)	1.0143
Horsepower (electric)	Joules/sec	746.0
Horsepower (electric)	Kilowatts	0.746
Horsepower (metric)	Btu (mean)/hr	2.5077×10^3
Horsepower (metric)	Ergs/sec	7.355×10^9
Horsepower (metric)	Foot-pounds/min	3.255×10^4
Horsepower (metric)	Horsepower (mechanical)	0.98632
Horsepower (metric)	Horsepower (boiler)	0.07498
Horsepower (metric)	Horsepower (electric)	0.9859
Horsepower (metric)	kg-meters/sec	75.0
Horsepower (metric)	Kilowatts	0.7355
Horsepower-hours	Btu (mean)	2.5425×10^3
Horsepower-hours	Foot-pounds	1.98×10^6
Horsepower-hours	Joules	2.6845×10^6
Horsepower-hours	kg-meters	2.73745×10^5
Horsepower-hours	kW-hours	0.7457
Joules (Int.)	Btu (IST.)	9.4799×10^{-4}
Joules (Int.)	Ergs	1.0002×10^7
Joules (Int.)	Foot-poundals	12.734
Joules (Int.)	Foot-pounds	0.73768
Joules (Int.)	kW-hours	2.778×10^{-7}

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Joules (Int.)/sec	Btu (mean)/min	0.05683
Joules (Int.)/sec	Cal. kg/min	0.01434
Joules (Int.)/sec	Horsepower	1.341×10^{-3}
Kilogram-meters	Btu (mean)	9.2878×10^{-3}
Kilogram-meters	Cal. kg (mean)	2.3405×10^{-3}
Kilogram-meters	Ergs	9.80665×10^{7}
Kilogram-meters	Foot-poundals	232.715
Kilogram-meters	Foot-pounds	7.233
Kilogram-meters	Hp-hours	3.653×10^{-6}
Kilogram-meters	Joules (Int.)	9.805
Kilogram-meters	kW-hours	2.724×10^{-6}
Kilogram-meters/sec	Watts	9.80665
Kilowatts (Int.)	Btu (IST.)/hr	3.413×10^{3}
Kilowatts (Int.)	Cal. kg (IST.)/hr	860.0
Kilowatts (Int.)	Ergs/sec	1.0002×10^{10}
Kilowatts (Int.)	Foot-poundals/min	1.424×10^{6}
Kilowatts (Int.)	Foot-pounds/min	4.4261×10^{4}
Kilowatts (Int.)	Horsepower (mechanical)	1.341
Kilowatts (Int.)	Horsepower (boiler)	0.10196
Kilowatts (Int.)	Horsepower (electric)	1.3407
Kilowatts (Int.)	Horsepower (metric)	1.3599
Kilowatts (Int.)	Joules (Int.)/hr	3.6×10^{6}
Kilowatts (Int.)	kg-meters/hr	3.6716×10^{5}
Kilowatt-hours (Int.)	Btu (mean)	3.41×10^{3}
Kilowatt-hours (Int.)	Foot-pounds	2.6557×10^{6}
Kilowatt-hours (Int.)	Hp-hours	1.341
Kilowatt-hours (Int.)	Joules (Int.)	3.6×10^{6}
Kilowatt-hours (Int.)	kg-meters	3.6716×10^{5}
Newton-meters	Gram-cm	1.01972×10^{4}
Newton-meters	kg-meters	0.101972

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Newton-meters	Pound-feet	0.73756
Force		
Dynes	Newtons	1.0×10^{-5}
Dynes	Poundals	7.233×10^{-5}
Dynes	Pounds	2.248×10^{-6}
Newtons	Dynes	1.0×10^{-5}
Newtons	Pounds (avdp.)	0.22481
Poundals	Dynes	1.383×10^{4}
Poundals	Newtons	0.1383
Poundals	Pounds (avdp.)	0.03108
Pounds (avdp.)	Dynes	4.448×10^{5}
Pounds (avdp.)	Newtons	4.448
Pounds (avdp.)	Poundals	32.174
Length		
Feet	Centimeters	30.48
Feet	Inches	12
Feet	Kilometers	3.048×10^{-4}
Feet	Meters	0.3048
Feet	Miles (statute)	1.894×10^{-4}
Inches	Centimeters	2.540
Inches	Feet	0.08333
Inches	Kilometers	2.54×10^{-5}
Inches	Meters	0.0254
Kilometers	Feet	3.2808×10^{3}
Kilometers	Meters	1000
Kilometers	Miles (statute)	0.62137
Kilometers	Yards	1.0936×10^{3}
Meters	Feet	3.2808
Meters	Inches	39.370
Micrometers	Angstrom units	1.0×10^{4}

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Micrometers	Centimeters	1.0×10^{-3}
Micrometers	Feet	3.2808×10^{-6}
Micrometers	Inches	3.9370×10^{-5}
Micrometers	Meters	1.0×10^{-6}
Micrometers	Millimeters	0.001
Micrometers	Nanometers	1000
Miles (statute)	Feet	5280
Miles (statute)	Kilometers	1.6093
Miles (statute)	Meters	1.6093×10^{3}
Miles (statute)	Yards	1760
Millimeters	Angstrom units	1.0×10^{7}
Millimeters	Centimeters	0.1
Millimeters	Inches	0.03937
Millimeters	Meters	0.001
Millimeters	Micrometers	1000
Millimeters	Mils	39.37
Nanometers	Angstrom units	10
Nanometers	Centimeters	1.0×10^{-7}
Nanometers	Inches	3.937×10^{-8}
Nanometers	Micrometers	0.001
Nanometers	Millimeters	1.0×10^{-6}
Yards	Centimeters	91.44
Yards	Meters	0.9144
Mass		
Grains	Grams	0.064799
Grains	Milligrams	64.799
Grains	Pounds (apoth. or troy)	1.7361×10^{-4}
Grains	Pounds (avdp.)	1.4286×10^{-4}
Grains	Tons (metric)	6.4799×10^{-8}
Grams	Dynes	980.67

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Grams	Grains	15.432
Grams	Kilograms	0.001
Grams	Micrograms	1×10^{6}
Grams	Pounds (avdp.)	2.205×10^{-3}
Grams	Tons, metric (megagrams)	1×10^{-6}
Kilograms	Grains	1.5432×10^{4}
Kilograms	Poundals	70.932
Kilograms	Pounds (apoth. or troy)	2.679
Kilograms	Pounds (avdp.)	2.2046
Kilograms	Tons (long)	9.842×10^{-4}
Kilograms	Tons (metric)	0.001
Kilograms	Tons (short)	1.1023×10^{-3}
Megagrams	Tons (metric)	1.0
Milligrams	Grains	0.01543
Milligrams	Grams	1.0×10^{-3}
Milligrams	Ounces (apoth. or troy)	3.215×10^{-5}
Milligrams	Ounces (avdp.)	3.527×10^{-5}
Milligrams	Pounds (apoth. or troy)	2.679×10^{-6}
Milligrams	Pounds (avdp.)	2.2046×10^{-6}
Ounces (apoth. or troy)	Grains	480
Ounces (apoth. or troy)	Grams	31.103
Ounces (apoth. or troy)	Ounces (avdp.)	1.097
Ounces (avdp.)	Grains	437.5
Ounces (avdp.)	Grams	28.350
Ounces (avdp.)	Ounces (apoth. or troy)	0.9115
Ounces (avdp.)	Pounds (apoth. or troy)	0.075955
Ounces (avdp.)	Pounds (avdp.)	0.0625
Pounds (avdp.)	Poundals	32.174
Pounds (avdp.)	Pounds (apoth. or troy)	1.2153
Pounds (avdp.)	Tons (long)	4.4643×10^{-4}

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Pounds (avdp.)	Tons (metric)	4.5359×10^{-4}
Pounds (avdp.)	Tons (short)	5.0×10^{-4}
Pounds (avdp.)	Grains	7000
Pounds (avdp.)	Grams	453.59
Pounds (avdp.)	Ounces (apoth. or troy)	14.583
Pounds (avdp.)	Ounces (avdp.)	16
Tons (long)	Kilograms	1.016×10^{3}
Tons (long)	Pounds (apoth. or troy)	2.722×10^{3}
Tons (long)	Pounds (avdp.)	2.240×10^{3}
Tons (long)	Tons (metric)	1.016
Tons (long)	Tons (short)	1.12
Tons (metric)	Grams	1.0×10^{6}
Tons (metric)	Megagrams	1.0
Tons (metric)	Pounds (apoth. or troy)	2.6792×10^{3}
Tons (metric)	Pounds (avdp.)	2.2046×10^{3}
Tons (metric)	Tons (long)	0.9842
Tons (metric)	Tons (short)	1.1023
Tons (short)	Kilograms	907.18
Tons (short)	Pounds (apoth. or troy)	2.4301×10^{3}
Tons (short)	Pounds (avdp.)	2000
Tons (short)	Tons (long)	0.8929
Tons (short)	Tons (metric)	0.9072
Pressure		
Atmospheres	cm of H_2O (4°C)	1.033×10^{3}
Atmospheres	Ft of H_2O (39.2°F)	33.8995
Atmospheres	In. of Hg (32°F)	29.9213
Atmospheres	kg/sq cm	1.033
Atmospheres	mm of Hg (0°C)	760
Atmospheres	Pounds/sq inch	14.696
Inches of Hg (60°F)	Atmospheres	0.03333

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Inches of Hg (60°F)	Grams/sq cm	34.434
Inches of Hg (60°F)	mm of Hg (60°F)	25.4
Inches of Hg (60°F)	Pounds/sq ft	70.527
Inches of H_2O (4°C)	Atmospheres	2.458×10^{-3}
Inches of H_2O (4°C)	In. of Hg (32°F)	0.07355
Inches of H_2O (4°C)	kg/sq meter	25.399
Inches of H_2O (4°C)	Pounds/sq ft	5.2022
Inches of H_2O (4°C)	Pounds/sq inch	0.036126
Kilograms/sq cm	Atmospheres	0.96784
Kilograms/sq cm	cm of Hg (0°C)	73.556
Kilograms/sq cm	Ft of H_2O (39.2°F)	32.809
Kilograms/sq cm	In. of Hg (32°F)	28.959
Kilograms/sq cm	Pounds/sq inch	14.223
Millimeters of Hg (0°C)	Atmospheres	1.3158×10^{-3}
Millimeters of Hg (0°C)	Grams/sq cm	1.3595
Millimeters of Hg (0°C)	Pounds/sq inch	0.019337
Pounds/sq inch	Atmospheres	0.06805
Pounds/sq inch	cm of Hg (0°C)	5.1715
Pounds/sq inch	cm of H_2O (4°C)	70.309
Pounds/sq inch	In. of Hg (32°F)	2.036
Pounds/sq inch	In. of H_2O (39.2°F)	27.681
Pounds/sq inch	kg/sq cm	0.07031
Pounds/sq inch	mm of Hg (0°C)	51.715
Velocity		
Centimeters/sec	Feet/min	1.9685
Centimeters/sec	Feet/sec	0.0328
Centimeters/sec	Kilometers/hr	0.036
Centimeters/sec	Meters/min	0.6
Centimeters/sec	Miles/hr	0.02237

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Feet/minute	cm/sec	0.508
Feet/minute	Kilometers/hr	0.01829
Feet/minute	Meters/min	0.3048
Feet/minute	Meters/sec	5.08×10^{-3}
Feet/minute	Miles/hr	0.01136
Feet/sec	cm/sec	30.48
Feet/sec	Kilometers/hr	1.0973
Feet/sec	Meters/min	18.288
Feet/sec	Miles/hr	0.6818
Kilometers/hr	cm/sec	27.778
Kilometers/hr	Feet/hr	3.2808×10^{3}
Kilometers/hr	Feet/min	54.681
Kilometers/hr	Meters/sec	0.27778
Kilometers/hr	Miles (statute)/hr	0.62137
Meters/min	cm/sec	1.6667
Meters/min	Feet/min	3.2808
Meters/min	Feet/sec	0.05468
Meters/min	Kilometers/hr	0.06
Miles/hr	cm/sec	44.704
Miles/hr	Feet/hr	5280
Miles/hr	Feet/min	88
Miles/hr	Feet/sec	1.4667
Miles/hr	Kilometers/hr	1.6093
Miles/hr	Meters/min	26.822
Volume		
Barrels (petroleum, U. S.)	Cu feet	5.6146
Barrels (petroleum, U. S.)	Gallons (U. S.)	42
Barrels (petroleum, U. S.)	Liters	158.98
Barrels (U. S., liq.)	Cu feet	4.2109
Barrels (U. S., liq.)	Cu inches	7.2765×10^{3}

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Barrels (U. S., liq.)	Cu meters	0.1192
Barrels (U. S., liq.)	Gallons (U. S., liq.)	31.5
Barrels (U. S., liq.)	Liters	119.24
Cubic centimeters	Cu feet	3.5315×10^{-5}
Cubic centimeters	Cu inches	0.06102
Cubic centimeters	Cu meters	1.0×10^{-6}
Cubic centimeters	Cu yards	1.308×10^{-6}
Cubic centimeters	Gallons (U. S., liq.)	2.642×10^{-4}
Cubic centimeters	Quarts (U. S., liq.)	1.0567×10^{-3}
Cubic feet	Cu centimeters	2.8317×10^{4}
Cubic feet	Cu meters	0.028317
Cubic feet	Gallons (U. S., liq.)	7.4805
Cubic feet	Liters	28.317
Cubic inches	Cu cm	16.387
Cubic inches	Cu feet	5.787×10^{-4}
Cubic inches	Cu meters	1.6387×10^{-5}
Cubic inches	Cu yards	2.1433×10^{-5}
Cubic inches	Gallons (U. S., liq.)	4.329×10^{-3}
Cubic inches	Liters	0.01639
Cubic inches	Quarts (U. S., liq.)	0.01732
Cubic meters	Barrels (U. S., liq.)	8.3864
Cubic meters	Cu cm	1.0×10^{6}
Cubic meters	Cu feet	35.315
Cubic meters	Cu inches	6.1024×10^{4}
Cubic meters	Cu yards	1.308
Cubic meters	Gallons (U. S., liq.)	264.17
Cubic meters	Liters	1000
Cubic yards	Bushels (Brit.)	21.022
Cubic yards	Bushels (U. S.)	21.696
Cubic yards	Cu cm	7.6455×10^{5}

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Cubic yards	Cu feet	27
Cubic yards	Cu inches	4.6656×10^4
Cubic yards	Cu meters	0.76455
Cubic yards	Gallons	168.18
Cubic yards	Gallons	173.57
Cubic yards	Gallons	201.97
Cubic yards	Liters	764.55
Cubic yards	Quarts	672.71
Cubic yards	Quarts	694.28
Cubic yards	Quarts	807.90
Gallons (U. S., liq.)	Barrels (U. S., liq.)	0.03175
Gallons (U. S., liq.)	Barrels (petroleum, U. S.)	0.02381
Gallons (U. S., liq.)	Bushels (U. S.)	0.10742
Gallons (U. S., liq.)	Cu centimeters	3.7854×10^3
Gallons (U. S., liq.)	Cu feet	0.13368
Gallons (U. S., liq.)	Cu inches	231
Gallons (U. S., liq.)	Cu meters	3.7854×10^{-3}
Gallons (U. S., liq.)	Cu yards	4.951×10^{-3}
Gallons (U. S., liq.)	Gallons (wine)	1.0
Gallons (U. S., liq.)	Liters	3.7854
Gallons (U. S., liq.)	Ounces (U. S., fluid)	128.0
Gallons (U. S., liq.)	Pints (U. S., liq.)	8.0
Gallons (U. S., liq.)	Quarts (U. S., liq.)	4.0
Liters	Cu centimeters	1000
Liters	Cu feet	0.035315
Liters	Cu inches	61.024
Liters	Cu meters	0.001
Liters	Gallons (U. S., liq.)	0.2642
Liters	Ounces (U. S., fluid)	33.814

CONVERSION FACTORS (cont.).

To Convert From	To	Multiply By
Volumetric Rate		
Cu ft/min	Cu cm/sec	471.95
Cu ft/min	Cu ft /hr	60. 0
Cu ft/min	Gal (U. S.)/min	7.4805
Cu ft/min	Liters/sec	0.47193
Cu meters/min	Gal (U. S.)/min	264.17
Cu meters/min	Liters/min	999.97
Gallons (U. S.)/hr	Cu ft/hr	0.13368
Gallons (U. S.)/hr	Cu meters/min	6.309×10^{-5}
Gallons (U. S.)/hr	Cu yd/min	8.2519×10^{-5}
Gallons (U. S.)/hr	Liters/hr	3.7854
Liters/min	Cu ft/min	0.0353
Liters/min	Gal (U. S., liq.)/min	0.2642

[a] Where appropriate, the conversion factors appearing in this table have been rounded to four to six significant figures for ease in use. The accuracy of these numbers is considered suitable for use with emissions data; if a more accurate number is required, tables containing exact factors should be consulted.

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS

AIRBORNE PARTICULATE MATTER

To Convert From	To	Multiply By
Milligrams/cu m	Grams/cu ft	283.2×10^{-6}
	Grams/cu m	0.001
	Micrograms/cu m	1000.0
	Micrograms/cu ft	28.32
	Pounds/1000 cu ft	62.43×10^{-6}
Grams/cu ft	Milligrams/cu m	35.3145×10^{3}
	Grams/cu m	35.314
	Micrograms/cu m	35.314×10^{6}
	Micrograms/cu ft	1.0×10^{6}
	Pounds/1000 cu ft	2.2046
Grams/cu m	Milligrams/cu m	1000.0
	Grams/cu ft	0.02832
	Micrograms/cu m	1.0×10^{6}
	Micrograms/cu ft	28.317×10^{3}
	Pounds/1000 cu ft	0.06243
Micrograms/cu m	Milligrams/cu m	0.001
	Grams/cu ft	28.317×10^{-9}
	Grams/cu m	1.0×10^{-6}
	Micrograms/cu ft	0.02832
	Pounds/1000 cu ft	62.43×10^{-9}
Micrograms/cu ft	Milligrams/cu m	35.314×10^{-3}
	Grams/cu ft	1.0×10^{-6}
	Grams/cu m	35.314×10^{-6}
	Micrograms/cu m	35.314
	Pounds/1000 cu ft	2.2046×10^{-6}
Pounds/1000 cu ft	Milligrams/cu m	16.018×10^{3}
	Grams/cu ft	0.35314
	Micrograms/cu m	16.018×10^{6}
	Grams/cu m	16.018
	Micrograms/cu ft	353.14×10^{3}

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS (cont.).

SAMPLING PRESSURE

To Convert From	To	Multiply By
Millimeters of mercury (0°C)	Inches of water (60°F)	0.5358
Inches of mercury (0°C)	Inches of water (60°F)	13.609
	Millimeters of mercury (0°C)	1.8663
Inches of water (60°F)	Inches of mercury (0°C)	73.48×10^{-3}

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS (cont.).

ATMOSPHERIC GASES

To Convert From	To	Multiply By
Milligrams/cu m	Micrograms/cu m	1000.0
	Micrograms/liter	1.0
	ppm by volume (20°C)	24.04/M
	ppm by weight	0.8347
	Pounds/cu ft	62.43×10^{-9}
Micrograms/cu m	Milligrams/cu m	0.001
	Micrograms/liter	0.001
	ppm by volume (20°C)	0.02404/M
	ppm by weight	834.7×10^{-6}
	Pounds/cu ft	62.43×10^{-12}
Micrograms/liter	Milligrams/cu m	1.0
	Micrograms/cu m	1000.0
	ppm by volume (20°C)	24.04/M
	ppm by weight	0.8347
	Pounds/cu ft	62.43×10^{-9}
ppm by volume (20°C)	Milligrams/cu m	M/24.04
	Micrograms/cu m	M/0.02404
	Micrograms/liter	M/24.04
	ppm by weight	M/28.8
	Pounds/cu ft	$M/385.1 \times 10^{6}$
ppm by weight	Milligrams/cu m	1.198
	Micrograms/cu m	1.198×10^{-3}
	Micrograms/liter	1.198
	ppm by volume (20°C)	28.8/M
	Pounds/cu ft	7.48×10^{-6}
Pounds/cu ft	Milligrams/cu m	16.018×10^{6}
	Micrograms/cu m	16.018×10^{9}
	Micrograms/liter	16.018×10^{6}
	ppm by volume (20°C)	$385.1 \times 10^{6}/M$
	ppm by weight	133.7×10^{3}

M = Molecular weight of gas.

CONVERSION FACTORS FOR COMMON AIR POLLUTION MEASUREMENTS (cont.).

VELOCITY

To Convert From	To	Multiply By
Meters/sec	Kilometers/hr	3.6
	Feet/sec	3.281
	Miles/hr	2.237
Kilometers/hr	Meters/sec	0.2778
	Feet/sec	0.9113
	Miles/hr	0.6214
Feet/sec	Meters/sec	0.3048
	Kilometers/hr	1.09728
	Miles/hr	0.6818
Miles/hr	Meters/sec	0.4470
	Kilometers/hr	1.6093
	Feet/sec	1.4667

ATMOSPHERIC PRESSURE

To Convert From	To	Multiply By
Atmospheres	Millimeters of mercury	760.0
	Inches of mercury	29.92
	Millibars	1013.2
Millimeters of mercury	Atmospheres	1.316×10^{-3}
	Inches of mercury	39.37×10^{-3}
	Millibars	1.333
Inches of mercury	Atmospheres	0.03333
	Millimeters of mercury	25.4005
	Millibars	33.35
Millibars	Atmospheres	0.00987
	Millimeters of mercury	0.75
	Inches of mercury	0.30

VOLUME EMISSIONS

To Convert From	To	Multiply By
Cubic m/min	Cubic ft/min	35.314
Cubic ft/min	Cubic m/min	0.0283

BOILER CONVERSION FACTORS

1 Megawatt = 10.5 x 10^6 BTU/hr
(8 to 14 x 10^6 BTU/hr)

1 Megawatt = 8 x 10^3 lb steam/hr
(6 to 11 x 10^3 lb steam/hr)

1 BHP = 34.5 lb steam/hr

1 BHP = 45 x 10^3 BTU/hr
(40 to 50 x 10^3 BTU/hr)

1 lb steam/hr = 1.4 x 10^3 BTU/hr
(1.2 to 1.7 x 10^3 BTU/hr)

NOTES: In the relationships,

Megawatt is the net electric power production of a steam electric power plant.

BHP is boiler horsepower.

Lb steam/hr is the steam production rate of the boiler.

BTU/hr is the heat input rate to the boiler (based on the gross or high heating value of the fuel burned).

For less efficient (generally older and/or smaller) boiler operations, use the higher values expressed. For more efficient operations (generally newer and/or larger), use the lower vlaues.

VOLUME	cu. in.	ml.	liters	ounces (U. S. fl.)	gallons (U. S.)	barrels (U. S.)	cu. ft.
Cubic inches	....	16.3868	.0163868	0.5541	4.3290×10^{-3}	1.37429×10^{-4}	5.78704×10^{-4}
Milliliters	0.061024	....	0.001	0.03381	2.6418×10^{-4}	8.387×10^{-6}	3.5316×10^{-5}
Liters	61.024	1000	....	33.8147	0.26418	8.387×10^{-3}	0.035316
Ounces (U. S. fl.)	1.80469	29.5729	0.029573	....	7.8125×10^{-3}	2.48×10^{-4}	1.0443×10^{-3}
Gallons (U. S.)*..	231	3785.3	3.7853	128	....	0.031746	0.13368
Barrels (U. S.)...	7276.5	1.1924×10^{5}	119.2369	4032.0	31.5	....	4.2109
Cubic feet	1728	2.8316×10^{4}	28.316	957.568	7.481	0.23743	....

[1] U. S. gallon of water at 16.7°C (62°F) weighs 3.780 kg. or 8.337 pounds (avoir.)

MASS	grams	kilograms	ounces (avoir.)	pounds (avoir.)	grains	tons (U. S.)	milligrams
Grams	....	0.001	3.527×10^{-2}	2.205×10^{-3}	15.432	1.102×10^{-6}	1000
Kilograms	1000	....	35.274	2.2046	15432	1.102×10^{-3}	1×10^{6}
Ounces (avoir.)...	28.350	0.028350	....	0.0625	437.5	3.125×10^{-5}	2.8350×10^{4}
Pounds (avoir.)*..	453.59	0.45359	16.0	....	7000	5.0×10^{-4}	4.5359×10^{5}
Grains	0.06480	6.480×10^{-5}	2.286×10^{-3}	1.429×10^{-4}	....	7.142×10^{-8}	64.799
Tons (U. S.)	9.072×10^{5}	907.19	3.200×10^{4}	2000	1.4×10^{7}	....	9.0718×10^{8}
Milligrams	0.001	1×10^{-6}	3.527×10^{-5}	2.205×10^{-6}	0.015432	1.102×10^{-9}	....

*Mass of 27.692 cubic inches water weighed in air at 4.0°C, 760 mm mercury pressure.

WORK AND ENERGY	g. cal.	kg. cal.	ergs	Joules	BTU	ft. lb.	kg. meters	L-Atm	HP Hours	ft. poundals	KWH	WH
Gram Calories (mean)...........	....	0.001	4.186×10^{7}	4.186	3.9680×10^{-3}	3.0874	0.42685	0.041311	1.5593×10^{-6}	99.334	1.1628×10^{-6}	1.1628×10^{-3}
Kilogram Calories.	1000	....	4.186×10^{10}	4186	3.9680	3087.4	426.85	41.311	1.5593×10^{-3}	99334	1.1628×10^{-3}	1.1628
Ergs	2.3889×10^{-8}	2.3889×10^{-11}	....	1×10^{-7}	9.4805×10^{-11}	7.3756×10^{-8}	1.0197×10^{-8}	9.8689×10^{-10}	3.7251×10^{-14}	2.3730×10^{-6}	2.7778×10^{-14}	2.7778×10^{-11}
Joules	0.23889	2.3889×10^{-4}	1×10^{7}	....	9.4805×10^{-4}	0.73756	0.10197	9.8689×10^{-3}	3.7251×10^{-7}	23.730	2.7778×10^{-7}	2.7778×10^{-4}
BTU (mean)	251.98	0.25198	1.0548×10^{10}	1054.8	....	777.98	107.56	10.409	3.9292×10^{-4}	2.5030×10^{4}	2.930×10^{-4}	0.2930
Foot Pounds	0.32389	3.2389×10^{-4}	1.35582×10^{7}	1.3558	1.2854×10^{-3}	....	0.13825	0.013381	5.0505×10^{-7}	32.174	3.7662×10^{-7}	3.7662×10^{-4}
Kilogram meters ..	2.3427	2.3427×10^{-3}	9.8066×10^{7}	9.8066	9.2967×10^{-3}	7.2330	....	0.096781	3.6529×10^{-6}	232.71	2.7241×10^{-6}	2.7241×10^{-3}
Liter Atmospheres (normal)	24.206	2.4206×10^{-2}	1.0133×10^{9}	101.328	0.09606	74.735	10.333	....	3.7745×10^{-5}	2404.5	2.8164×10^{-5}	2.8164×10^{-2}
Horsepower Hours .	6.4130×10^{5}	641.30	2.6845×10^{13}	2.6845×10^{6}	2454.0	1.9800×10^{6}	2.7374×10^{5}	26494	....	6.3705×10^{7}	0.7457	745.7
Foot poundals	0.010067	10.067×10^{-6}	4.21402×10^{5}	0.04214	3.9952×10^{-5}	0.031081	4.2972×10^{-3}	4.1558×10^{-4}	1.5697×10^{-8}	....	1.17055×10^{-8}	1.17055×10^{-5}
Kilowatt Hours ...	8.6001×10^{5}	860.01	3.6000×10^{13}	3.6000×10^{6}	3413.0	2.6552×10^{6}	3.6709×10^{-5}	3.5529×10^{6}	1.3440	8.5430×10^{7}	....	1000
Watt Hours	860.01	0.86001	3.6000×10^{10}	3600	3.4130	2655.3	367.09	3.5529×10^{3}	1.3410×10^{-3}	8.5430×10^{1}	0.001	....

POWER	watts	kw	ft. lb./sec	erg/sec	BTU/min	g. cm/sec	kg. cal/min	HP	Lumens	Joules/sec	BTU/hr.
Watts	....	0.001	0.73756	1x10^{7}	0.056884	1.0197x10^{4}	0.01433	1.341x10^{-3}	668	1	3.41304
Kilowatts	1000	....	737.56	1x10^{10}	56.884	1.0197x10^{7}	14.3334	1.3410	6.68x10^{5}	1000	3413.04
Foot pounds per second..........	1.35582	1.3558x10^{-3}	....	1.3558x10^{7}	0.077124	1.3826x10^{4}	0.019433	1.8182x10^{-3}	906.28	1.3558	4.6274
Ergs per second ..	1x10^{-7}	1x10^{-10}	7.3756x10^{-8}	....	5.688x10^{-9}	1.0197x10^{-3}	1.4333x10^{-9}	1.3410x10^{-10}	6.6845x10^{-5}	1x10^{-7}	3.4130x10^{-7}
BTU* per minute ..	17.580	0.017580	12.9600	1.7580x10^{8}	....	1.7926x10^{5}	0.2520	0.023575	11751	17.580	60
Gram Centimeters per second	9.8067x10^{-5}	9.8067x10^{-8}	7.2330x10^{-5}	980.665	5.5783x10^{-6}	....	1.4056x10^{-6}	1.3151x10^{-7}	0.065552	9.8067x10^{-5}	3.3470x10^{-4}
Kilogram colories per minute	69.767	.069767	51.457	6.9770x10^{8}	3.9685	7.1146x10^{5}	....	0.093557	46636	69.769	238.11
Horsepower (U. S.)	745.7	0.7457	550	7.457x10^{9}	42.4176	7.6042x10^{6}	10.688	....	498129	745.7	2545.1
Lumens	1.496x10^{-3}	1.496x10^{-6}	1.0034x10^{-3}	1.496x10^{4}	8.5096x10^{-5}	15.254	2.1437x10^{-5}	2.0061x10^{-6}	....	1.496x10^{-3}	5.1069x10^{-3}
Joules per second	1	0.001	0.73756	1x10^{7}	0.056884	1.0197x10^{4}	0.01433	1.341x10^{-3}	668	....	3.41304
BTU* per hour.....	0.29299	2.9299x10^{-4}	0.21610	2.9299x10^{6}	0.01667	2.9878x10^{3}	4.1997x10^{-3}	3.9291x10^{-4}	195.80	0.29299	....

*British Thermal Units (Mean)

CONVERSION FACTORS FOR VARIOUS SUBSTANCES[a]

Type Of Substance	Conversion Factors
Fuel	
Oil	1 bbl = 159 liters (42 gal)
Natural gas	1 therm = 100,000 Btu (approx.25000 kcal)
Gaseous Pollutants	
O_3	1 ppm, volume = $1960 \mu g/m^3$
NO_2	1 ppm, volume = $1880 \mu g/m^3$
SO_2	1 ppm, volume = $2610 \mu g/m^3$
H_2S	1 ppm, volume = $1390\ \mu g/m^3$
CO	1 ppm, volume = $1.14\ mg/m^3$
HC (as methane)	1 ppm, volume = $0.654\ mg/m^3$
Agricultural products	
Corn	1 bu = 25.4 kg = 56 lb
Milo	1 bu = 25.4 kg = 56 lb
Oats	1 bu = 14.5 kg = 32 lb
Barley	1 bu = 21.8 kg = 48 lb
Wheat	1 bu = 27.2 kg = 60 lb
Cotton	1 bale = 226 kg = 500 lb
Mineral products	
Brick	1 brick = 2.95 kg = 6.5 lb
Cement	1 bbl = 170 kg = 375 lb
Cement	1 yd^3 = 1130 kg = 2500 lb
Concrete	1 yd^3 = 1820 kg = 4000 lb
Mobile sources, fuel efficiency	
Motor vehicles	1.0 mi/gal = 0.426 km/liter
Waterborne vessels	1.0 gal/naut mi = 2.05 liters/km
Miscellaneous liquids	
Beer	1 bbl = 31.5 gal
Paint	1 gal = 4.5 to 6.82 kg = 10 to 15 lb
Varnish	1 gal = 3.18 kg = 7 lb
Whiskey	1 bbl = 190 liters = 50.2 gal
Water	1 gal = 3.81 kg = 8.3 lb

[a] Many of the conversion factors in this table represent average values and approximations and some of the values vary with temperature and pressure. These conversion factors should, however, be sufficiently accurate for general field use.

APPENDIX B.1

PARTICLE SIZE DISTRIBUTION DATA AND SIZED EMISSION FACTORS FOR SELECTED SOURCES

CONTENTS

AP-42
Section   Page

Introduction B.1-5

1.8 BAGASSE-FIRED BOILER: EXTERNAL COMBUSTION B.1-6

2.1 REFUSE INCINERATION:
    MUNICIPAL WASTE MASS BURN INCINERATOR B.1-8
    MUNICIPAL WASTE MODULAR INCINERATOR B.1-10

4.2.2.8 AUTOMOBILE AND LIGHT-DUTY TRUCK SURFACE COATING OPERATIONS: AUTOMOBILE SPRAY BOOTHS (WATER-BASE ENAMEL) . B.1-12

6.1 CARBON BLACK: OIL FURNACE PROCESS OFFGAS BOILER B.1-14

8.4 AMMONIUM SULFATE FERTILIZER: ROTARY DRYER B.1-16

8.10 SULFURIC ACID:
    ABSORBER (ACID ONLY) B.1-18
    ABSORBER, 20% OLEUM B.1-20
    ABSORBER, 32% OLEUM B.1-22
    SECONDARY ABSORBER B.1-24

8.xx BORIC ACID DRYER B.1-26

8.xx POTASH (POTASSIUM CHLORIDE) DRYER B.1-28

8.xx POTASH (POTASSIUM SULFATE) DRYER B.1-30

9.7 COTTON GINNING:
    BATTERY CONDENSER B.1-32
    LINT CLEANER AIR EXHAUST B.1-34

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS:
    GRAIN UNLOADING IN COUNTRY ELEVATORS B.1-36
    CONVEYING B.1-38
    RICE DRYER B.1-40

9.9.2 FEED AND GRAIN MILLS AND ELEVATORS: CEREAL DRYER B.1-42

9.9.4 ALFALFA DEHYDRATING: DRUM DRYER PRIMARY CYCLONE B.1-44

9.9.xx FEED AND GRAIN MILLS AND ELEVATORS: CAROB KIBBLE ROASTER . B.1-46

10.5 WOODWORKING WASTE COLLECTION OPERATIONS:
    BELT SANDER HOOD EXHAUST CYCLONE B.1-48

CONTENTS (cont.).

AP-42
Section

Page

11.10 COAL CLEANING:
- DRY PROCESS B.1-50
- THERMAL DRYER B.1-52
- THERMAL INCINERATOR B.1-54

11.20 LIGHTWEIGHT AGGREGATE (CLAY):
- COAL-FIRED ROTARY KILN B.1-56
- DRYER B.1-58
- RECIPROCATING GRATE CLINKER COOLER B.1-60

11.20 LIGHTWEIGHT AGGREGATE (SHALE):
- RECIPROCATING GRATE CLINKER COOLER B.1-62

11.20 LIGHTWEIGHT AGGREGATE (SLATE):
- COAL-FIRED ROTARY KILN B.1-64
- RECIPROCATING GRATE CLINKER COOLER B.1-66

11.21 PHOSPHATE ROCK PROCESSING:
- CALCINER B.1-68
- OIL-FIRED ROTARY AND FLUIDIZED-BED TANDEM DRYERS B.1-70
- OIL-FIRED ROTARY DRYER B.1-72
- BALL MILL B.1-74
- ROLLER MILL AND BOWL MILL GRINDING B.1-76

11.26 NONMETALLIC MINERALS: TALC PEBBLE MILL B.1-78

11.xx NONMETALLIC MINERALS:
- ELDSPAR BALL MILL B.1-80
- FLUORSPAR ORE ROTARY DRUM DRYER B.1-82

12.1 PRIMARY ALUMINUM PRODUCTION:
- BAUXITE PROCESSING - FINE ORE STORAGE B.1-84
- BAUXITE PROCESSING - UNLOADING ORE FROM SHIP B.1-86

12.13 STEEL FOUNDRIES:
- CASTINGS SHAKEOUT B.1-88
- OPEN HEARTH EXHAUST B.1-90

12.15 STORAGE BATTERY PRODUCTION:
- GRID CASTING B.1-92
- GRID CASTING AND PASTE MIXING B.1-94
- LEAD OXIDE MILL B.1-96
- PASTE MIXING AND LEAD OXIDE CHARGING B.1-98
- THREE-PROCESS OPERATION B.1-100

12.xx BATCH TINNER B.1-102

APPENDIX B.1

PARTICLE SIZE DISTRIBUTION DATA AND SIZED EMISSION FACTORS FOR SELECTED SOURCES

Introduction

This appendix presents particle size distributions and emission factors for miscellaneous sources or processes for which documented emission data were available. Generally, the sources of data used to develop particle size distributions and emission factors for this appendix were:

1. Source test reports in the files of the Emissions Monitoring, and Analysis Division of EPA's Office Of Air Quality Planning And Standards.

2. Source test reports in the Fine Particle Emission Information System (FPEIS), a computerized data base maintained by EPA's Air And Energy Engineering Research Laboratory, Office Of Research And Development.

3. A series of source tests titled *Fine Particle Emissions From Stationary And Miscellaneous Sources In The South Coast Air Basin*, by H. J. Taback.

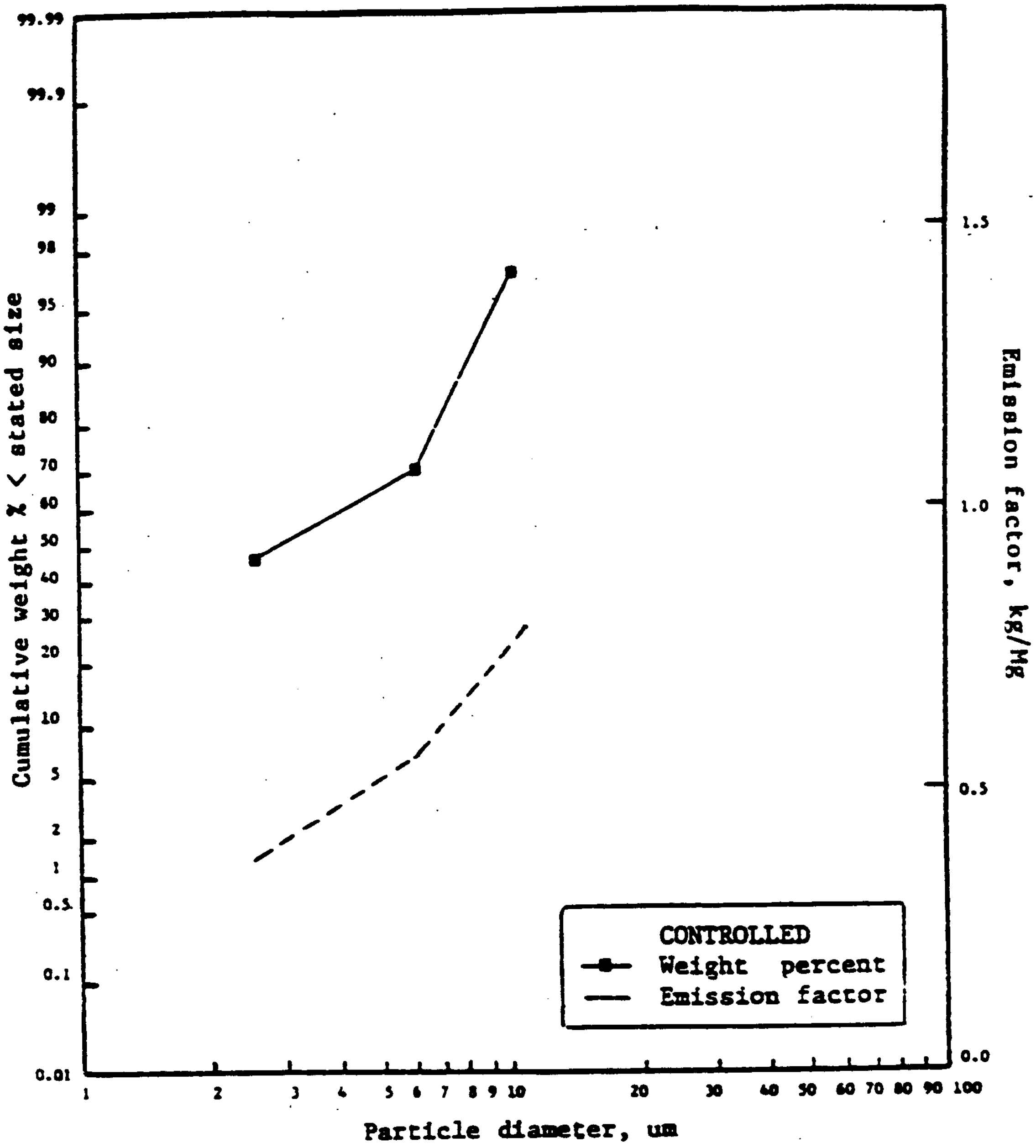
4. Particle size distribution data reported in the literature by various individuals and companies.

Particle size data from FPEIS were mathematically normalized into more uniform and consistent data. Where EMB tests and Taback report data were filed in FPEIS, the normalized data were used in developing this appendix.

Information on each source category in Appendix B.1 is presented in a 2-page format: For a source category, a graph provided on the first page presents a particle size distribution expressed as the cumulative weight percent of particles less than a specified aerodynamic diameter (cut point), in micrometers. A sized emission factor can be derived from the mathematical product of a mass emission factor and the cumulative weight percent of particles smaller than a specific cut point in the graph. At the bottom of the page is a table of numerical values for particle size distributions and sized emission factors, in micrometers, at selected values of aerodynamic particle diameter. The second page gives some information on the data used to derive the particle size distributions.

Portions of the appendix denoted TBA in the table of contents refer to information that will be added at a later date.

1.8 BAGASSE-FIRED BOILER: EXTERNAL COMBUSTION



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Wet scrubber controlled	Wet scrubber controlled
2.5	46.3	0.37
6.0	70.5	0.56
10.0	97.1	0.78

1.8 BAGASSE-FIRED BOILER: EXTERNAL COMBUSTION

NUMBER OF TESTS: 2, conducted after wet scrubber control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	46.3	70.5	97.1
	Standard deviation (Cum. %):	0.9	0.9	1.9
	Min (Cum. %):	45.4	69.6	95.2
	Max (Cum. %):	47.2	71.4	99.0

TOTAL PARTICULATE EMISSION FACTOR: Approximately 0.8 kg particulate/Mg bagasse charged to boiler. This factor is derived from AP-42, Section 1.8, 4/77, which states that the particulate emission factor from an uncontrolled bagasse-fired boiler is 8 kg/Mg and that wet scrubbers typically provide 90% particulate control.

SOURCE OPERATION: Source is a Riley Stoker Corp. vibrating grate spreader stoker boiler rated at 120,000 lb/hr but operated during this testing at 121% of rating. Average steam temperature and pressure were 579°F and 199 psig, respectively. Bagasse feed rate could not be measured, but was estimated to be about 41 (wet) tons/hr.

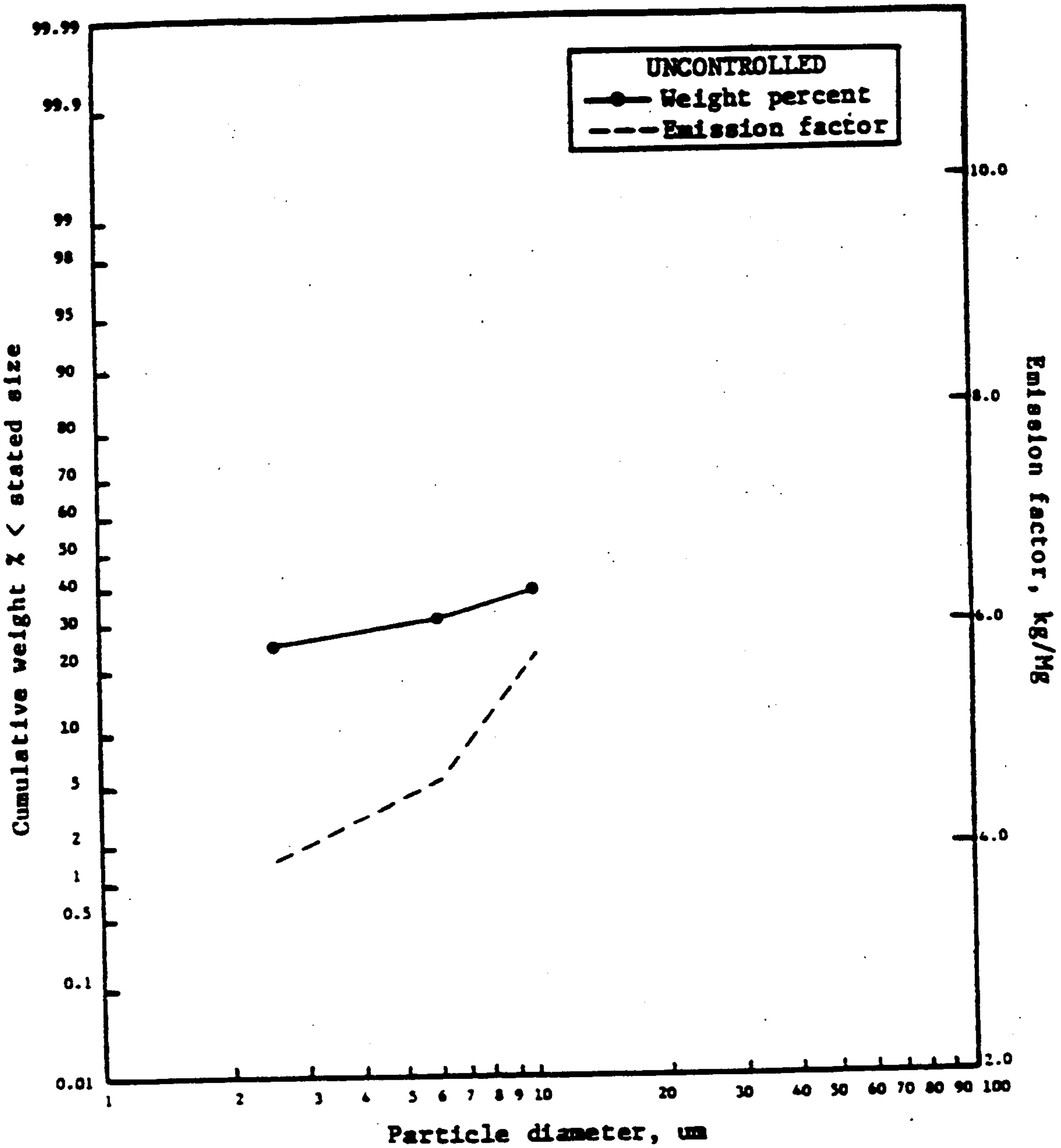
SAMPLING TECHNIQUE: Andersen Cascade Impactor

EMISSION FACTOR RATING: D

REFERENCE:

> *Emission Test Report, U. S. Sugar Company, Bryant, FL*, EMB-80-WFB-6, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1980.

2.1 REFUSE INCINERATION: MUNICIPAL WASTE MASS BURN INCINERATOR



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	26.0	3.9
6.0	30.6	4.6
10.0	38.0	5.7

2.1 REFUSE INCINERATION: MUNICIPAL WASTE MASS BURN INCINERATOR

NUMBER OF TESTS: 7, conducted before control

STATISTICS:	Aerodynamic Particle Diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	26.0	30.6	38.0
	Standard deviation (Cum. %):	9.5	13.0	14.0
	Min (Cum. %):	18	22	24
	Max (Cum. %):	40	49	54

TOTAL PARTICULATE EMISSION FACTOR: 15 kg of particulate/Mg of refuse charged. Emission factor from AP-42 Section 2.1.

SOURCE OPERATION: Municipal incinerators reflected in the data base include various mass burning facilities of typical design and operation.

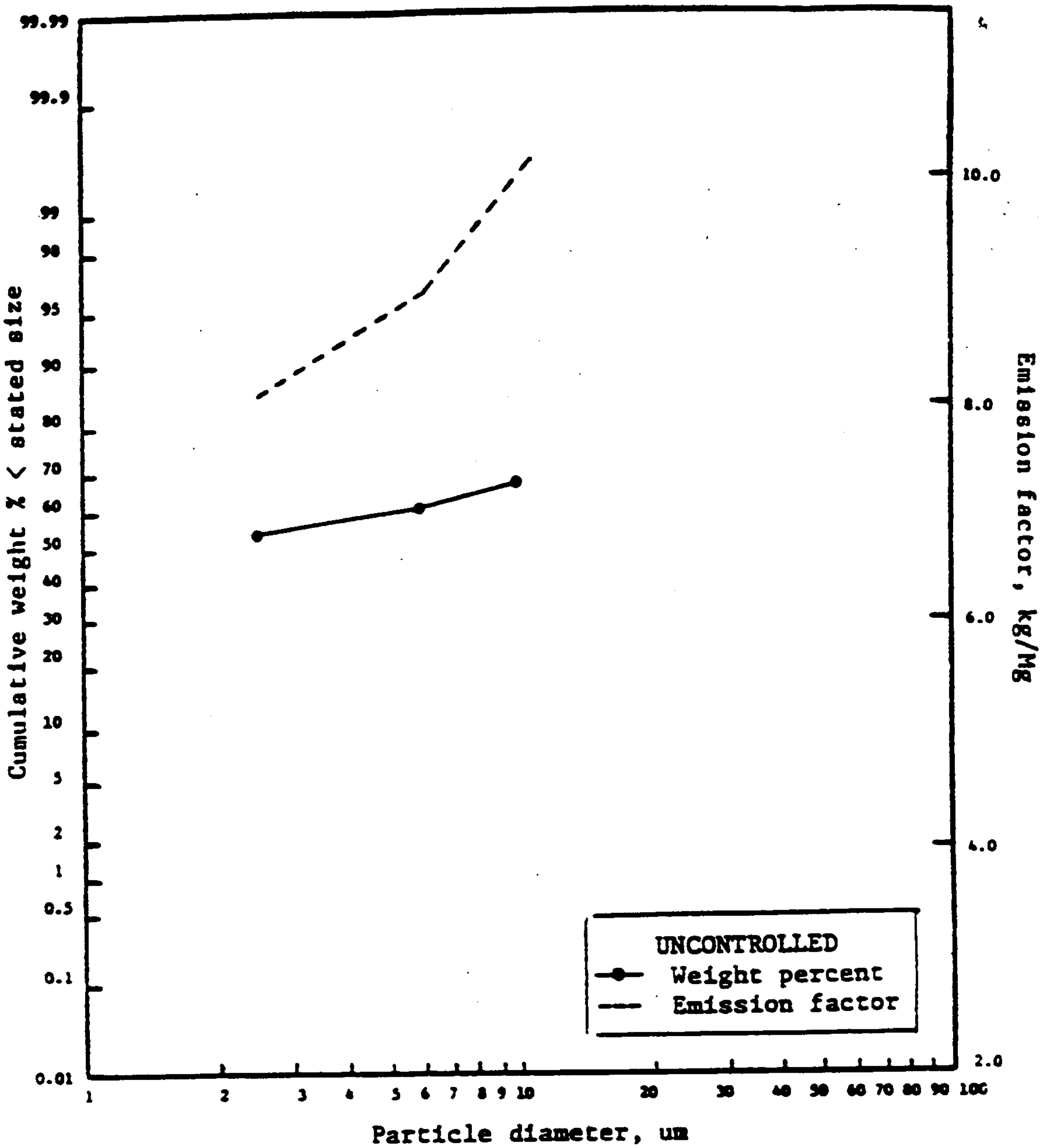
SAMPLING TECHNIQUE: Unknown

EMISSION FACTOR RATING: D

REFERENCE:

Determination of Uncontrolled Emissions, Product 2B, Montgomery County, Maryland, Roy F. Weston, Inc., West Chester, PA, August 1984.

2.1 REFUSE INCINERATION: MUNICIPAL WASTE MODULAR INCINERATOR



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	54.0	8.1
6.0	60.1	9.0
10.0	67.1	10.1

2.1 REFUSE INCINERATION: MUNICIPAL WASTE MODULAR INCINERATOR

NUMBER OF TESTS: 3, conducted before control

STATISTICS:	Aerodynamic Particle Diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	54.0	60.1	67.1
	Standard deviation (Cum. %):	19.0	20.8	23.2
	Min (Cum. %):	34.5	35.9	37.5
	Max (Cum. %):	79.9	86.6	94.2

TOTAL PARTICULATE EMISSION FACTOR: 15 kg of particulate/Mg of refuse charged. Emission factor from AP-42 Section 2.1.

SOURCE OPERATION: Modular incinerator (2-chambered) operation was at 75.9% of the design process rate (10,000 lb/hr) and 101.2% of normal steam production rate. Natural gas is required to start the incinerator each week. Average waste charge rate was 1.983T/hr. Net heating value of garbage 4200-4800 Btu/lb garbage charged.

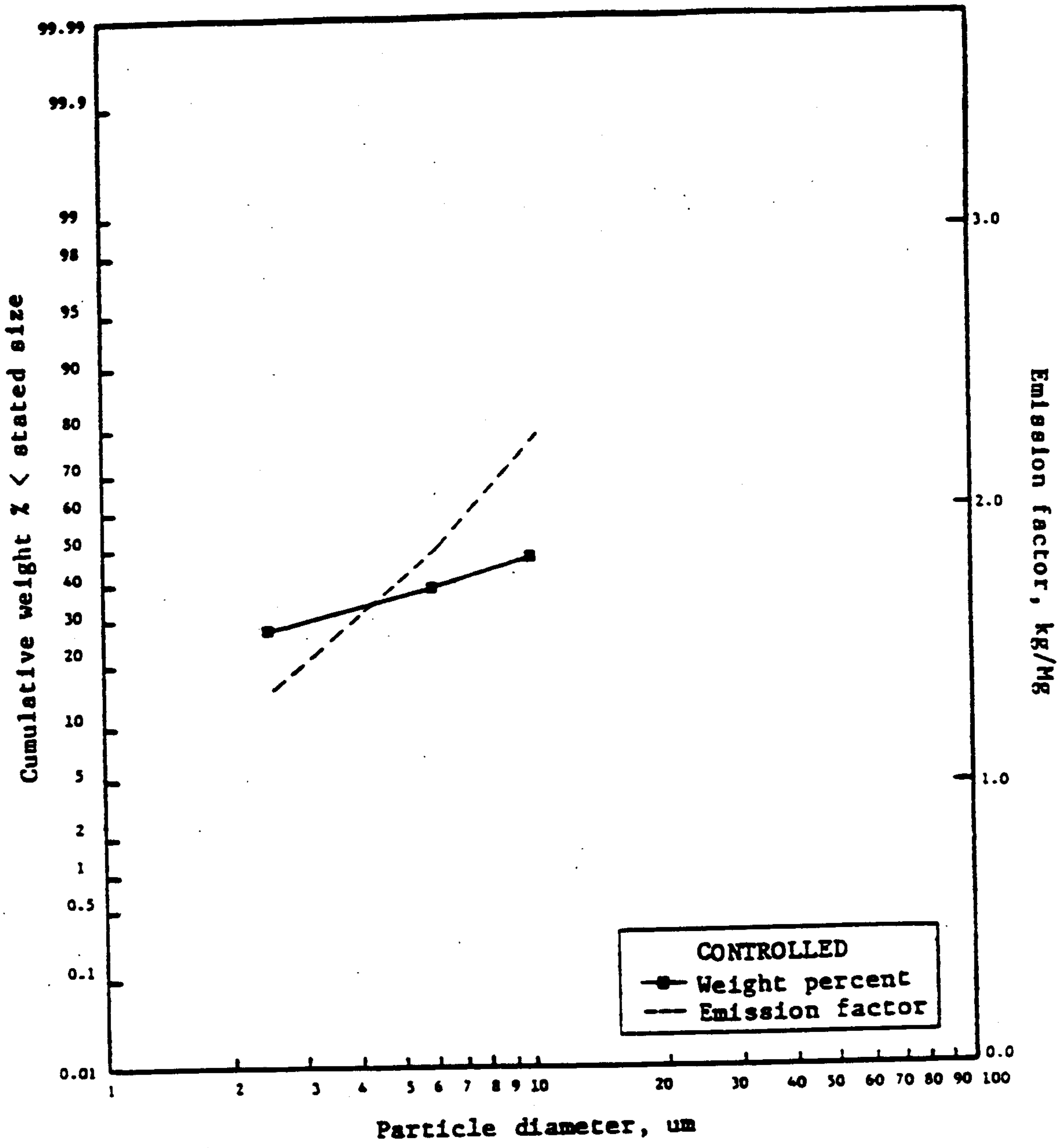
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Emission Test Report, City of Salem, Salem, Va, EMB-80-WFB-1, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1980.

4.2.2.8 AUTOMOBILE AND LIGHT-DUTY TRUCK SURFACE COATING OPERATIONS: AUTOMOBILE SPRAY BOOTHS (WATER-BASE ENAMEL)



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Water curtain controlled	Water curtain controlled
2.5	28.6	1.39
6.0	38.2	1.85
10.0	46.7	2.26

4.2.2.8 AUTOMOBILE AND LIGHT-DUTY TRUCK SURFACE COATING OPERATIONS: AUTOMOBILE SPRAY BOOTHS (WATER-BASE ENAMEL)

NUMBER OF TESTS: 2, conducted after water curtain control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	28.6	38.2	46.7
	Standard deviation (Cum. %):	14.0	16.8	20.6
	Min (Cum. %):	15.0	21.4	26.1
	Max (Cum. %):	42.2	54.9	67.2

TOTAL PARTICULATE EMISSION FACTOR: 4.84 kg particulate/Mg of water-base enamel sprayed. From References a and b.

SOURCE OPERATION: Source is a water-base enamel spray booth in an automotive assembly plant. Enamel spray rate is 568 lb/hour, but spray gun type is not identified. The spray booth exhaust rate is 95,000 scfm. Water flow rate to the water curtain control device is 7181 gal/min. Source is operating at 84% of design rate.

SAMPLING TECHNIQUE: SASS and Joy trains with cyclones

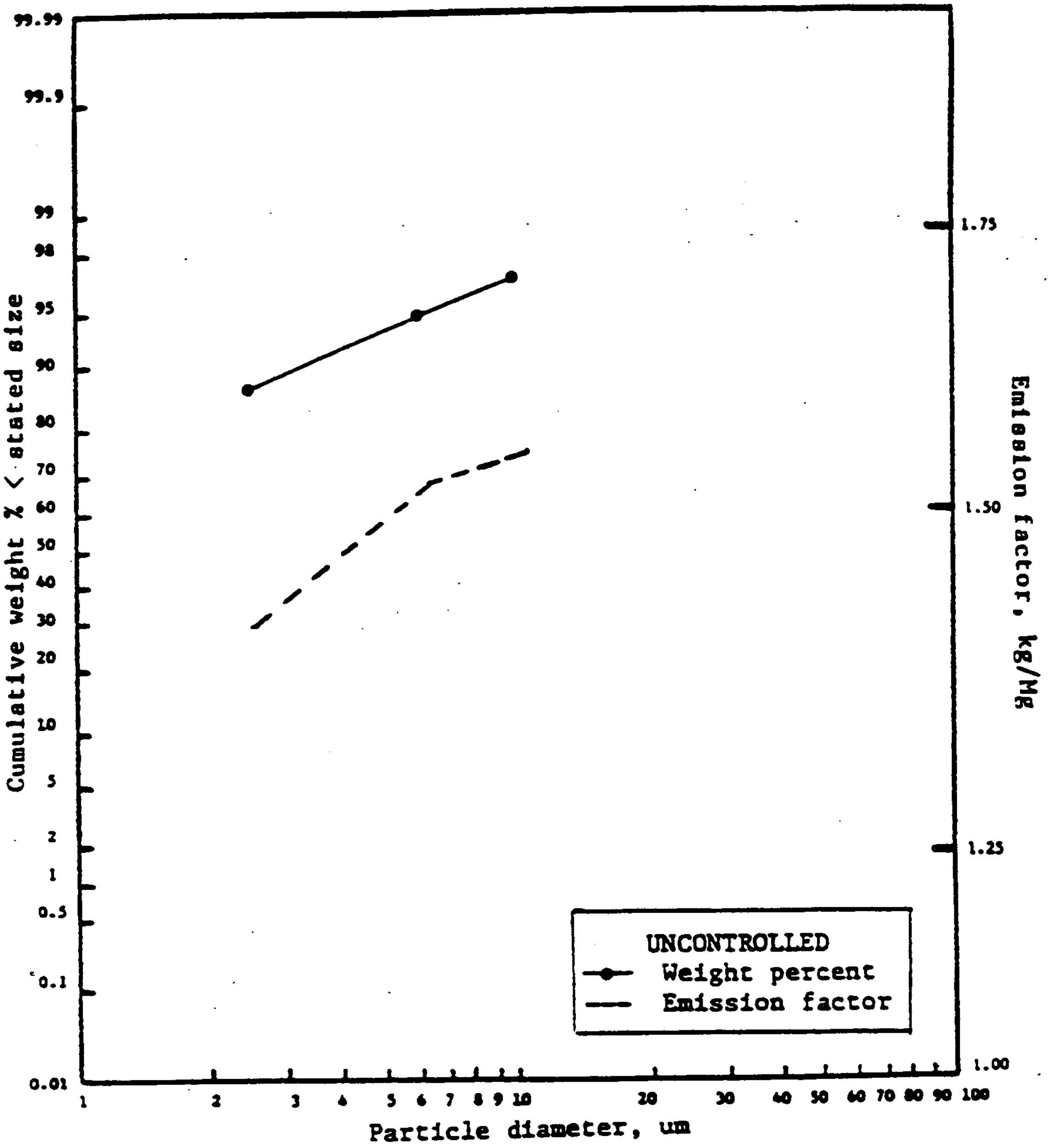
EMISSION FACTOR RATING: D

REFERENCES:

a. H. J. Taback, *Fine Particle Emissions from Stationary and Miscellaneous Sources in the South Coast Air Basin*, PB 293 923/AS, National Technical Information Service, Springfield, VA, February 1979.

b. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 234, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

6.1 CARBON BLACK: OIL FURNACE PROCESS OFFGAS BOILER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	87.3	1.40
6.0	95.0	1.52
10.0	97.0	1.55

6.1 CARBON BLACK: OIL FURNACE PROCESS OFFGAS BOILER

NUMBER OF TESTS: 3, conducted at offgas boiler outlet

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	87.3	95.0	97.0
	Standard Deviation (Cum. %):	2.3	3.7	8.0
	Min (Cum. %):	76.0	90.0	94.5
	Max (Cum. %):	94.0	99	100

TOTAL PARTICULATE EMISSION FACTOR: 1.6 kg particulate/Mg carbon black produced, from reference.

SOURCE OPERATION: Process operation: "normal" (production rate = 1900 kg/hr). Product is collected in fabric filter, but the offgas boiler outlet is uncontrolled.

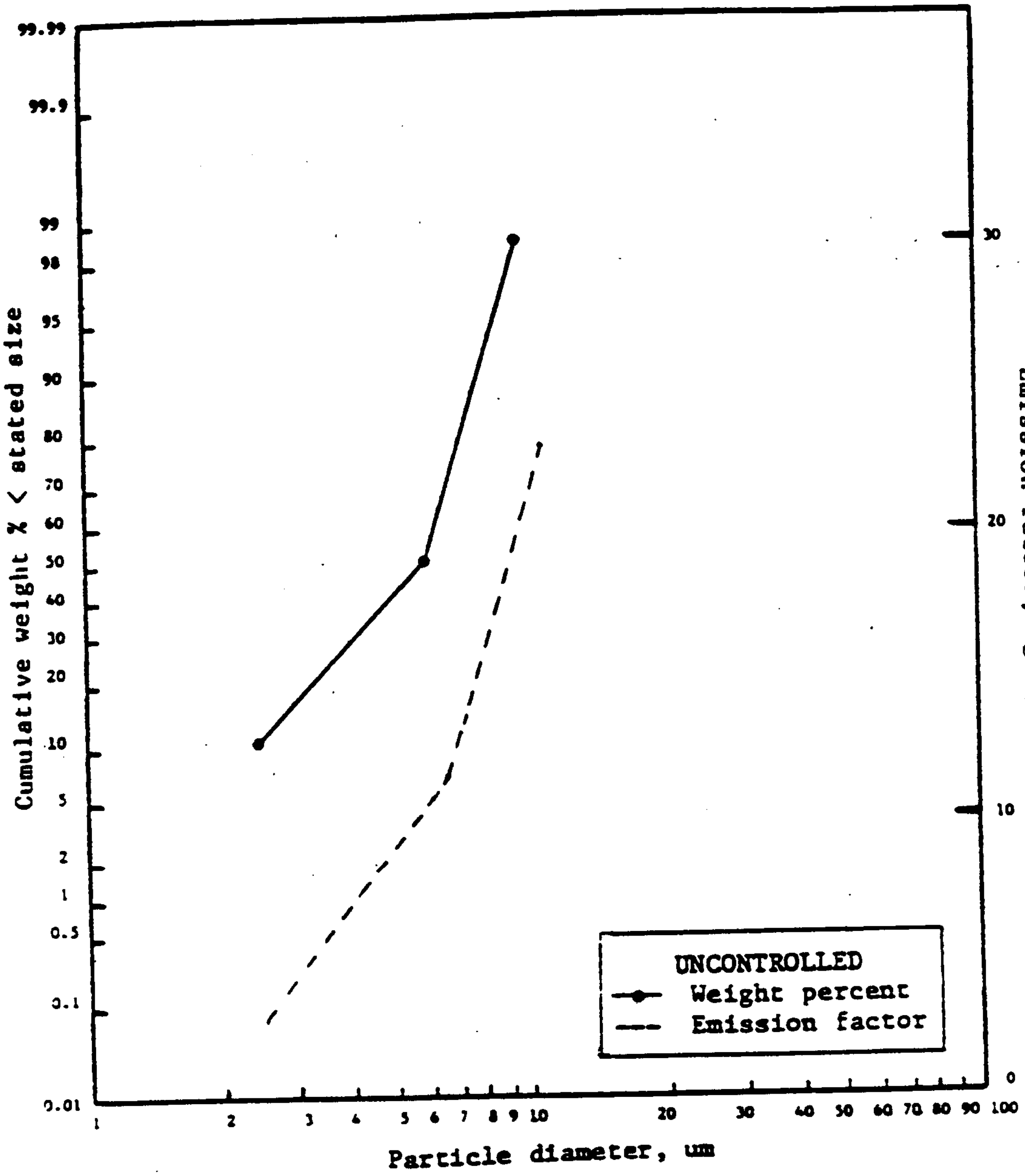
SAMPLING TECHNIQUE: Brink Cascade Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Air Pollution Emission Test, Phillips Petroleum Company, Toledo, OH, EMB-73-CBK-1, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1974.

8.4 AMMONIUM SULFATE FERTILIZER: ROTARY DRYER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	10.8	2.5
6.0	49.1	11.3
10.0	98.6	22.7

8.4 AMMONIUM SULFATE FERTILIZER: ROTARY DRYER

NUMBER OF TESTS: 3, conducted before control

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	10.8	49.1	98.6
Standard Deviation (Cum. %):	5.1	21.5	1.8
Min (Cum. %):	4.5	20.3	96.0
Max (Cum. %):	17.0	72.0	100.0

TOTAL PARTICULATE EMISSION FACTOR: 23 kg particulate/Mg of ammonium sulfate produced. Factor from AP-42, Section 8.4.

SOURCE OPERATION: Testing was conducted at 3 ammonium sulfate plants operating rotary dryers within the following production parameters:

Plant	A	C	D
% of design process rate	100.6	40.1	100
production rate, Mg/hr	16.4	6.09	8.4

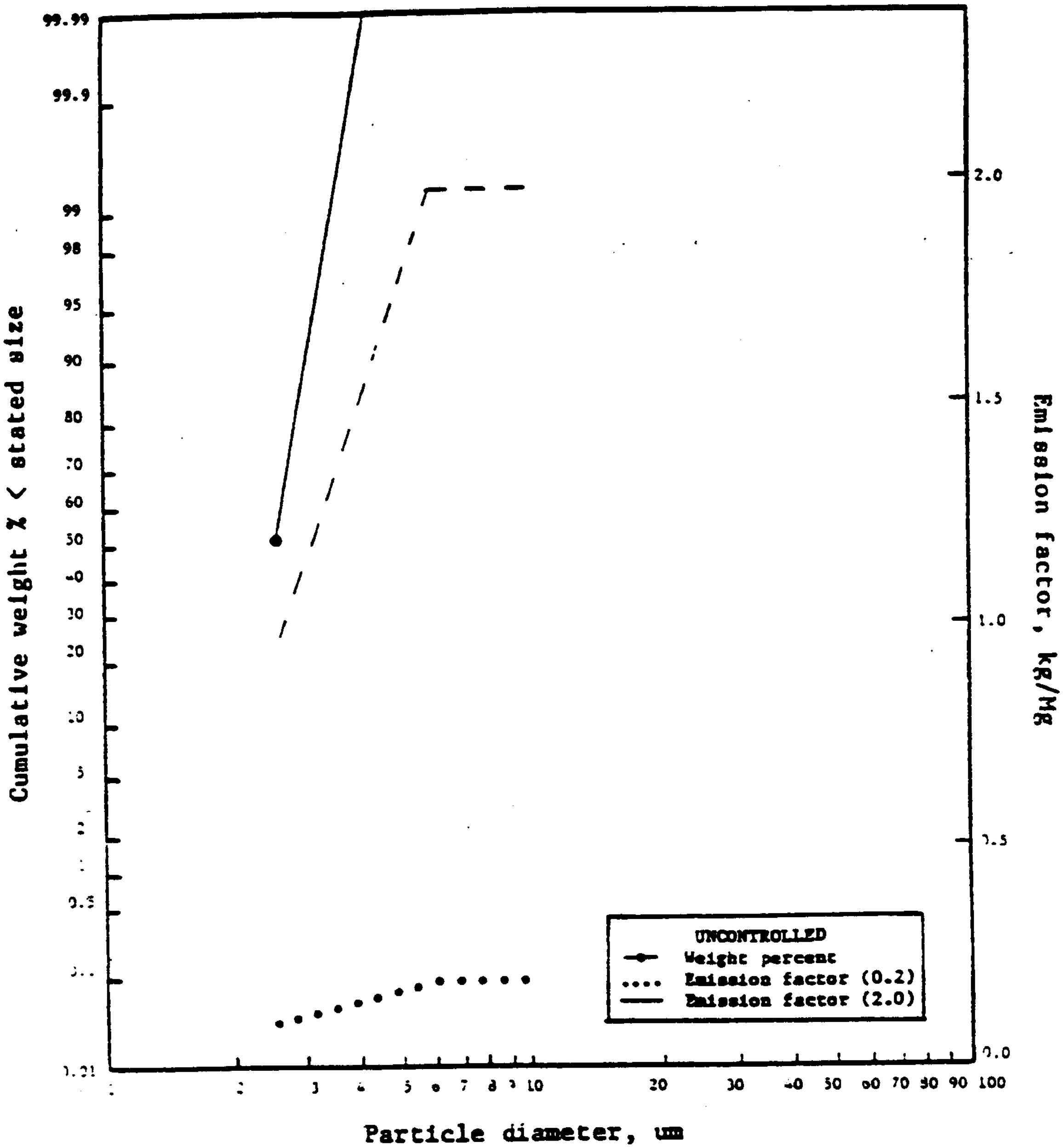
SAMPLING TECHNIQUE: Andersen Cascade Impactors

EMISSION FACTOR RATING: C

REFERENCE:

> *Ammonium Sulfate Manufacture — Background Information For Proposed Emission Standards*, EPA-450/3-79-034a, U. S. Environmental Protection Agency, Research Triangle Park, NC, December 1979.

8.10 SULFURIC ACID: ABSORBER (ACID ONLY)



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg	
		Uncontrolled	
	Uncontrolled	(0.2)	(2.0)
2.5	51.2	0.10	1.0
6.0	100	0.20	2.0
10.0	100	0.20	2.0

8.10 SULFURIC ACID: ABSORBER (ACID ONLY)

NUMBER OF TESTS: Not available

STATISTICS:

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	51.2	100	100
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.2 to 2.0 kg acid mist/Mg sulfur charged, for uncontrolled 98% acid plants burning elemental sulfur. Emission factors are from AP-42 Section 8.10.

SOURCE OPERATION: Not available

SAMPLING TECHNIQUE: Brink Cascade Impactor

EMISSION FACTOR RATING: E

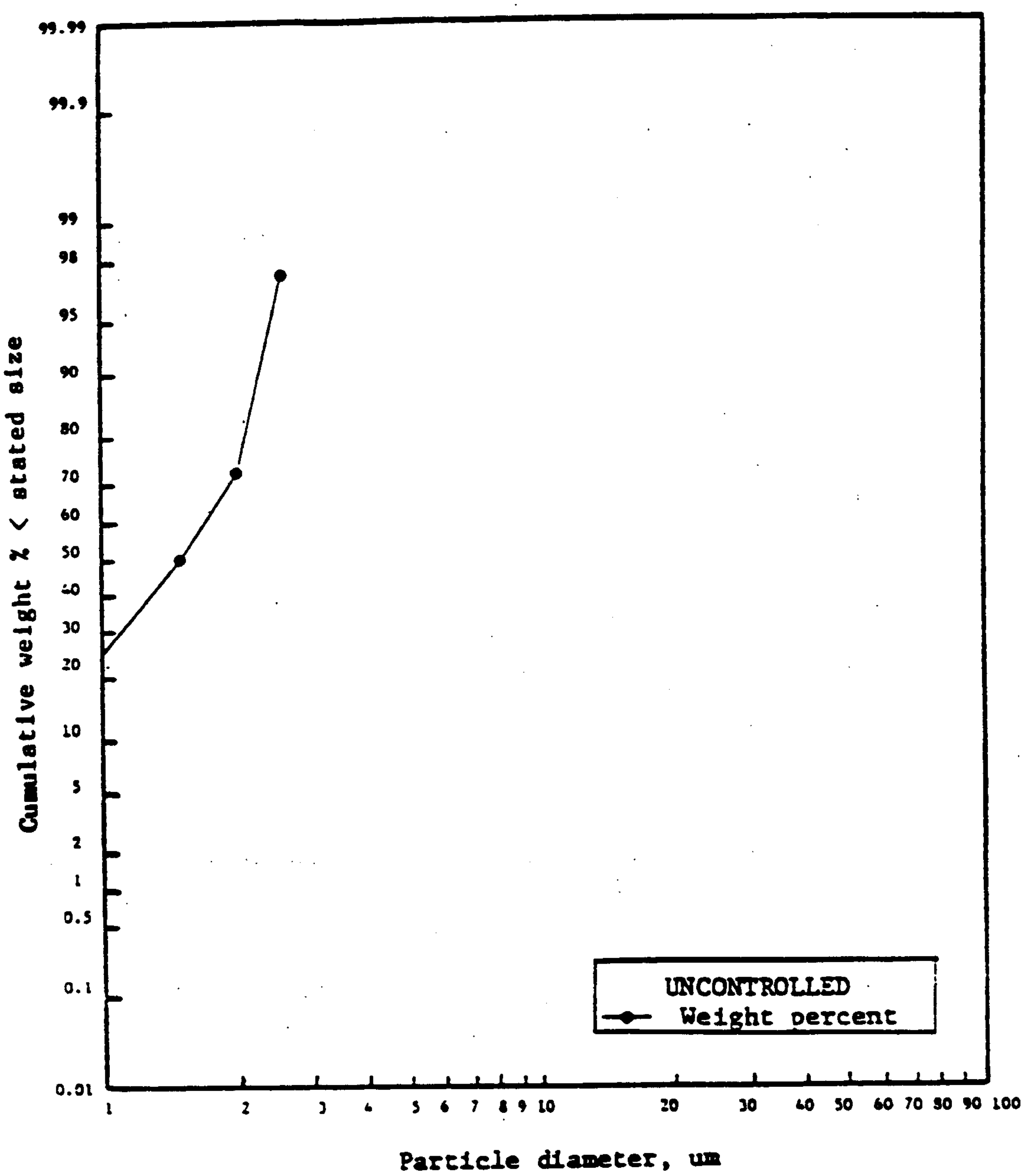
REFERENCES:

a. *Final Guideline Document: Control Of Sulfuric Acid Mist Emissions From Existing Sulfuric Acid Production Units*, EPA-450/2-77-019, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1977.

b. R. W. Kurek, *Special Report On EPA Guidelines For State Emission Standards For Sulfuric Acid Plant Mist*, E. I. du Pont de Nemours and Company, Wilmington, DE, June 1974.

c. J. A. Brink, Jr., "Cascade Impactor For Adiabatic Measurements", *Industrial and Engineering Chemistry*, *50*:647, April 1958.

8.10 SULFURIC ACID: ABSORBER, 20% OLEUM



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	97.5	See Table 8.10-2
6.0	100	
10.0	100	

8.10 SULFURIC ACID: ABSORBER, 20% OLEUM

NUMBER OF TESTS: Not available

STATISTICS:	Aerodynamic particle diameter (μm)*:	1.0	1.5	2.0
	Mean (Cum. %):	26	50	73
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: Acid mist emissions from sulfuric acid plants are a function of type of feed as well as oleum content of product. See AP-42, Section 8.10, Tables 8.10-2 and 8.10-3.

SOURCE OPERATION: Not available

SAMPLING TECHNIQUE: Brink Cascade Impactor

EMISSION FACTOR RATING: E

REFERENCES:

a. *Final Guideline Document: Control Of Sulfuric Acid Mist Emissions From Existing Sulfuric Acid Production Units*, EPA-450/2-77-019, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1977.

b. R. W. Kurek, *Special Report On EPA Guidelines For State Emission Standards For Sulfuric Acid Plant Mist*, E. I. du Pont de Nemours and Company, Wilmington, DE, June 1974.

c. J. A. Brink, Jr., "Cascade Impactor For Adiabatic Measurements", *Industrial and Engineering Chemistry*, *50*:647, April 1958.

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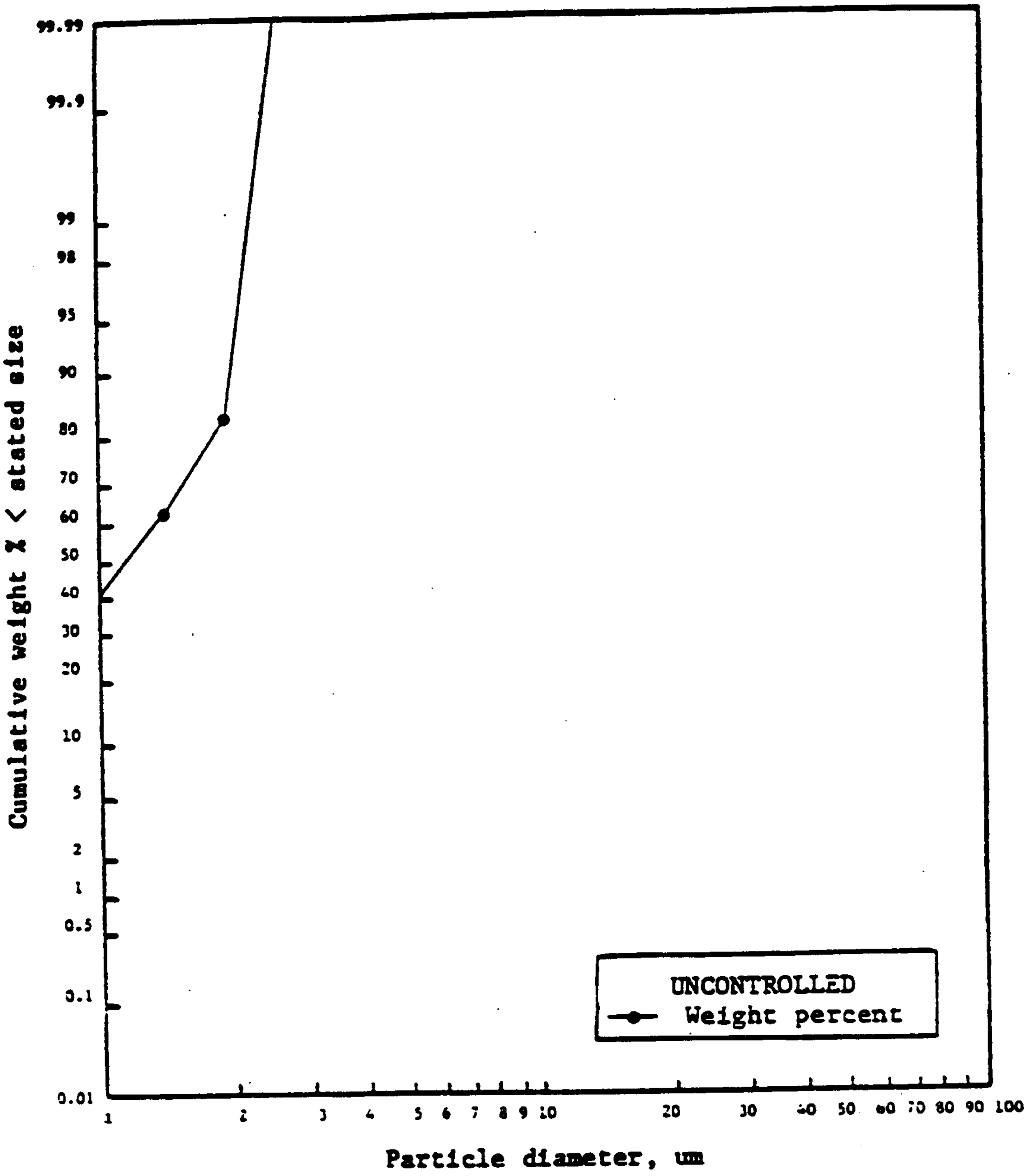
*100% of the particulate is less than 2.5 μm in diameter.

8.10 SULFURIC ACID: ABSORBER, 32% OLEUM



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	100	See Table 8.10-2
6.0	100	
10.0	100	

8.10 SULFURIC ACID: ABSORBER, 32% OLEUM

NUMBER OF TESTS: Not available

STATISTICS:	Aerodynamic particle diameter (μm)*:	1.0	1.5	2.0
	Mean (Cum. %):	41	63	84
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %);			

TOTAL PARTICULATE EMISSION FACTOR: Acid mist emissions from sulfuric acid plants are a function of type of feed as well as oleum content of product. See AP-42, Section 8.10, Table 8.10-2.

SOURCE OPERATION: Not available

SAMPLING TECHNIQUE: Brink Cascade Impactor

EMISSION FACTOR RATING: E

REFERENCES:

a. *Final Guideline Document: Control Of Sulfuric Acid Mist Emissions From Existing Sulfuric Acid Production Units*, EPA-450/2-77-019, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1977.

b. R. W. Kurek, *Special Report On EPA Guidelines For State Emission Standards For Sulfuric Acid Plant Mist*, E. I. du Pont de Nemours and Company, Wilmington, DE, June 1974.

c. J. A. Brink, Jr., "Cascade Impactor For Adiabatic Measurements", *Industrial and Engineering Chemistry*, *50*:647, April 1958.

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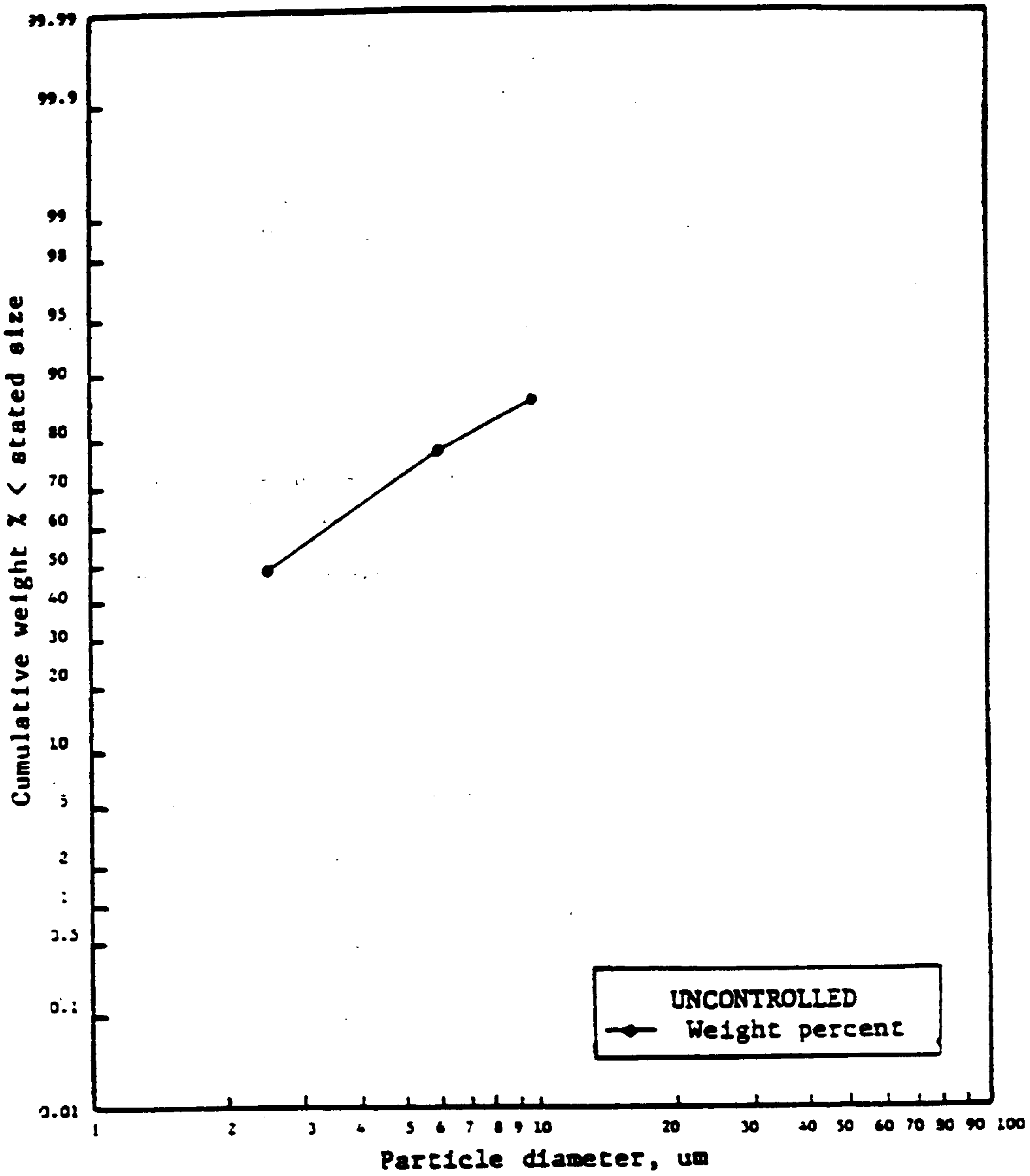
*100% of the particulate is less than 2.5 μm in diameter.

8.10 SULFURIC ACID: SECONDARY ABSORBER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	48	Not Available
6.0	78	Not Available
10.0	87	Not Available

8.10 SULFURIC ACID: SECONDARY ABSORBER

NUMBER OF TESTS: Not available

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	48	78	87
	Standard Deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: Acid mist emission factors vary widely according to type of sulfur feedstock. See AP-42 Section 8.10 for guidance.

SOURCE OPERATION: Source is the second absorbing tower in a double absorption sulfuric acid plant. Acid mist loading is 175 - 350 mg/m^3.

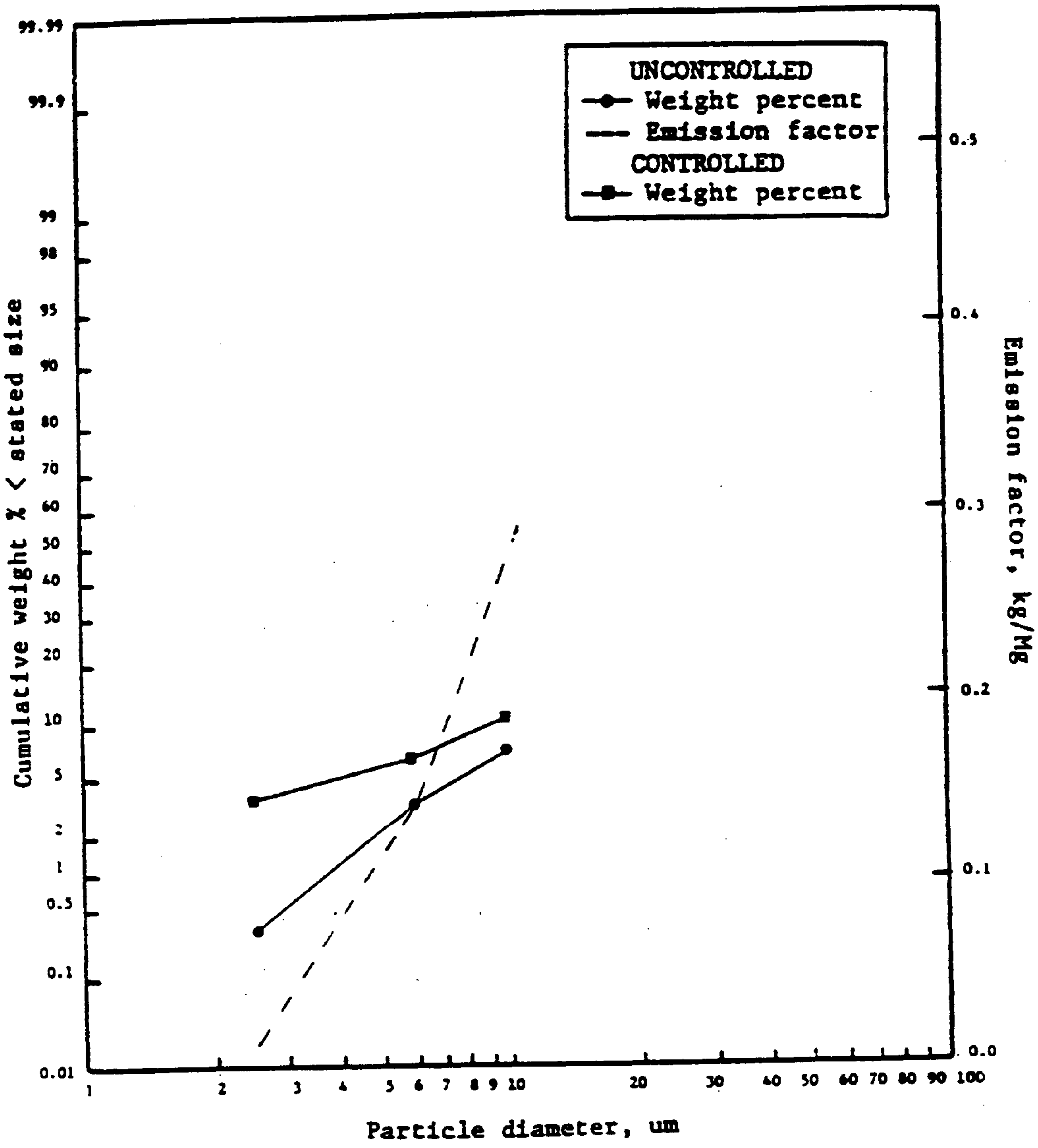
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: E

REFERENCE:

G. E. Harris and L. A. Rohlack, "Particulate Emissions From Non-fired Sources In Petroleum Refineries: A Review Of Existing Data", Publication No. 4363, American Petroleum Institute, Washington, DC, December 1982.

8.xx BORIC ACID DRYER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/Mg	
	Uncontrolled	Fabric filter	Uncontrolled	Fabric filter controlled
2.5	0.3	3.3	0.01	0.004
6.0	3.3	6.7	0.14	0.007
10.0	6.9	10.6	0.29	0.011

8.xx BORIC ACID DRYER

NUMBER OF TESTS: (a) 1, conducted before controls
(b) 1, conducted after fabric filter control

STATISTICS: (a)	Aerodynamic particle diameter (µm):	2.5	6.0	10.0
	Mean (Cum. %):	0.3	3.3	6.9
	Standard Deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			
(b)	Aerodynamic particle diameter (µm):	2.5	6.0	10.0
	Mean (Cum. %):	3.3	6.7	10.6
	Standard Deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: Before control, 4.15 kg particulate/Mg boric acid dried. After fabric filter control, 0.11 kg particulate/Mg boric acid dried. Emission factors from Reference a.

SOURCE OPERATION: 100% of design process rate.

SAMPLING TECHNIQUE: (a) Joy train with cyclones
(b) SASS train with cyclones

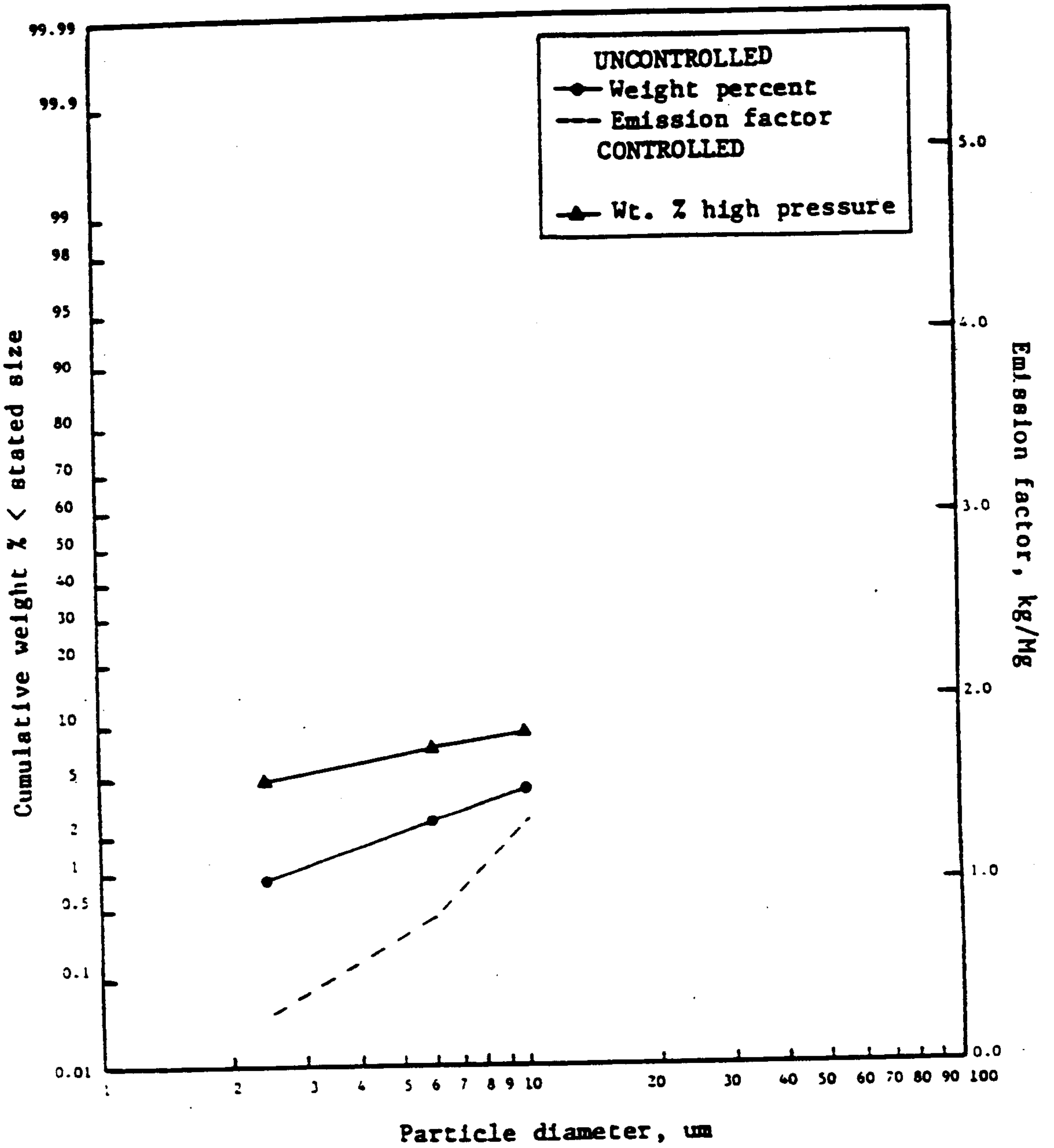
EMISSION FACTOR RATING: E

REFERENCES:

a. H. J. Taback, *Fine Particle Emissions From Stationary And Miscellaneous Sources In The South Coast Air Basin*, PB 293 923/AS, National Technical Information Service, Springfield, VA, February 1979.

b. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 236, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

8.xx POTASH (POTASSIUM CHLORIDE) DRYER



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size		Emission factor (kg/Mg)
	Uncontrolled	High pressure drop venturi scrubber	Uncontrolled
2.5	0.95	5.0	0.31
6.0	2.46	7.5	0.81
10.0	4.07	9.0	1.34

8.xx POTASH (POTASSIUM CHLORIDE) DRYER

NUMBER OF TESTS: (a) 7, before control
(b) 1, after cyclone and high pressure drop venturi scrubber control

STATISTICS: (a)

Aerodynamic particle diameter (µm):	2.5	6.0	10.0
Mean (Cum. %):	0.95	2.46	4.07
Standard deviation (Cum. %):	0.68	2.37	4.34
Min (Cum. %):	0.22	0.65	1.20
Max (Cum. %):	2.20	7.50	13.50

(b)

Aerodynamic particle diameter (µm):	2.5	6.0	10.0
Mean (Cum. %):	5.0	7.5	9.0
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: Uncontrolled emissions of 33 kg particulate/Mg of potassium chloride product from dryer, from AP-42. It is assumed that particulate emissions from rotary gas-fired dryers for potassium chloride are similar to particulate emissions from rotary steam tube dryers for sodium carbonate.

SOURCE OPERATION: Potassium chloride is dried in a rotary gas-fired dryer.

SAMPLING TECHNIQUE: (a) Andersen Impactor
(b) Andersen Impactor

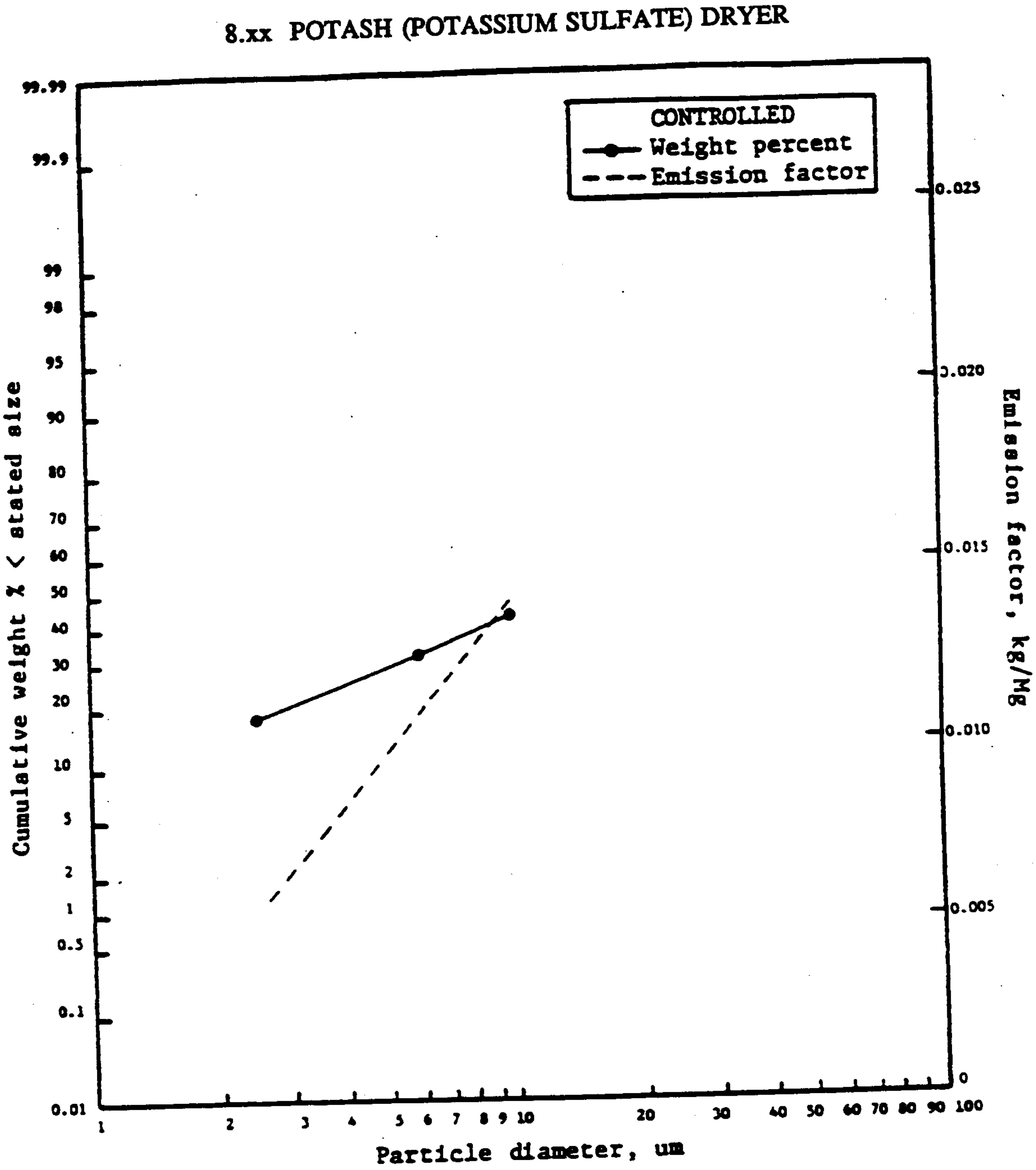
EMISSION FACTOR RATING: C

REFERENCES:

a. *Emission Test Report, Kerr-Magee, Trona, CA*, EMB-79-POT-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1979.

b. *Emission Test Report, Kerr-Magee, Trona, CA*, EMB-79-POT-5, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1979.

8.xx POTASH (POTASSIUM SULFATE) DRYER



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Controlled with fabric filter	Controlled with fabric filter
2.5	18.0	0.006
6.0	32.0	0.011
10.0	43.0	0.014

8.xx POTASH (POTASSIUM SULFATE) DRYER

NUMBER OF TESTS: 2, conducted after fabric filter

STATISTICS:	Aerodynamic particle diameter (µm):	2.5	6.0	10.0
	Mean (Cum. %):	18.0	32.0	43.0
	Standard deviation (Cum. %):	7.5	11.5	14.0
	Min (Cum. %):	10.5	21.0	29.0
	Max (Cum. %):	24.5	44.0	14.0

TOTAL PARTICULATE EMISSION FACTOR: After fabric filter control, 0.033 kg of particulate per Mg of potassium sulfate product from the dryer. Calculated from an uncontrolled emission factor of 33 kg/Mg and control efficiency of 99.9%. From Reference a and AP-42, Section 8.12. It is assumed that particulate emissions from rotary gas-fired dryers are similar to those from rotary steam tube dryers.

SOURCE OPERATION: Potassium sulfate is dried in a rotary gas-fired dryer.

SAMPLING TECHNIQUE: Andersen Impactor

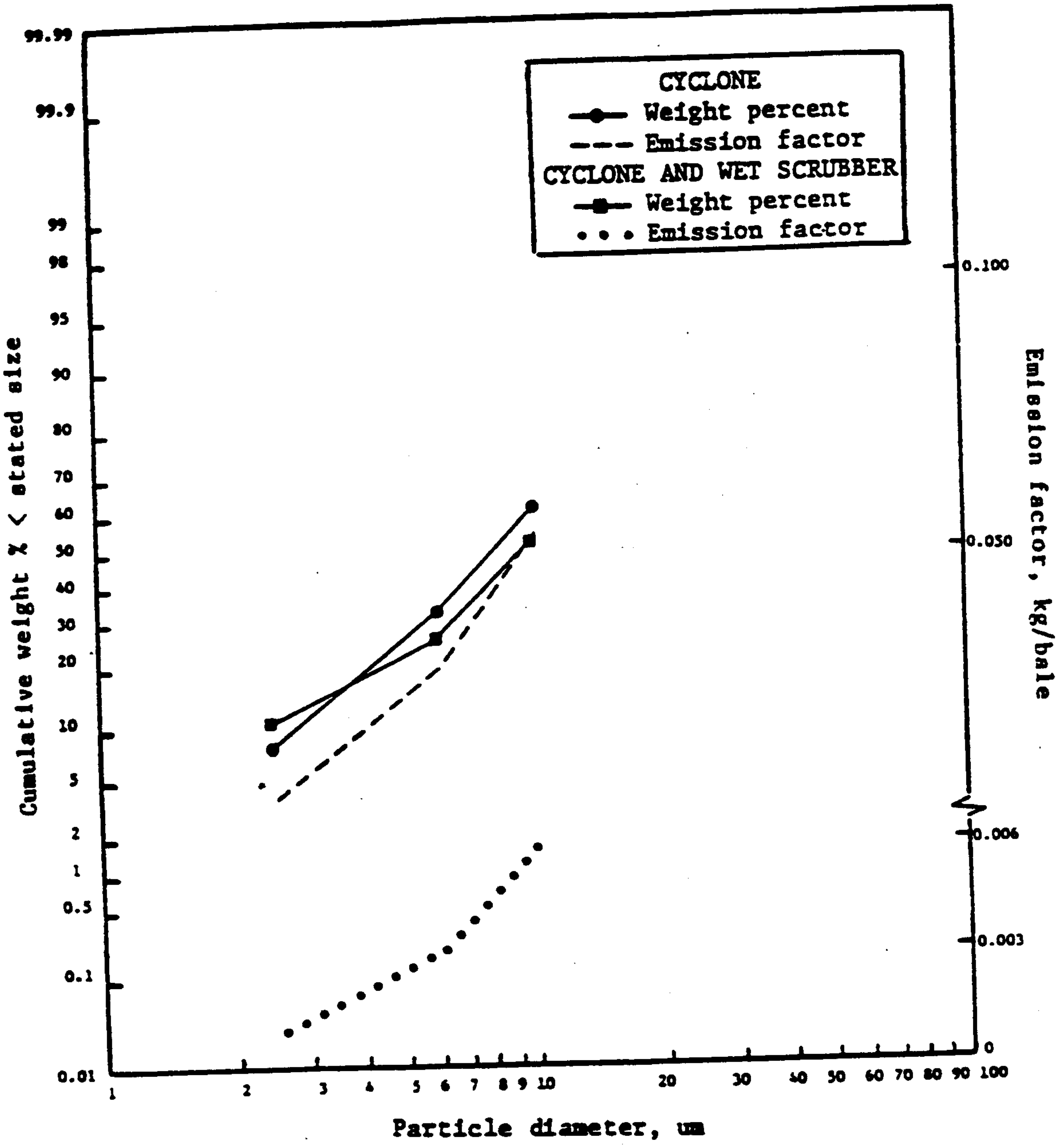
EMISSION FACTOR RATING: E

REFERENCES:

a. *Emission Test Report, Kerr-McGee, Trona, CA*, EMB-79-POT-4, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1979.

b. *Emission Test Report, Kerr-McGee, Trona, CA*, EMB-79-POT-5, Office Of Air Quality Planning And Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC, April 1979.

9.7 COTTON GINNING: BATTERY CONDENSER



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size		Emission factor (kg/bale)	
	With cyclone	With cyclone & wet scrubber	With cyclone	With cyclone & wet scrubber
2.5	8	11	0.007	0.001
6.0	33	26	0.028	0.003
10.0	62	52	0.053	0.006

9.7 COTTON GINNING: BATTERY CONDENSER

NUMBER OF TESTS: (a) 2, after cyclone
(b) 3, after wet scrubber

STATISTICS: (a)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	8	33	62
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			
(b)	Aerodynamic particle diameter (μm)			
	Mean (Cum. %.):	11	26	52
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: Particulate emission factor for battery condensers with typical controls is 0.09 kg (0.19 lb)/bale of cotton. Factor is from AP-42, Section 9.7. Factor with wet scrubber after cyclone is 0.012 kg (0.026 lb)/bale. Scrubber efficiency is 86%. From Reference b.

SOURCE OPERATION: During tests, source was operating at 100% of design capacity. No other information on source is available.

SAMPLING TECHNIQUE: UW Mark 3 Impactor

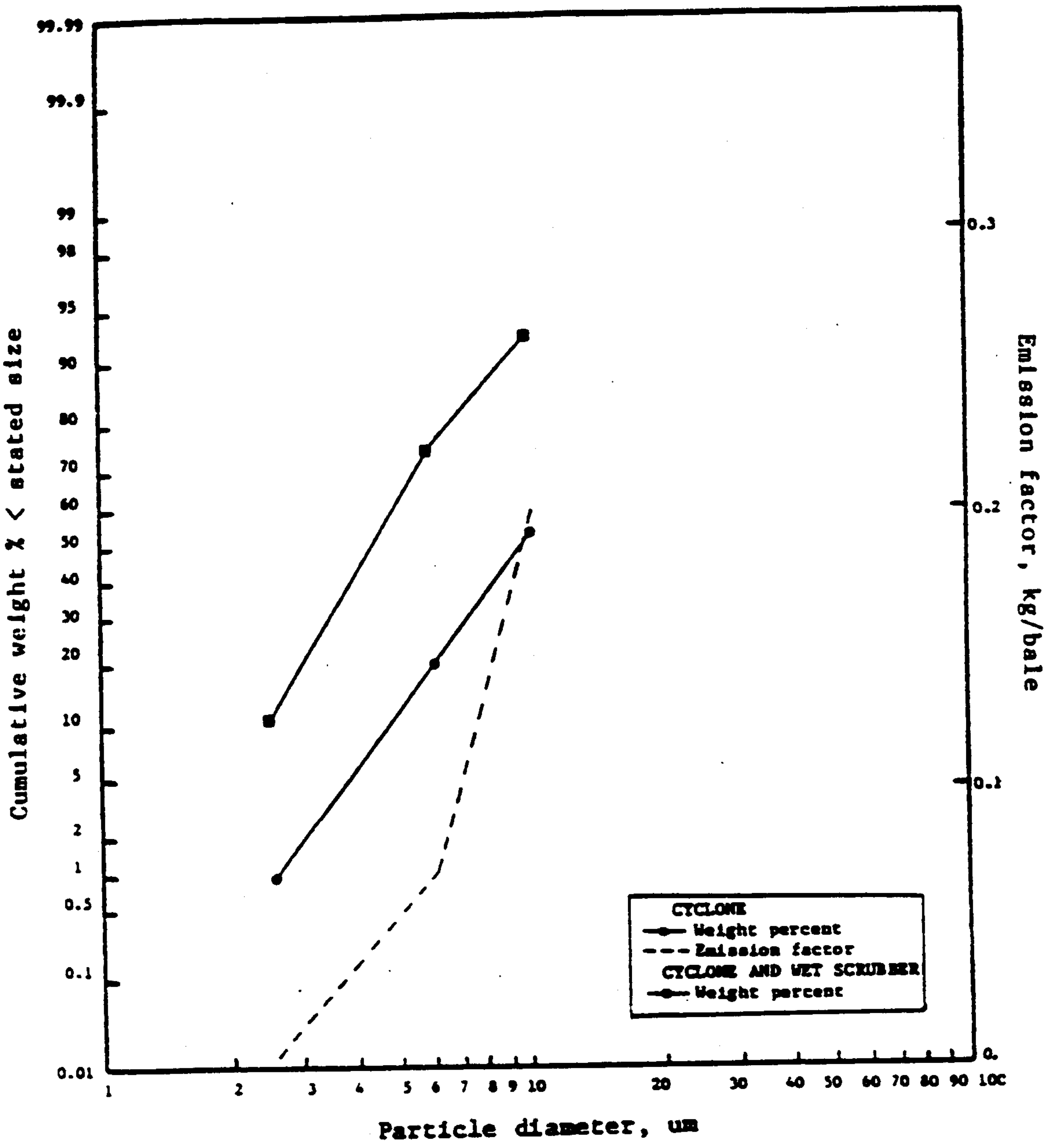
EMISSION FACTOR RATING: E

REFERENCES:

a. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System (FPEIS), Series Report No. 27, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

b. Robert E. Lee, Jr., *et al.*, "Concentration And Size Of Trace Metal Emissions From A Power Plant, A Steel Plant, And A Cotton Gin", *Environmental Science And Technology*, *9*(7)643-7, July 1975.

9.7 COTTON GINNING: LINT CLEANER AIR EXHAUST



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size		Emission factor (kg/bale)
	After cyclone	After cyclone & wet scrubber	After cyclone
2.5	1	11	0.004
6.0	20	74	0.07
10.0	54	92	0.20

9.7 COTTON GINNING: LINT CLEANER AIR EXHAUST

NUMBER OF TESTS: (a) 4, after cyclone
(b) 4, after cyclone and wet scrubber

STATISTICS: (a)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	1	20	54
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

(b)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	11	74	92
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.37 kg particulate/bale of cotton processed, with typical controls. Factor is from AP-42, Section 9.7.

SOURCE OPERATION: Testing was conducted while processing both machine-picked and ground-harvested upland cotton, at a production rate of about 6.8 bales/hr.

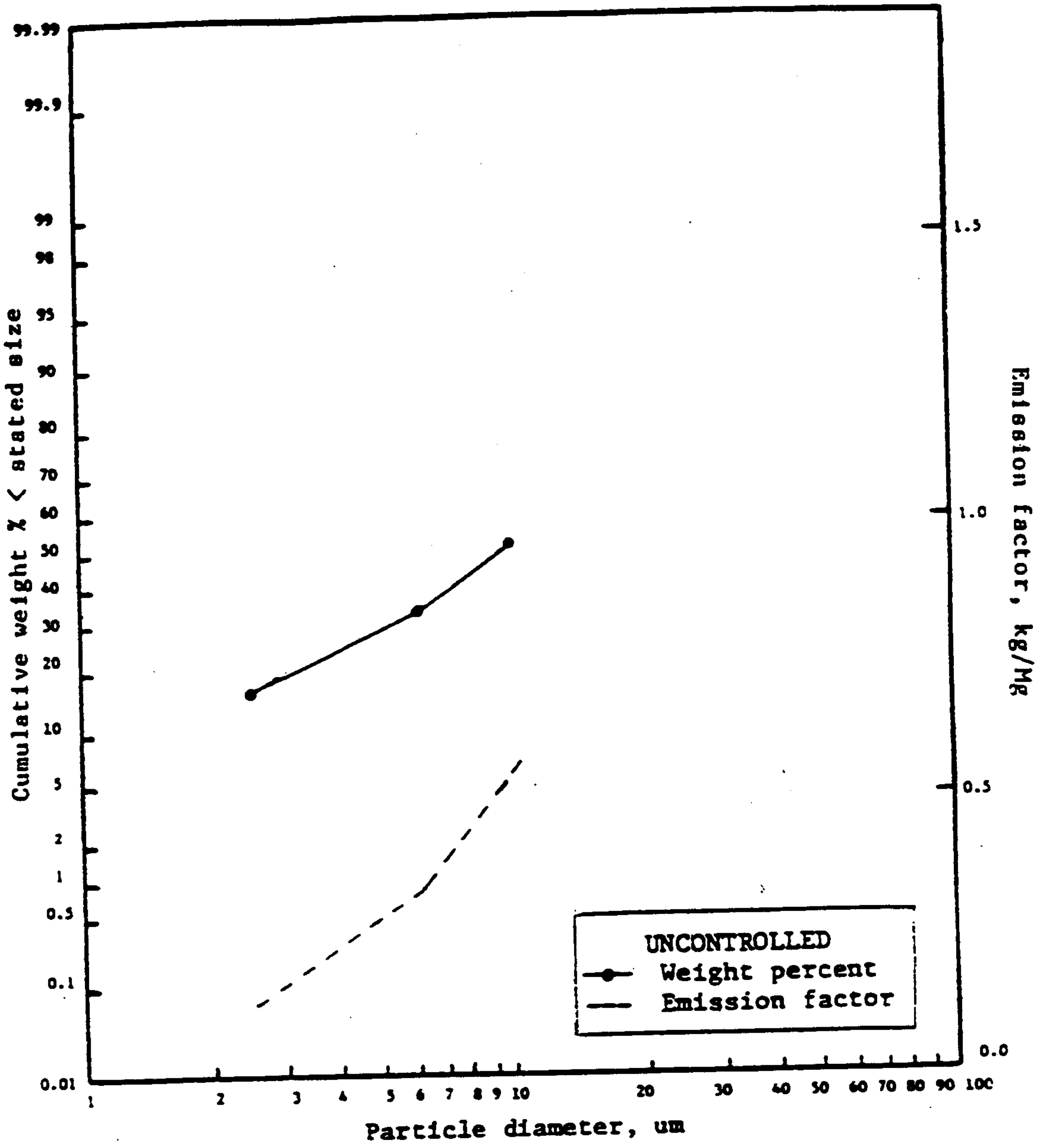
SAMPLING TECHNIQUE: Coulter counter

EMISSION FACTOR RATING: E

REFERENCE:

S. E. Hughs, *et al.*, "Collecting Particles From Gin Lint Cleaner Air Exhausts", presented at the 1981 Winter Meeting of the American Society Of Agricultural Engineers, Chicago, IL, December 1981.

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS: GRAIN UNLOADING IN COUNTRY ELEVATORS



Aerodynamic particle diameter, um	Cumulative wgt. % <stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	13.8	0.13
6.0	30.5	0.33
10.0	49.0	0.56

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS: GRAIN UNLOADING IN COUNTRY ELEVATORS

NUMBER OF TESTS: 2, conducted before control

STATISTICS:

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	13.8	30.5	49.0
Standard deviation (Cum. %):	3.3	2.5	—
Min (Cum. %):	10.5	28.0	49.0
Max (Cum. %):	17.0	33.0	49.0

TOTAL PARTICULATE EMISSION FACTOR: 0.3 kg particulate/Mg of grain unloaded, without control. Emission factor from AP-42, Section 9.9.1.

SOURCE OPERATION: During testing, the facility was continuously receiving wheat of low dockage. The elevator is equipped with a dust collection system that serves the dump pit boot and leg.

SAMPLING TECHNIQUE: Nelson Cascade Impactor

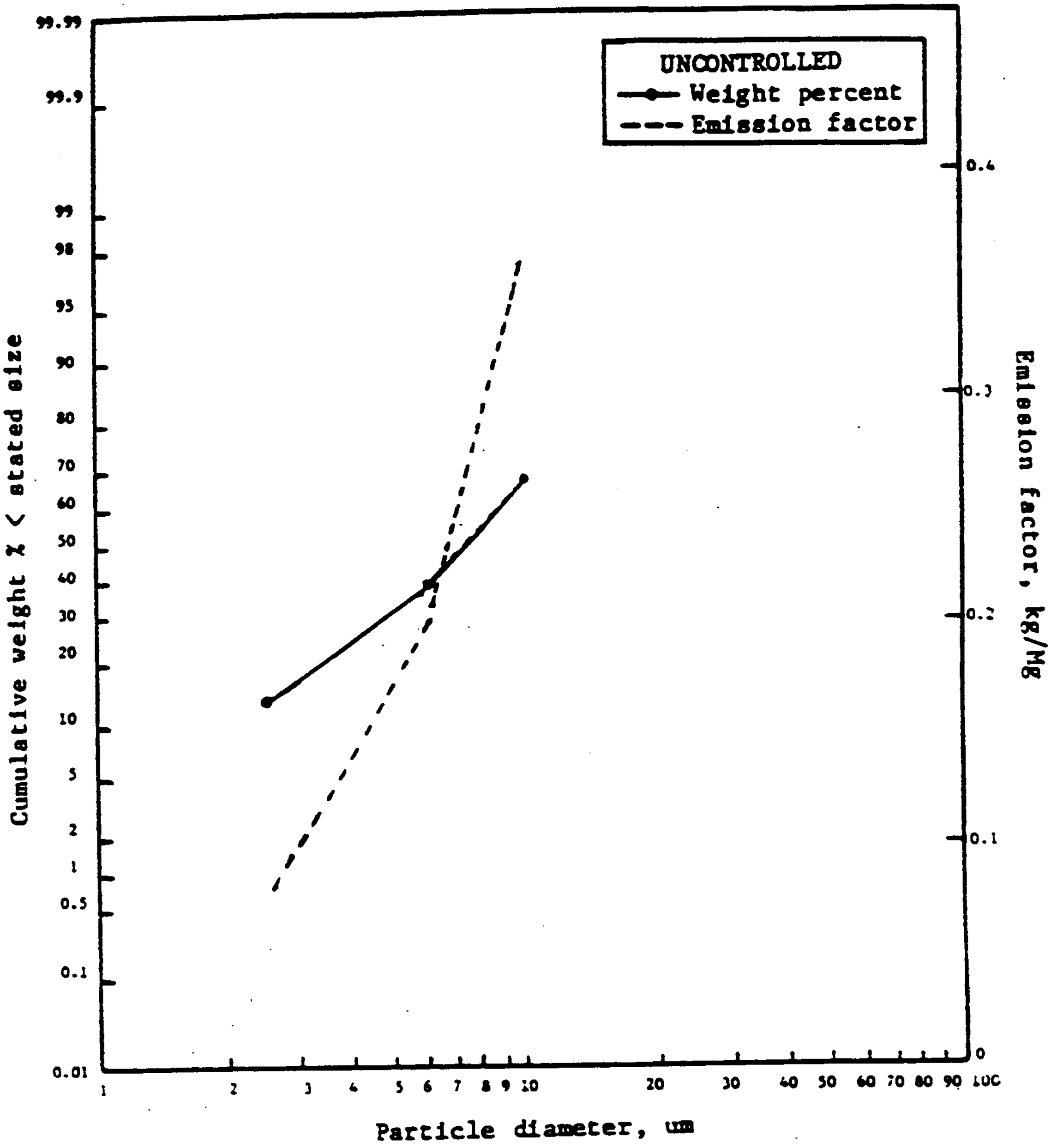
EMISSION FACTOR RATING: D

REFERENCES:

a. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System (FPEIS), Series Report No. 154, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

b. *Emission Test Report, Uniontown Co-op, Elevator No. 2, Uniontown, WA*, Report No. 75-34, Washington State Department Of Ecology, Olympia, WA, October 1975.

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS: CONVEYING



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	16.8	0.08
6.0	41.3	0.21
10.0	69.4	0.35

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS: CONVEYING

NUMBER OF TESTS: 2, conducted before control

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	16.8	41.3	69.4
Standard deviation (Cum. %):	6.9	16.3	27.3
Min (Cum. %):	9.9	25.0	42.1
Max (Cum. %):	23.7	57.7	96.6

TOTAL PARTICULATE EMISSION FACTOR: 0.5 kg particulate/Mg of grain processed, without control. Emission factor from AP-42, Section 9.9.1.

SOURCE OPERATION: Grain is unloaded from barges by "marine leg" buckets lifting the grain from the barges and discharging it onto an enclosed belt conveyer, which transfers the grain to the elevator. These tests measured the combined emissions from the "marine leg" bucket unloader and the conveyer transfer points. Emission rates averaged 1956 lb particulate/hour (0.67 kg/Mg grain unloaded). Grains are corn and soy beans.

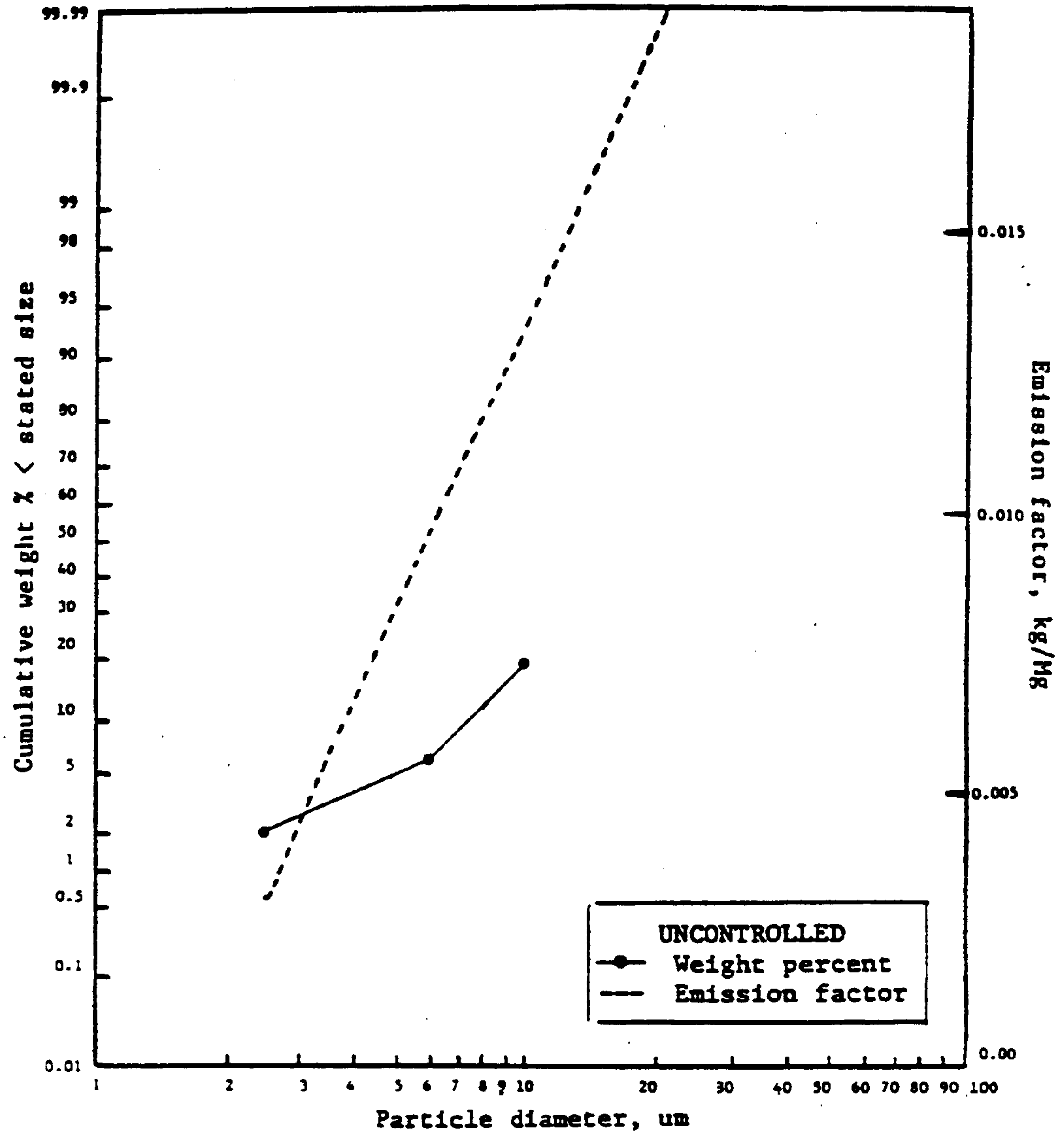
SAMPLING TECHNIQUE: Brink Model B Cascade Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Air Pollution Emission Test, Bunge Corporation, Destrehan, LA, EMB-74-GRN-7, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1974.

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS: RICE DRYER



Aerodynamic Particle diameter, um	Cumulative wt. % < Stated Size	Emission Factor (kg/Mg)
	Uncontrolled	Uncontrolled
2.5	2.0	0.003
6.0	8.0	0.01
10.0	19.5	0.029

9.9.1 FEED AND GRAIN MILLS AND ELEVATORS: RICE DRYER

NUMBER OF TESTS: 2, conducted on uncontrolled source.

STATISTICS:	Aerodynamic Particle Diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	2.0	8.0	19.5
	Standard Deviation (Cum. %):	—	3.3	9.4
	Min (Cum. %):	2.0	3.1	10.1
	Max (Cum. %):	2.0	9.7	28.9

TOTAL PARTICULATE EMISSION FACTOR: 0.15 kg particulate/Mg of rice dried. Factor from AP-42, Section 9.9.1. Table 9.9.1-1, footnote b for column dryer.

SOURCE OPERATION: Source operated at 100% of rated capacity, drying 90.8 Mg rice/hr. The dryer is heated by 4 9.5-kg/hr burners.

SAMPLING TECHNIQUE: SASS train with cyclones

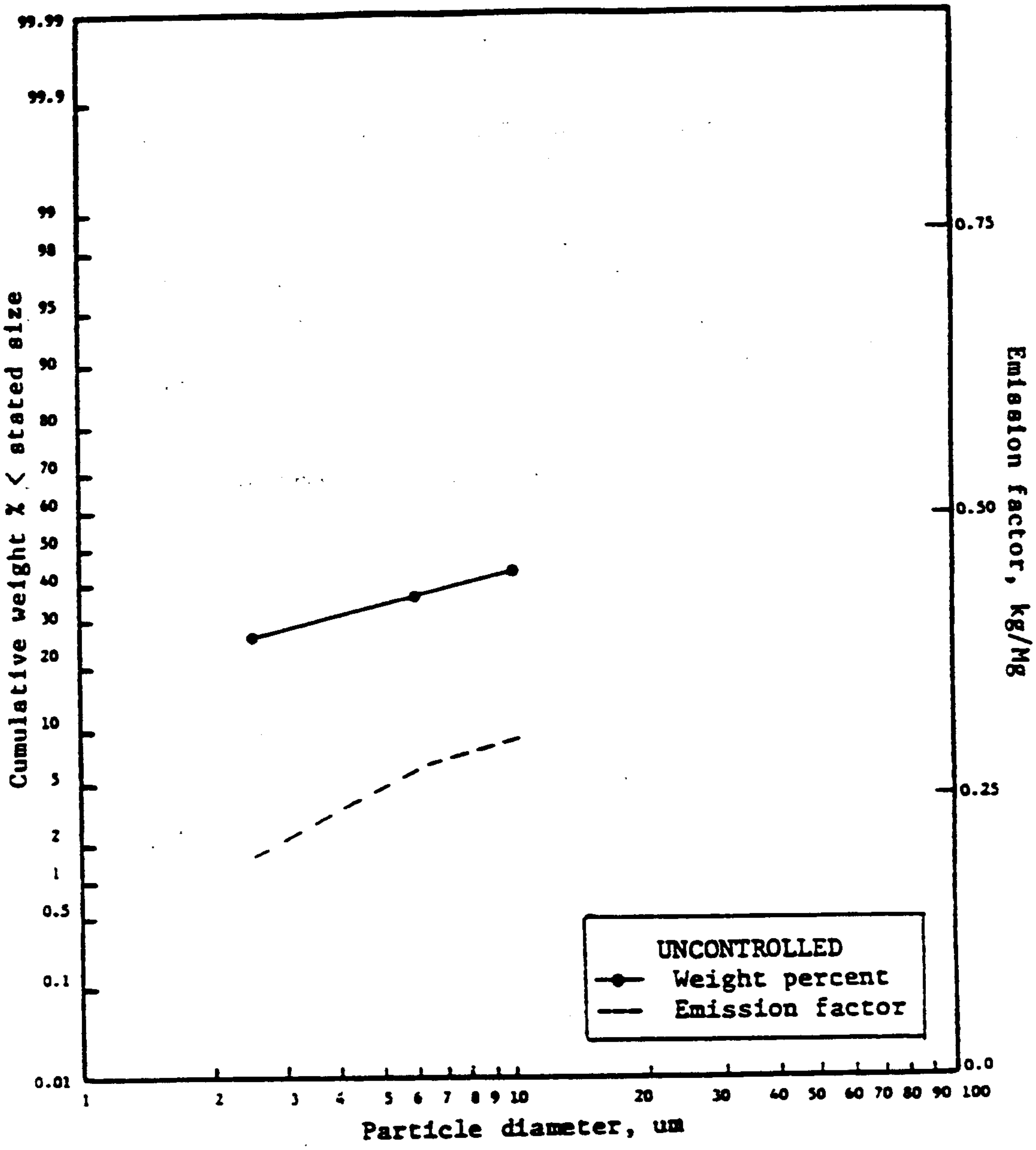
EMISSION FACTOR RATING: D

REFERENCES:

a. H. J. Taback, *Fine Particle Emissions From Stationary And Miscellaneous Sources In The South Coast Air Basin*, PB 293 923/AS, National Technical Information Service, Springfield, VA, February 1979.

b. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 228, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

9.9.2 FEED AND GRAIN MILLS AND ELEVATORS: CEREAL DRYER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	27	0.20
6.0	37	0.28
10.0	44	0.33

9.9.2 FEED AND GRAIN MILLS AND ELEVATORS: CEREAL DRYER

NUMBER OF TESTS: 6, conducted before controls

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	27	37	44
Standard deviation (Cum. %):	17	18	20
Min (Cum. %):	13	20	22
Max (Cum. %):	47	56	58

TOTAL PARTICULATE EMISSION FACTOR: 0.75 kg particulate/Mg cereal dried. Factor taken from AP-42, Section 9.9.2.

SOURCE OPERATION: Confidential

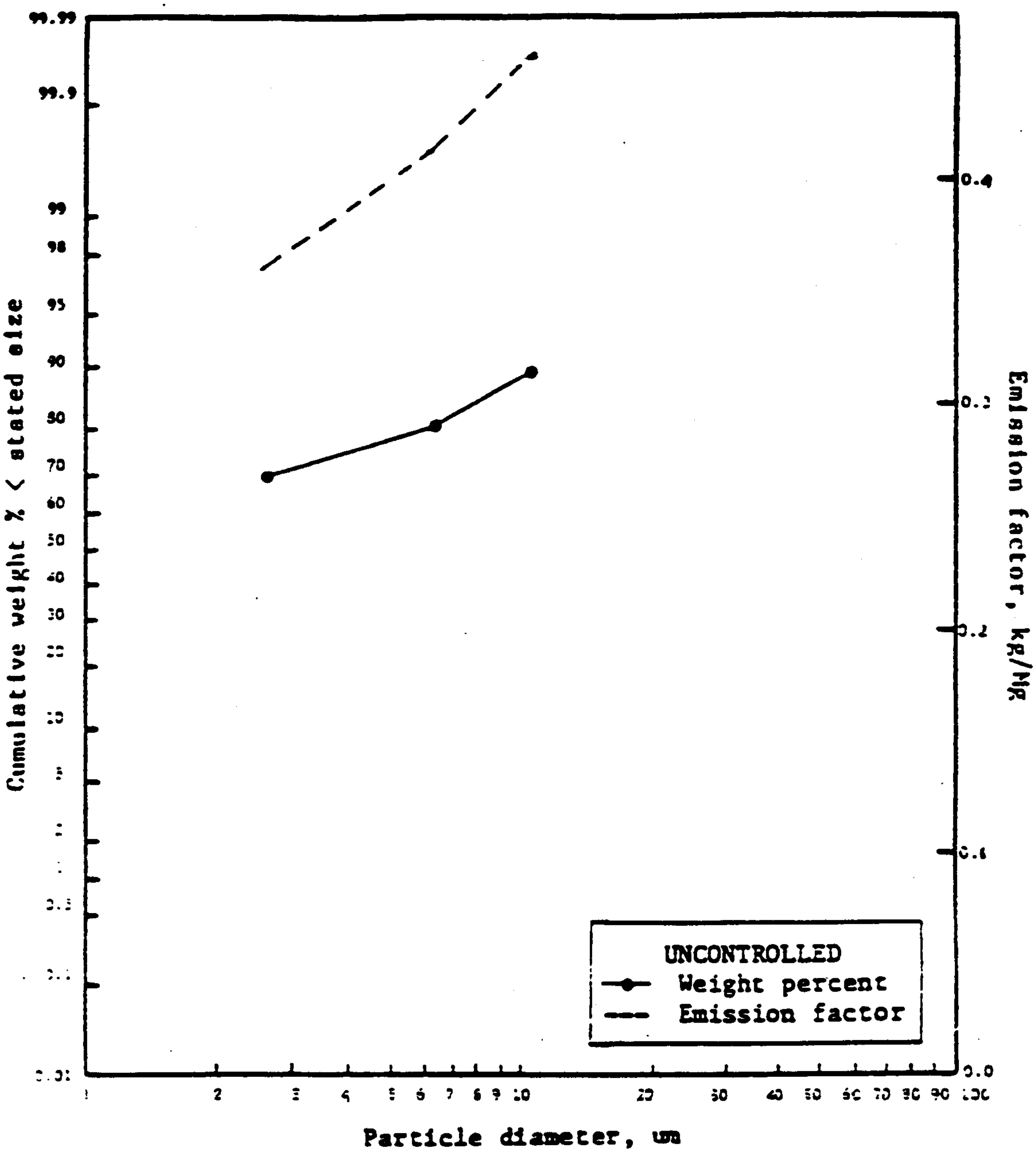
SAMPLING TECHNIQUE: Andersen Mark III Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Confidential test data from a major grain processor, PEI Associates, Inc., Golden, CO, January 1985.

9.9.4 ALFALFA DEHYDRATING: DRUM DRYER PRIMARY CYCLONE



Aerodynamic Particle diameter, um	Cum. wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	70.6	3.5
6.0	82.7	4.1
10.0	90.0	4.5

9.9.4 ALFALFA DEHYDRATING: DRUM DRYER PRIMARY CYCLONE

NUMBER OF TESTS: 1, conducted before control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	70.6	82.7	90.0
	Standard deviation (Cum. %)			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 5.0 kg particulate/Mg alfalfa pellets before control. Factor from AP-42, Section 9.9.4.

SOURCE OPERATION: During this test, source dried 10 tons of alfalfa/hour in a direct-fired rotary dryer.

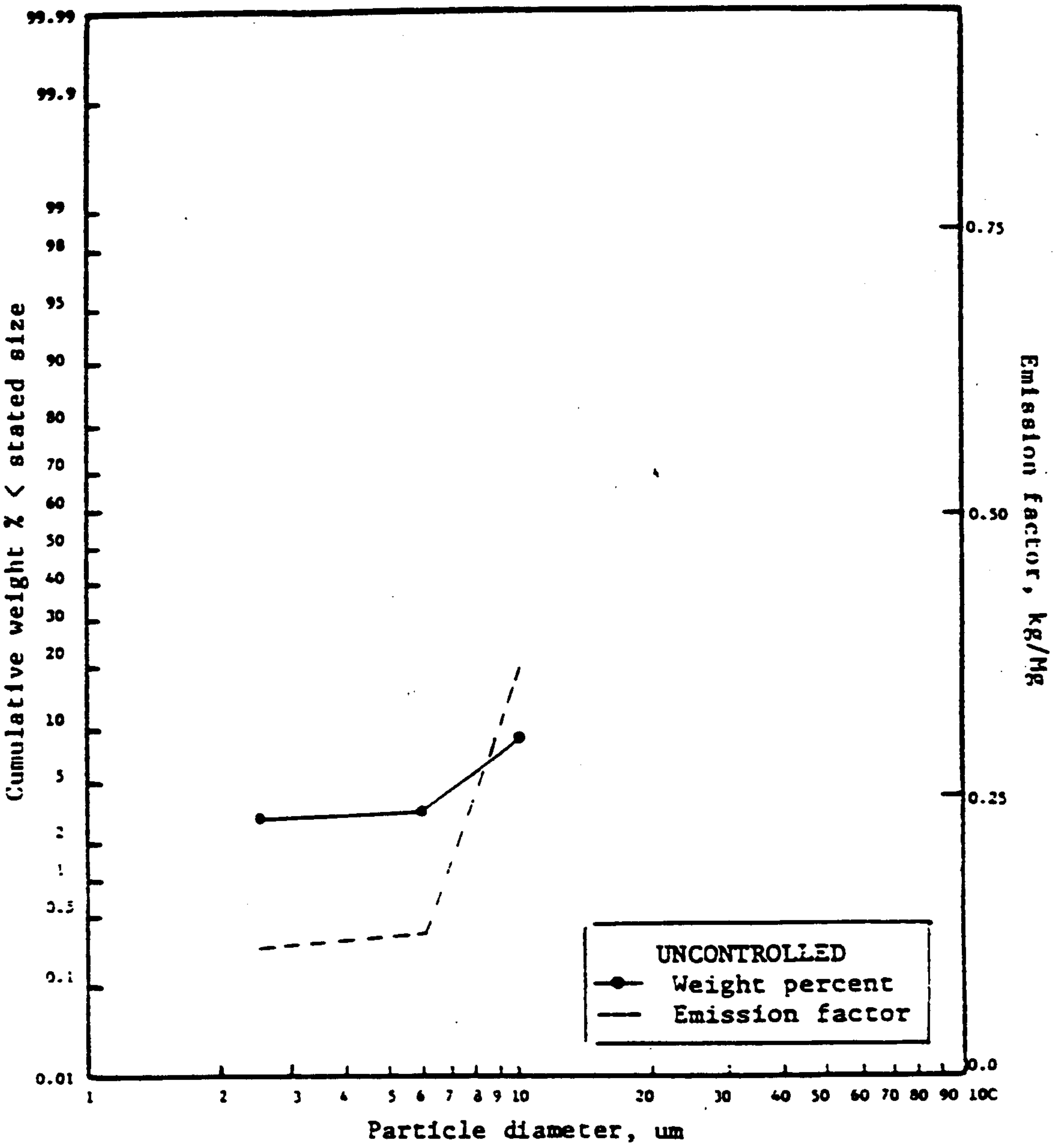
SAMPLING TECHNIQUE: Nelson Cascade Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 152, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

9.9.xx FEED AND GRAIN MILLS AND ELEVATORS: CAROB KIBBLE ROASTER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	3.0	0.11
6.0	3.2	0.12
10.0	9.6	0.36

9.9.xx FEED AND GRAIN MILLS AND ELEVATORS: CAROB KIBBLE ROASTER

NUMBER OF TESTS: 1, conducted before controls

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	3.0	3.2	9.6
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 3.8 kg/Mg carob kibble roasted. Factor from Reference a, p. 4-175.

SOURCE OPERATION: Source roasts 300 kg carob pods per hour, 100% of the design rate. Roaster heat input is 795 kJ/hr of natural gas.

SAMPLING TECHNIQUE: Joy train with 3 cyclones

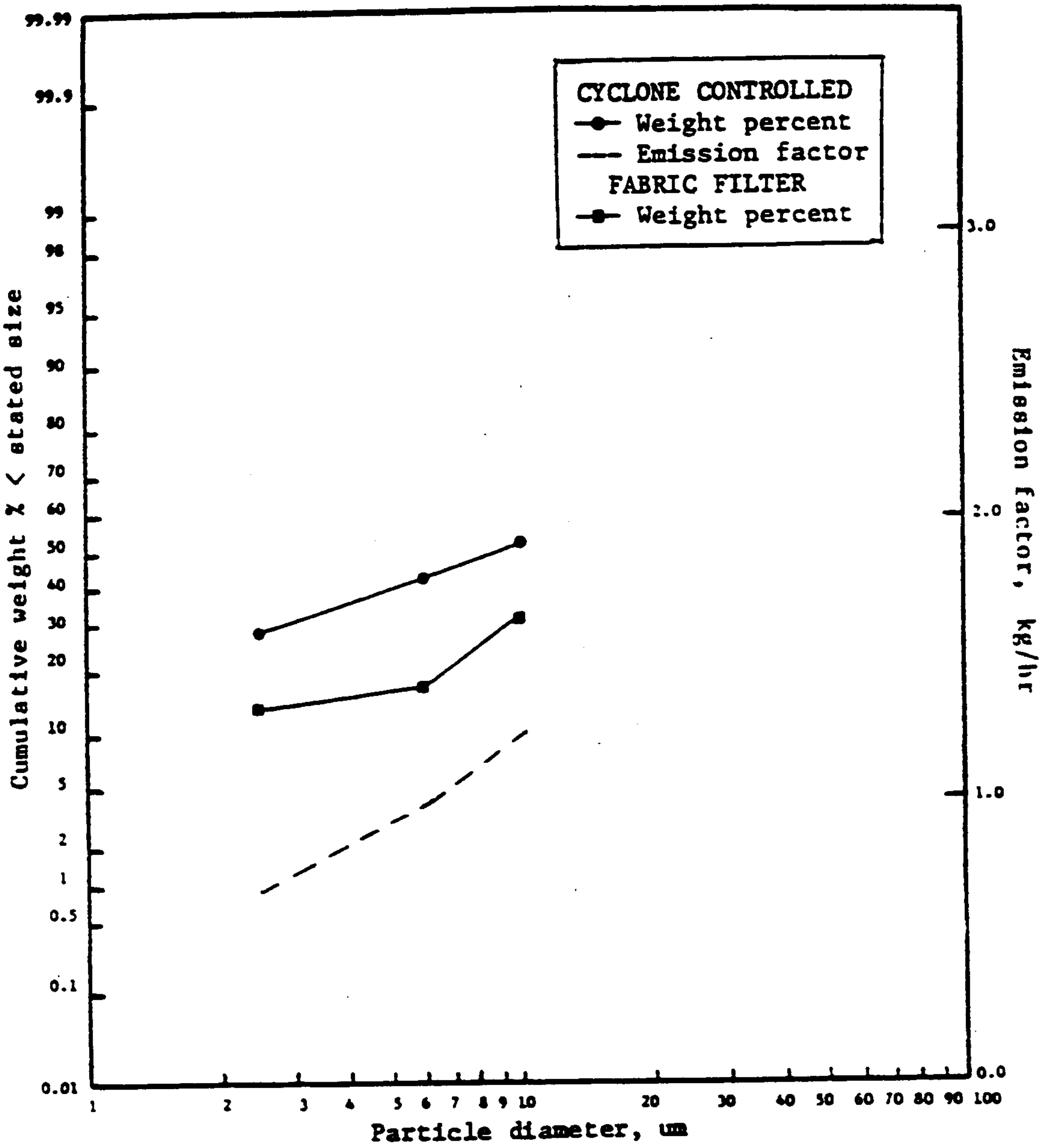
EMISSION FACTOR RATING: E

REFERENCES:

a. H. J. Taback, *Fine Particle Emissions From Stationary And Miscellaneous Sources In The South Coast Air Basin*, PB 293 923/AS, National Technical Information Service, Springfield, VA, February 1979.

b. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System Series, Report No. 229, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

10.5 WOODWORKING WASTE COLLECTION OPERATIONS: BELT SANDER HOOD EXHAUST CYCLONE



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/hour of cyclone operation
	Cyclone	After cyclone and fabric filter	After cyclone collector
2.5	29.5	14.3	0.68
6.0	42.7	17.3	0.98
10.0	52.9	32.1	1.22

10.5 WOODWORKING WASTE COLLECTION OPERATIONS: BELT SANDER HOOD EXHAUST CYCLONE

NUMBER OF TESTS: (a) 1, conducted after cyclone control
(b) 1, after cyclone and fabric filter control

STATISTICS: (a)

Aerodynamic particle diameter (µm):	2.5	6.0	10.0
Mean (Cum. %):	29.5	42.7	52.9
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

(b)

Aerodynamic particle diameter (µm):	2.5	6.0	10.0
Mean (Cum. %.):	14.3	17.3	32.1
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 2.3 kg particulate/hr of cyclone operation. For cyclone-controlled source, this emission factor applies to typical large diameter cyclones into which wood waste is fed directly, not to cyclones that handle waste previously collected in cyclones. If baghouses are used for waste collection, particulate emissions will be negligible. Accordingly, no emission factor is provided for the fabric filter-controlled source. Factors from AP-42.

SOURCE OPERATION: Source was sanding 2-ply panels of mahogany veneer, at 100% of design process rate of 1110 m^2/hr.

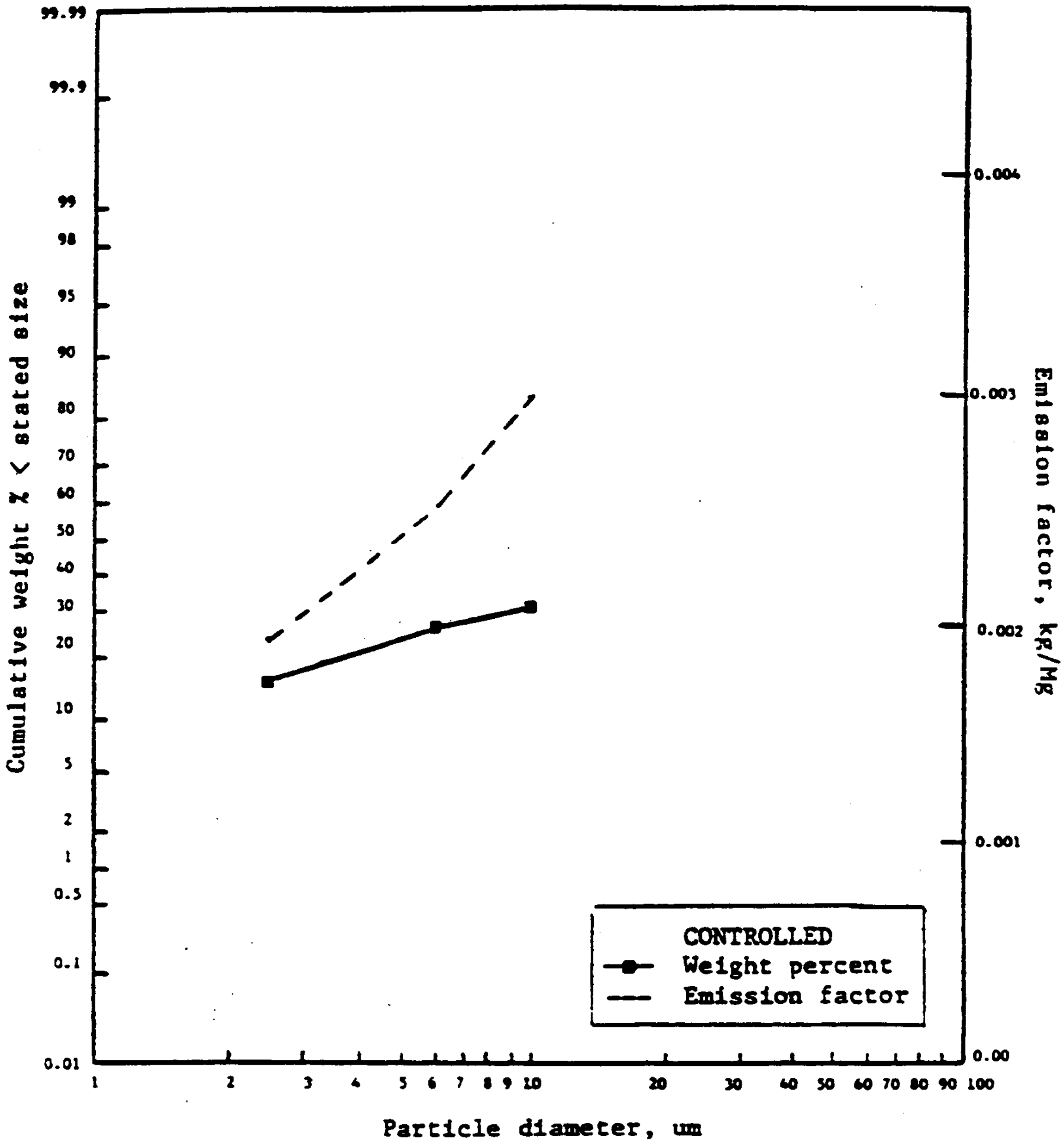
SAMPLING TECHNIQUE: (a) Joy train with 3 cyclones
(b) SASS train with cyclones

EMISSION FACTOR RATING: E

REFERENCE:

Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 238, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

11.10 COAL CLEANING: DRY PROCESS



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	After fabric filter control	After fabric filter control
2.5	16	0.002
6.0	26	0.0025
10.0	31	0.003

11.10 COAL CLEANING: DRY PROCESS

NUMBER OF TESTS: 1, conducted after fabric filter control

STATISTICS:

Aerodynamic particle diameter (µm):	2.5	6.0	10.0
Mean (Cum. %):	16	26	31
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.01 kg particulate/Mg of coal processed. Emission factor is calculated from data in AP-42, Section 11.10, assuming 99% particulate control by fabric filter.

SOURCE OPERATION: Source cleans coal with the dry (air table) process. Average coal feed rate during testing was 70 tons/hr/table.

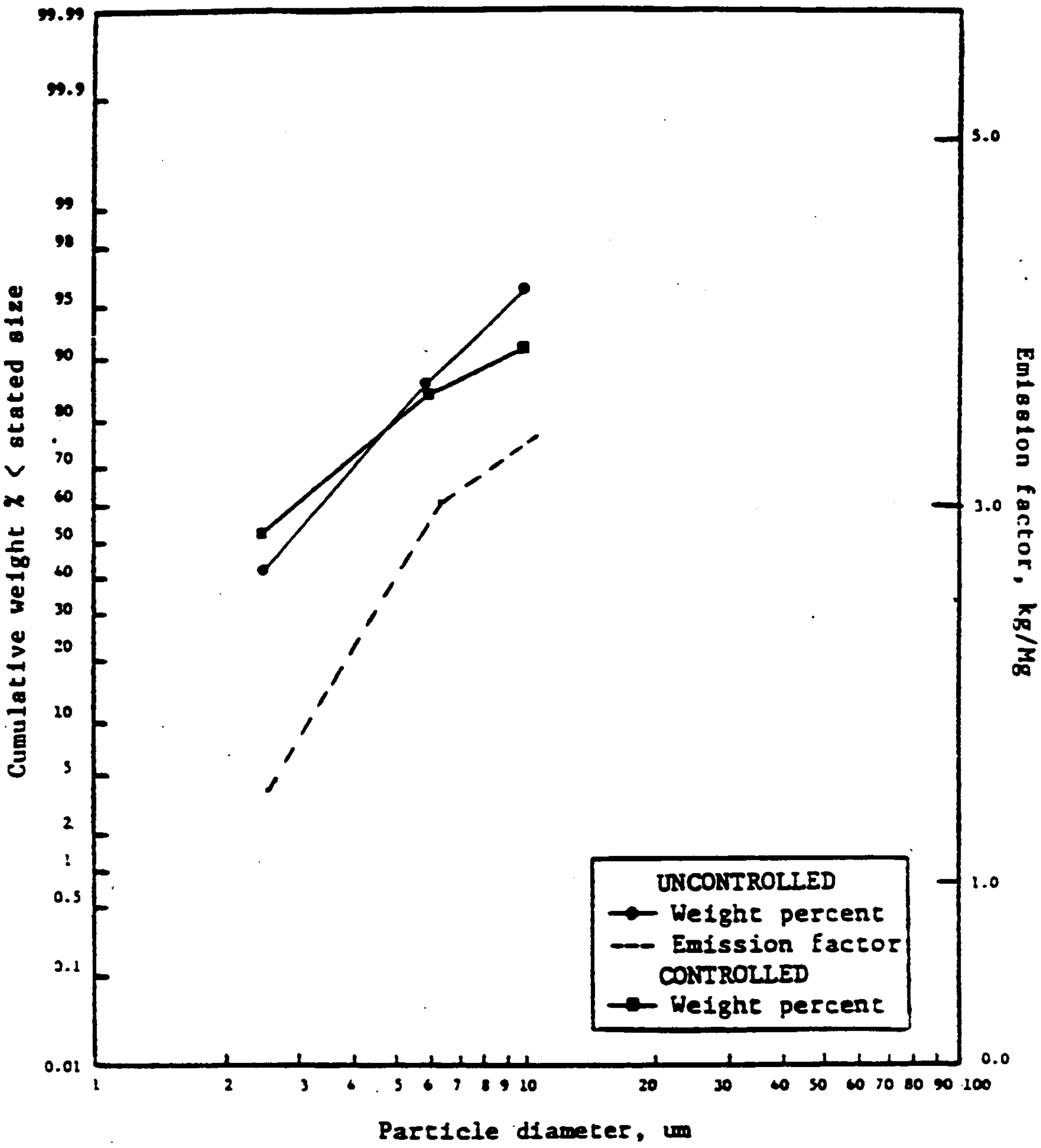
SAMPLING TECHNIQUE: Coulter counter

EMISSION FACTOR RATING: E

REFERENCE:

R. W. Kling, *Emissions From The Florence Mining Company Coal Processing Plant At Seward, PA*, Report No. 72-CI-4, York Research Corporation, Stamford, CT, February 1972.

11.10 COAL CLEANING: THERMAL DRYER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/Mg	
	Uncontrolled	After wet scrubber	Uncontrolled	After wet scrubber
2.5	42	53	1.47	0.016
6.0	86	85	3.01	0.026
10.0	96	91	3.36	0.027

11.10 COAL CLEANING: THERMAL DRYER

NUMBER OF TESTS: (a) 1, conducted before control
(b) 1, conducted after wet scrubber control

STATISTICS: (a)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	42	86	96
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

(b)

Aerodynamic particle diamter (μm):	2.5	6.0	10.0
Mean (Cum. %):	53	85	91
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 3.5 kg particulate/Mg of coal processed (after cyclone) before wet scrubber control. After wet scrubber control, 0.03 kg/Mg. These are site-specific emission factors and are calculated from process data measured during source testing.

SOURCE OPERATION: Source operates a thermal dryer to dry coal cleaned by wet cleaning process. Combustion zone in the thermal dryer is about 1000°F, and the air temperature at the dryer exit is about 125°F. Coal processing rate is about 450 tons per hour. Product is collected in cyclones.

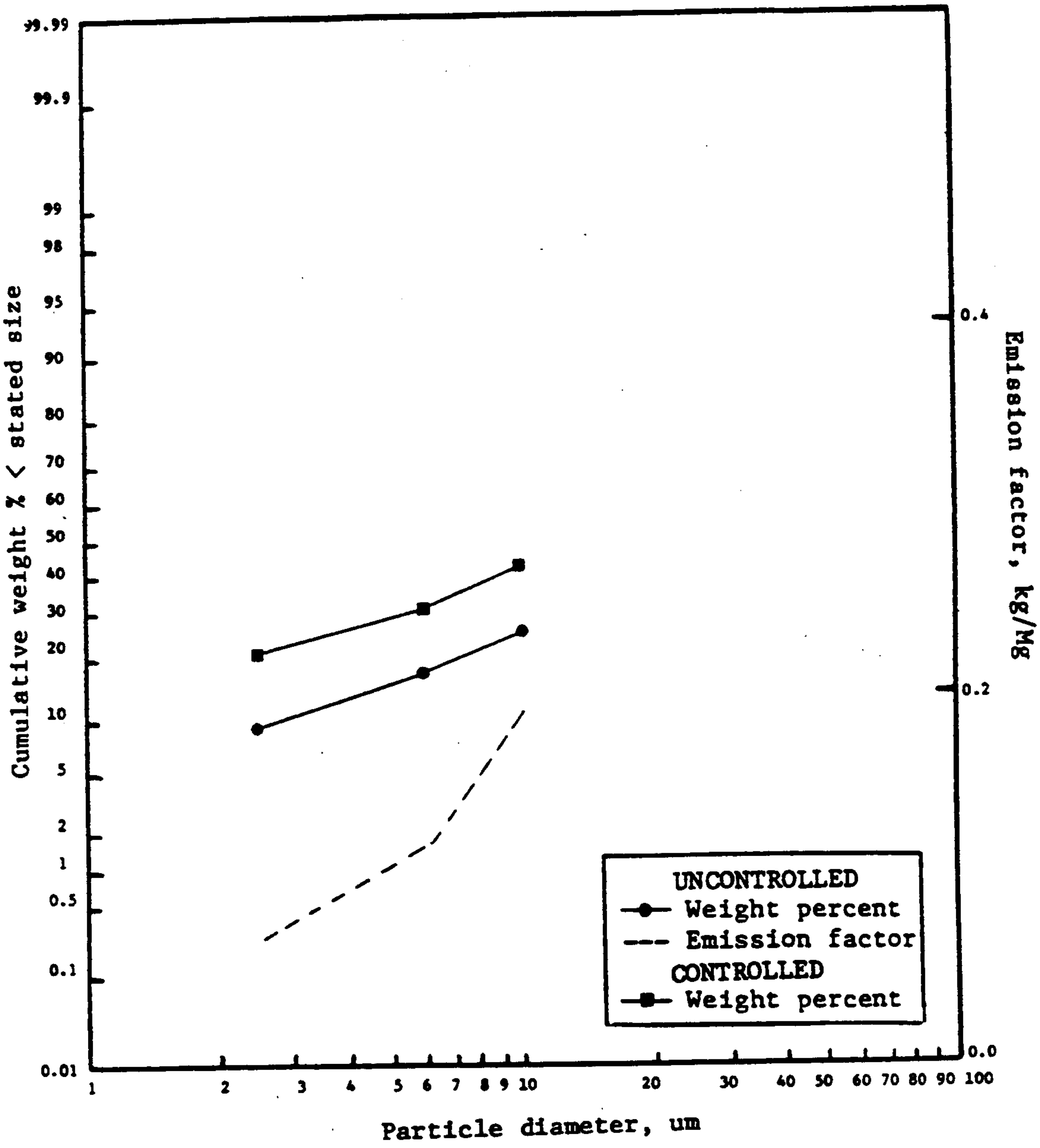
SAMPLING TECHNIQUE: (a) Coulter counter
(b) Each sample was dispersed with aerosol OT, and further dispersed using an ultrasonic bath. Isoton was the electrolyte used.

EMISSION FACTOR RATING: E

REFERENCE:

R. W. Kling, *Emission Test Report, Island Creek Coal Company Coal Processing Plant, Vansant, Virgina*, Report No. Y-7730-H, York Research Corporation, Stamford, CT, February 1972.

11.10 COAL PROCESSING: THERMAL INCINERATOR



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/Mg
	Uncontrolled	Cyclone controlled	Uncontrolled
2.5	9.6	21.3	0.07
6.0	17.5	31.8	0.12
10.0	26.5	43.7	0.19

11.10 COAL PROCESSING: THERMAL INCINERATOR

NUMBER OF TESTS: (a) 2, conducted before controls
(b) 2, conducted after multicyclone control

STATISTICS:

(a)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	9.6	17.5	26.5
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			
(b)	Aerodynamic particle diamter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	26.4	35.8	46.6
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.7 kg particulate/Mg coal dried, before multicyclone control. Factor from AP-42, Section 11.10.

SOURCE OPERATION: Source is a thermal incinerator controlling gaseous emissions from a rotary kiln drying coal. No additional operating data are available.

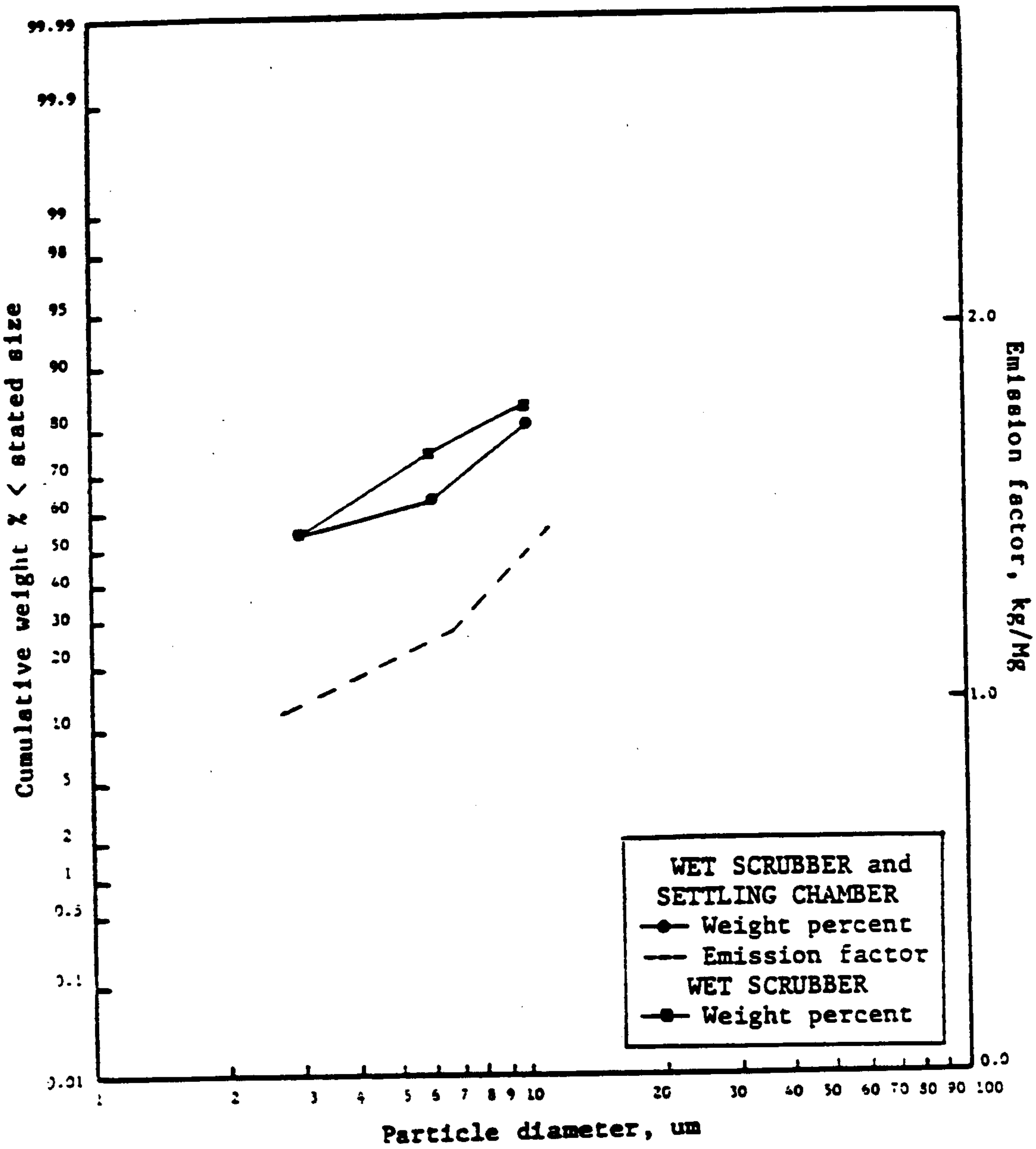
SAMPLING TECHNIQUE: Andersen Mark III Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Confidential test data from a major coal processor, PEI Associates, Inc., Golden, CO, January 1985.

11.20 LIGHTWEIGHT AGGREGATE (CLAY): COAL-FIRED ROTARY KILN



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size		Emission factor (kg/Mg)
	Wet scrubber and settling chamber	Wet scrubber	Wet scrubber and settling chamber
2.5	55	55	0.97
6.0	65	75	1.15
10.0	81	84	1.43

11.20 LIGHTWEIGHT AGGREGATE (CLAY): COAL-FIRED ROTARY KILN

NUMBER OF TESTS: (a) 4, conducted after wet scrubber control
(b) 8, conducted after settling chamber and wet scrubber control

STATISTICS:

(a)	Aerodynamic particle diameter, (μm):	2.5	6.0	10.0
	Mean (Cum. %):	55	75	84
	Standard Deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			
(b)	Aerodynamic particle diameter, (μm):	2.5	6.0	10.0
	Mean (Cum. %):	55	65	81
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 1.77 kg particulate/Mg of clay processed, after control by settling chamber and wet scrubber. Calculated from data in Reference c.

SOURCE OPERATION: Sources produce lightweight clay aggregate in pulverized coal-fired rotary kilns. Kiln capacity for Source b is 750 tons/day, and operation is continuous.

SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: C

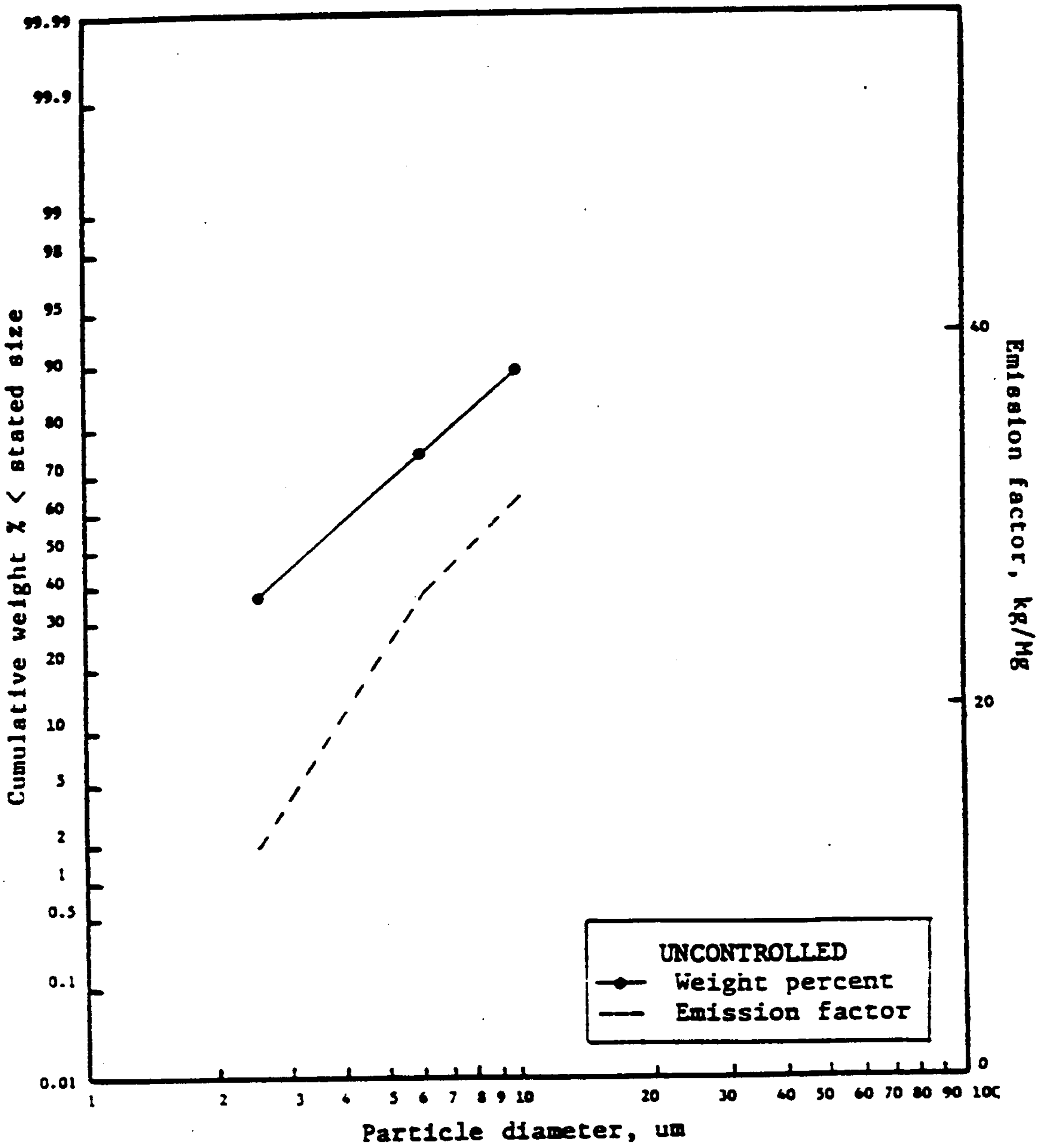
REFERENCES:

a. *Emission Test Report, Lightweight Aggregate Industry, Texas Industries, Inc.*, EMB-80-LWA-3, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1981.

b. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 341, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

c. *Emission Test Report, Lightweight Aggregate Industry, Arkansas Lightweight Aggregate Corporation*, EMB-80-LWA-2, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1981.

11.20 LIGHTWEIGHT AGGREGATE (CLAY): DRYER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	37.2	13.0
6.0	74.8	26.2
10.0	89.5	31.3

11.20 LIGHTWEIGHT AGGREGATE (CLAY): DRYER

NUMBER OF TESTS: 5, conducted before controls

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	37.2	74.8	89.5
Standard deviation (Cum. %):	3.4	5.6	3.6
Min (Cum. %):	32.3	68.9	85.5
Max (Cum. %):	41.0	80.8	92.7

TOTAL PARTICULATE EMISSION FACTOR: 65 kg/Mg clay feed to dryer. From AP-42, Section 11.20.

SOURCE OPERATION: No information on source operation is available

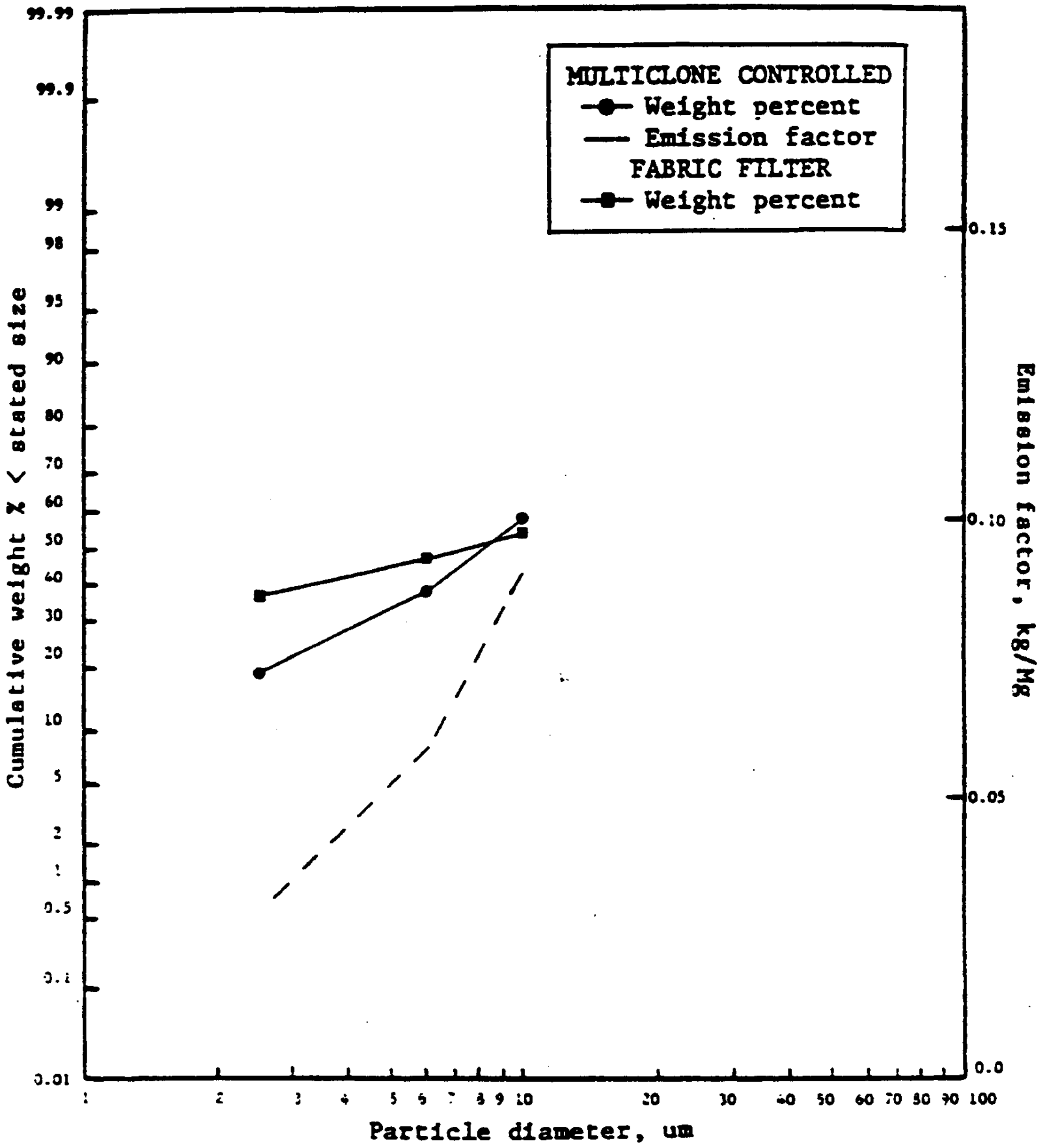
SAMPLING TECHNIQUE: Brink Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 88, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

11.20 LIGHTWEIGHT AGGREGATE (CLAY): RECIPROCATING GRATE CLINKER COOLER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/Mg
	Multiclone	Fabric filter	Multiclone
2.5	19.3	39	0.03
6.0	38.1	48	0.06
10.0	56.7	54	0.09

11.20 LIGHTWEIGHT AGGREGATE (CLAY): RECIPROCATING GRATE CLINKER COOLER

NUMBER OF TESTS: (a) 12, conducted after Multicyclone control
(b) 4, conducted after Multicyclone and fabric filter control

STATISTICS:

(a)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	19.3	38.1	56.7
	Standard deviation (Cum. %):	7.9	14.9	17.9
	Min (Cum. %):	9.3	18.6	29.2
	Max (Cum. %):	34.6	61.4	76.6
(b)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	39	48	54
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.157 kg particulate/Mg clay processed, after multicyclone control. Factor calculated from data in Reference b. After fabric filter control, particulate emissions are negligible.

SOURCE OPERATION: Sources produce lightweight clay aggregate in a coal-fired rotary kiln and reciprocating grate clinker cooler.

SAMPLING TECHNIQUE: (a) Andersen Impactor
(b) Andersen Impactor

EMISSION FACTOR RATING: C

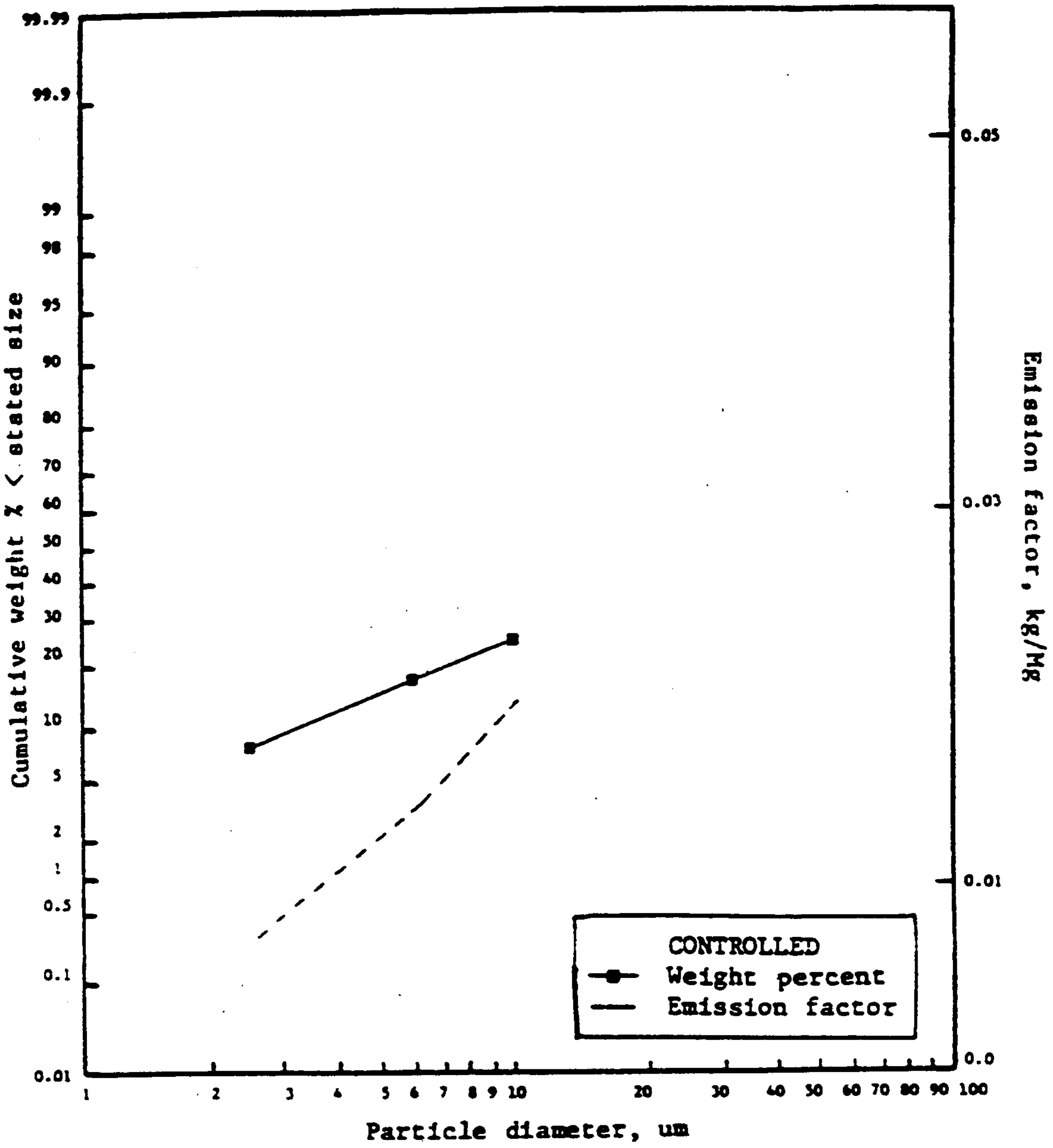
REFERENCES:

a. *Emission Test Report, Lightweight Aggregate Industry, Texas Industries, Inc.*, EMB-80-LWA-3, in U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1981.

b. *Emission Test Report, Lightweight Aggregate Industry, Arkansas Lightweight Aggregate Corporation*, EMB-80-LWA-2, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1981.

c. Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 342, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

11.20 LIGHTWEIGHT AGGREGATE (SHALE): RECIPROCATING GRATE CLINKER COOLER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Settling chamber control	Settling chamber control
2.5	8.2	0.007
6.0	17.6	0.014
10.0	25.6	0.020

11.20 LIGHTWEIGHT AGGREGATE (SHALE): RECIPROCATING GRATE CLINKER COOLER

NUMBER OF TESTS: 4, conducted after settling chamber control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	8.2	17.6	25.6
	Standard deviation (Cum. %):	4.3	2.8	1.7
	Min (Cum. %):	4.0	15.0	24.0
	Max (Cum. %):	14.0	21.0	28.0

TOTAL PARTICULATE EMISSION FACTOR: 0.08 kg particulate/Mg of aggregate produced. Factor calculated from data in reference.

SOURCE OPERATION: Source operates 2 kilns to produce lightweight shale aggregate, which is cooled and classified on a reciprocating grate clinker cooler. Normal production rate of the tested kiln is 23 tons/hr, about 66% of rated capacity. Kiln rotates at 2.8 rpm. Feed end temperature is 1100°F.

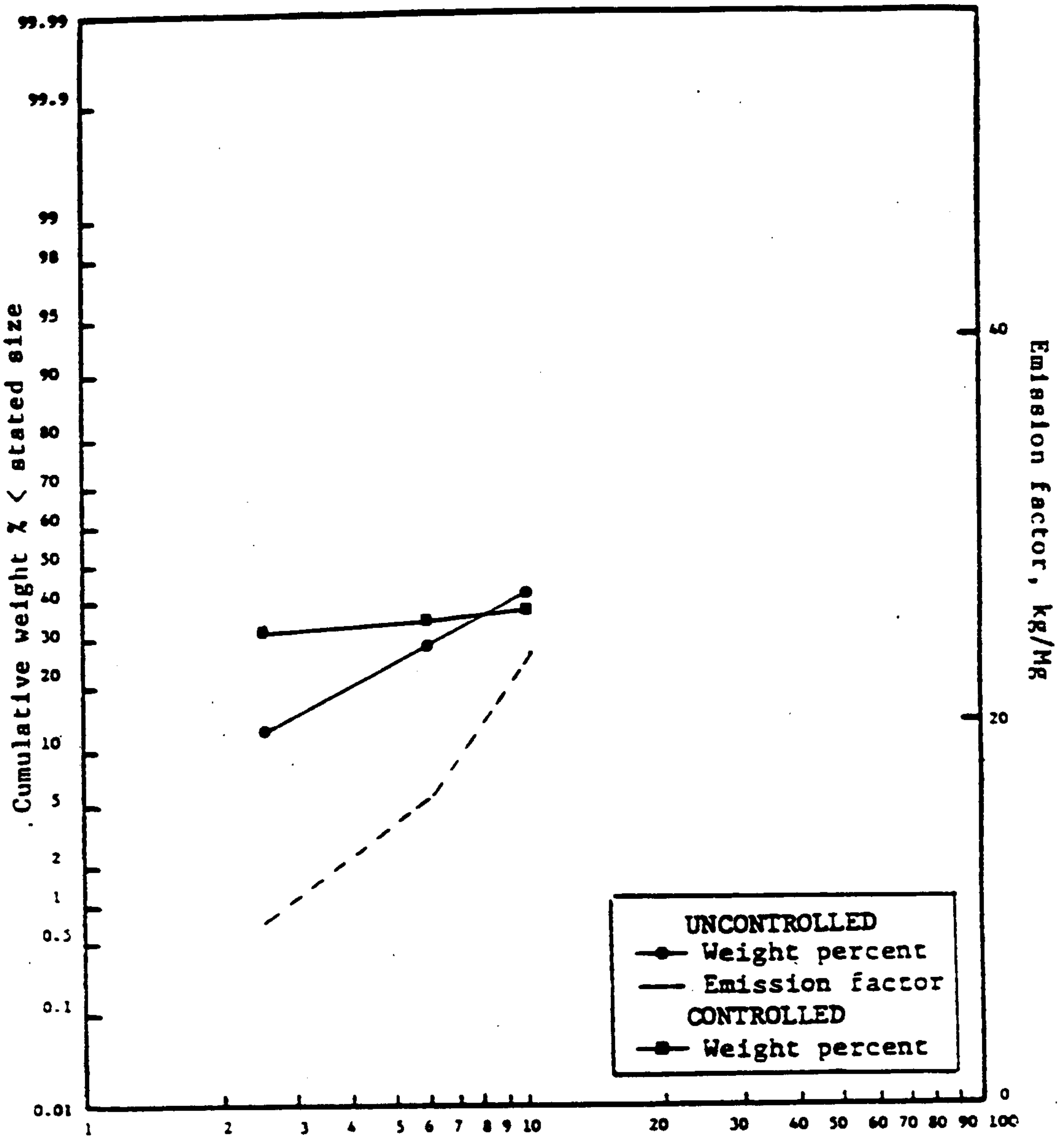
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: B

REFERENCE:

Emission Test Report, Lightweight Aggregate Industry, Vulcan Materials Company, EMB-80-LWA-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, March 1982.

11.20 LIGHTWEIGHT AGGREGATE (SLATE): COAL-FIRED ROTARY KILN



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/Mg	
	Without controls	After wet scrubber control	Without controls	After wet scrubber control
2.5	13	33	7.3	0.59
6.0	29	36	16.2	0.65
10.0	42	39	23.5	0.70

11.20 LIGHTWEIGHT AGGREGATE (SLATE): COAL-FIRED ROTARY KILN

NUMBER OF TESTS: (a) 3, conducted before control
(b) 5, conducted after wet scrubber control

STATISTICS: (a)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	13.0	29.0	42.0
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

(b)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	33.0	36.0	39.0
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: For uncontrolled source, 56.0 kg particulate/Mg of feed. After wet scrubber control, 1.8 kg particulate/Mg of feed. Factors are calculated from data in reference.

SOURCE OPERATION: Source produces lightweight aggregate from slate in coal-fired rotary kiln and reciprocating grate clinker cooler. During testing source was operating at a feed rate of 33 tons/hr, 83% rated capacity. Firing zone temperatures are about 2125°F and kiln rotates at 3.25 rpm.

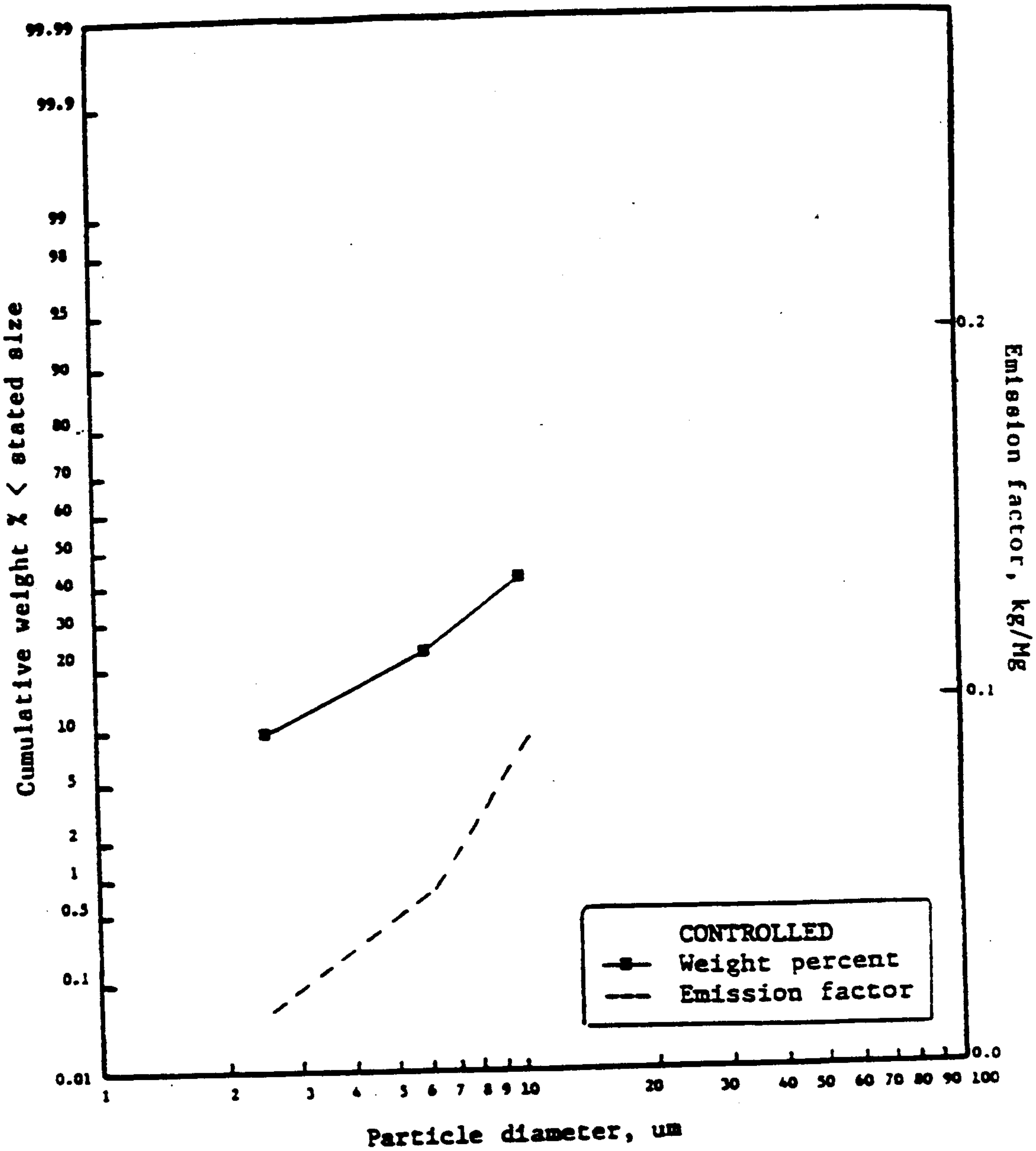
SAMPLING TECHNIQUE: (a) Bacho
(b) Andersen Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Emission Test Report, Lightweight Aggregate Industry, Galite Corporation, EMB-80-LWA-6, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1982.

11.20 LIGHTWEIGHT AGGREGATE (SLATE): RECIPROCATING GRATE CLINKER COOLER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	After settling chamber control	After settling chamber control
2.5	9.8	0.02
6.0	23.6	0.05
10.0	41.0	0.09

11.20 LIGHTWEIGHT AGGREGATE (SLATE): RECIPROCATING GRATE CLINKER COOLER

NUMBER OF TESTS: 5, conducted after settling chamber control

STATISTICS:			
Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	9.8	23.6	41.0
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.22 kg particulate/Mg of raw material feed. Factor calculated from data in reference.

SOURCE OPERATION: Source produces lightweight slate aggregate in a coal-fired kiln and a reciprocating grate clinker cooler. During testing, source was operating at a feed rate of 33 tons/hr, 83% of rated capacity. Firing zone temperatures are about 2125°F, and kiln rotates at 3.25 rpm.

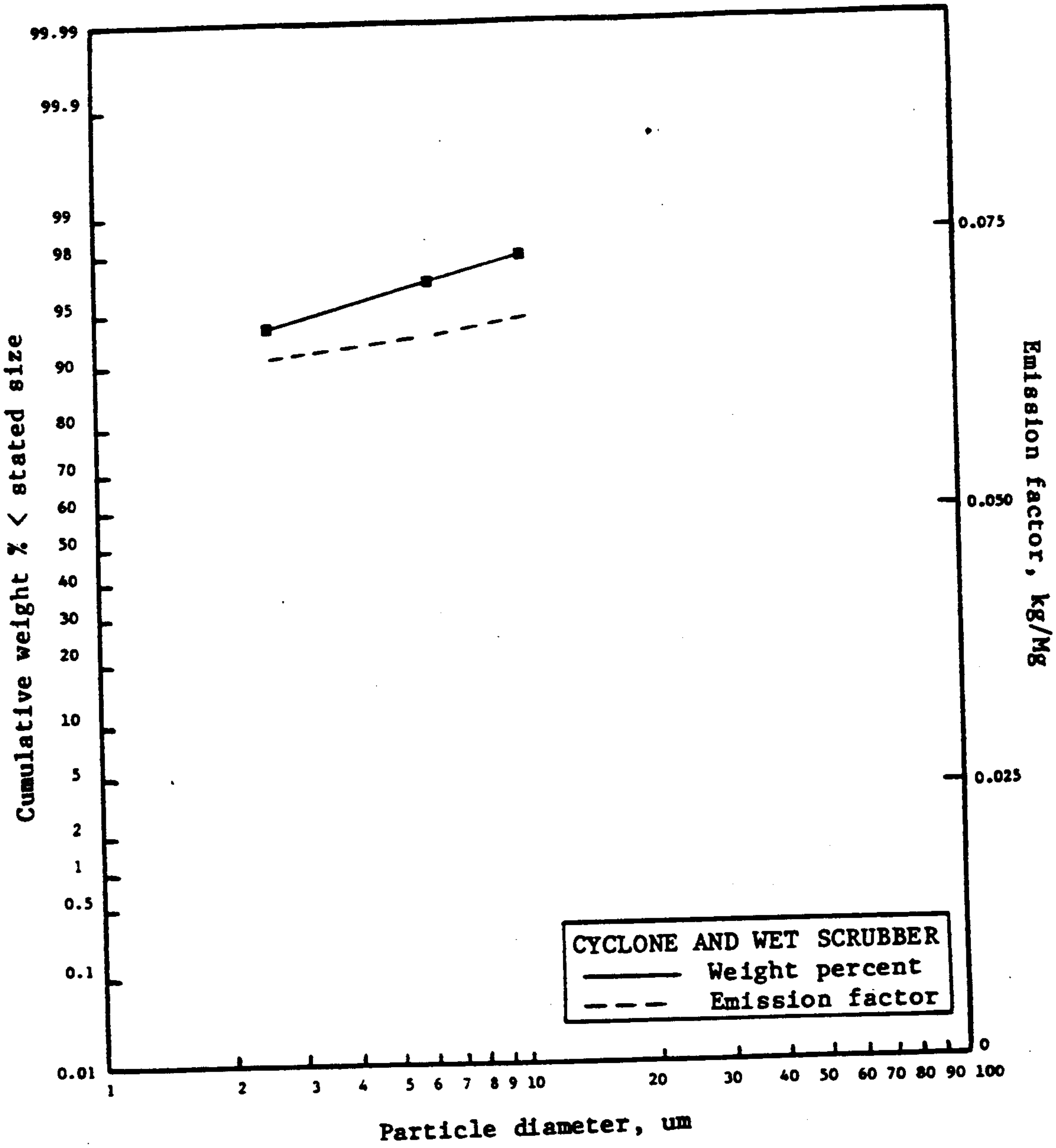
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Emission Test Report, Lightweight Aggregate Industry, Galite Corporation, EMB-80-LWA-6, U. S. Environmental Protection Agency, Research Triangle Park, NC, February 1982.

11.21 PHOSPHATE ROCK PROCESSING: CALCINER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	After cyclone[a] and wet scrubber	After cyclone[a] and wet scrubber
2.5	94.0	0.064
6.0	97.0	0.066
10.0	98.0	0.067

[a] Cyclones are typically used in phosphate rock processing as product collectors. Uncontrolled emissions are emissions in the air exhausted from such cyclones.

11.21 PHOSPHATE ROCK PROCESSING: CALCINER

NUMBER OF TESTS: 6, conducted after wet scrubber control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	94.0	97.0	98.0
	Standard deviation (Cum. %):	2.5	1.6	1.5
	Min (Cum. %):	89.0	95.0	96.0
	Max (Cum. %):	98.0	99.2	99.7

TOTAL PARTICULATE EMISSION FACTOR: 0.0685 kg particulate/Mg of phosphate rock calcined, after collection of airborne product in a cyclone, and wet scrubber controls. Factor from reference cited below.

SOURCE OPERATION: Source is a phosphate rock calciner fired with No. 2 oil, with a rated capacity of 70 tons/hr. Feed to the calciner is beneficiated rock.

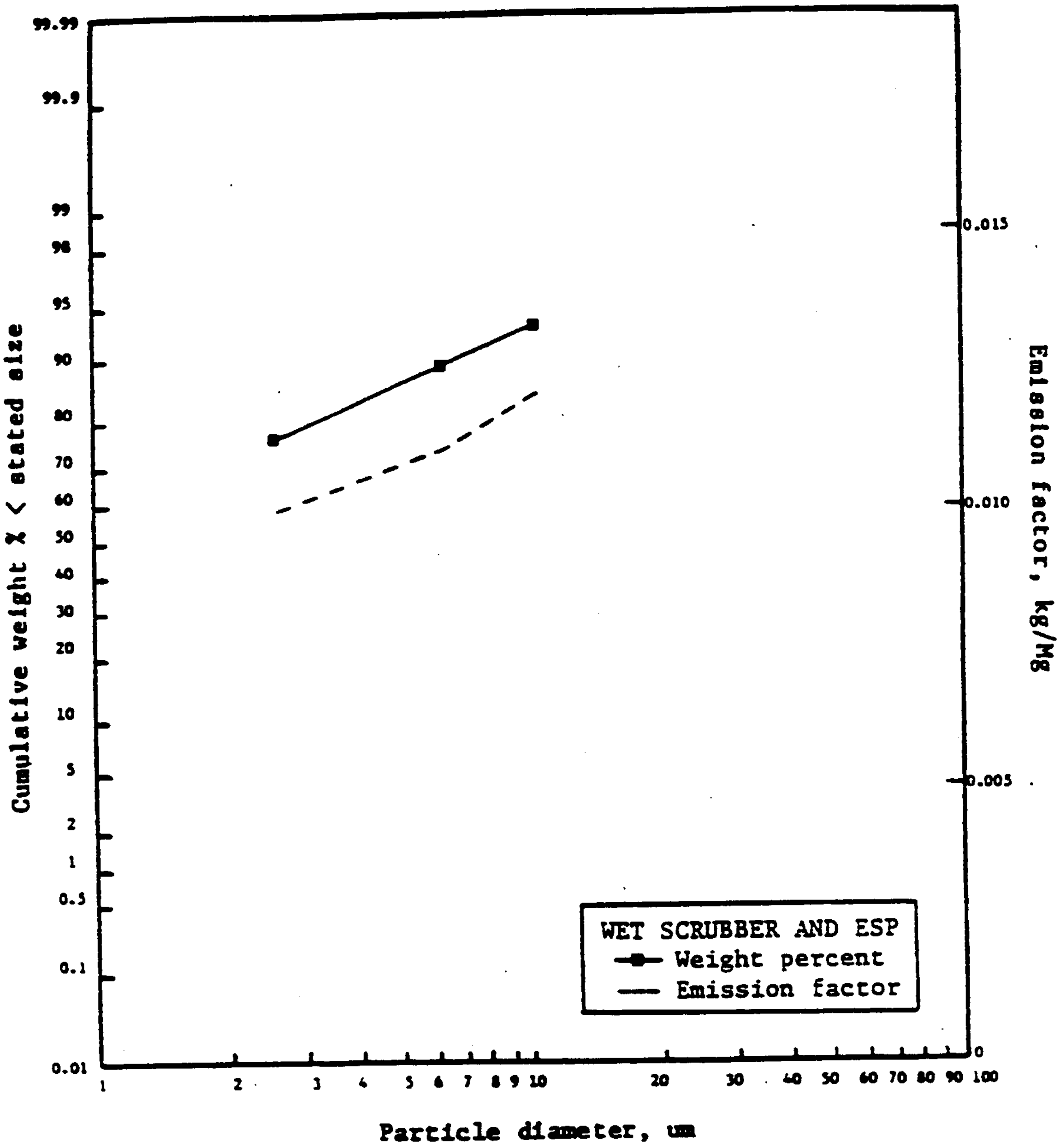
SAMPLING TECHNIQUE: Andersen Impactor.

EMISSION FACTOR RATING: C

REFERENCE:

Air Pollution Emission Test, Beker Industries, Inc., Conda, ID, EMB-75-PRP-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 1975.

11.21 PHOSPHATE ROCK PROCESSING:
OIL-FIRED ROTARY AND FLUIDIZED-BED TANDEM DRYERS



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	After wet scrubber and ESP control	After wet scrubber and ESP control
2.5	78.0	0.010
6.0	88.8	0.011
10.0	93.8	0.012

11.21 PHOSPHATE ROCK PROCESSING: OIL-FIRED ROTARY AND FLUIDIZED-BED TANDEM DRYERS

NUMBER OF TESTS: 2, conducted after wet scrubber and electrostatic precipitator control

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	78.0	88.8	93.8
Standard deviation (Cum. %):	22.6	9.6	2.5
Min (Cum. %):	62	82	92
Max (Cum. %):	94	95	95

TOTAL PARTICULATE EMISSION FACTOR: 0.0125 kg particulate/Mg phosphate rock processed, after collection of airborne product in a cyclone and wet scrubber/ESP controls. Factor from reference cited below.

SOURCE OPERATION: Source operates a rotary and a fluidized bed dryer to dry various types of phosphate rock. Both dryers are fired with No. 5 fuel oil, and exhaust into a common duct. The rated capacity of the rotary dryer is 300 tons/hr, and that of the fluidized bed dryer is 150-200 tons/hr. During testing, source was operating at 67.7% of rated capacity.

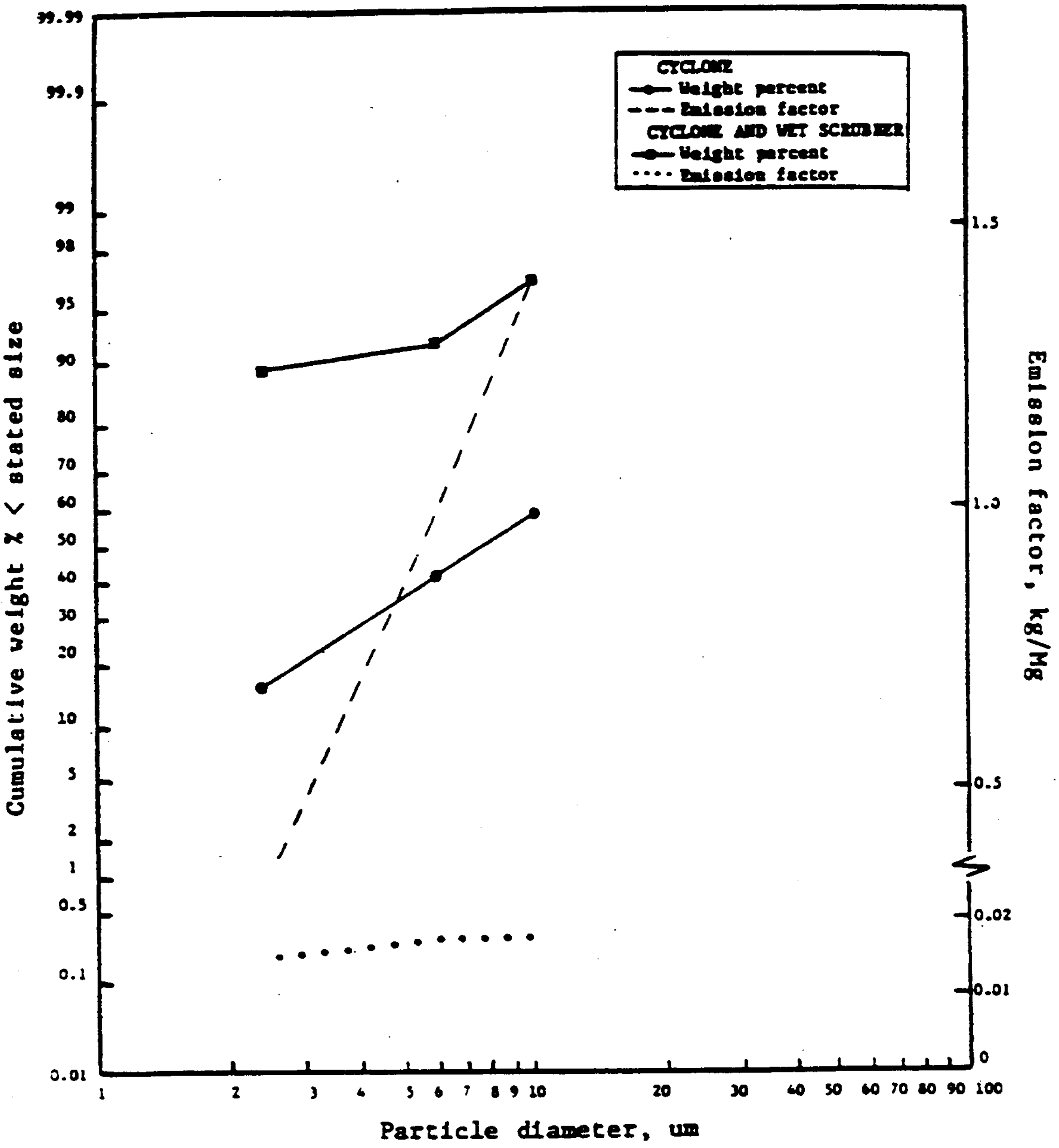
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Air Pollution Emission Test, W. R. Grace Chemical Company, Bartow, FL, EMB-75-PRP-1, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1976.

11.21 PHOSPHATE ROCK PROCESSING: OIL-FIRED ROTARY DRYER



Aerodynamic particle diameter, (um)	Cumulative wt. % < stated size		Emission factor, kg/Mg	
	After cyclone[a]	After wet scrubber	After cyclone[a]	After wet scrubber
2.5	15.7	89	0.38	0.017
6.0	41.3	92.3	1.00	0.018
10.0	58.3	96.6	1.41	0.018

[a] Cyclones are typically used in phosphate rock processing as product collectors. Uncontrolled emissions are emissions in the air exhausted from such cyclones.

11.21 PHOSPHATE ROCK PROCESSING: OIL-FIRED ROTARY DRYER

NUMBER OF TESTS: (a) 3, conducted after cyclone
(b) 2, conducted after wet scrubber control

STATISTICS:

(a)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	15.7	41.3	58.3
	Standard deviation (Cum. %):	5.5	9.6	13.9
	Min (Cum. %):	12	30	43
	Max (Cum. %):	22	48	70

(b)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	89.0	92.3	96.6
	Standard Deviation (Cum. %):	7.1	6.0	3.7
	Min (Cum. %):	84	88	94
	Max (Cum. %):	94	96	99

Impactor cut points for the tests conducted before control are small, and many of the data points are extrapolated. These particle size distributions are related to specific equipment and source operation, and are most applicable to particulate emissions from similar sources operating similar equipment. Table 11.21-2, Section 11.21, AP-42 presents particle size distributions for generic phosphate rock dryers.

TOTAL PARTICULATE EMISSION FACTORS: After cyclone, 2.419 kg particulate/Mg rock processed. After wet scrubber control, 0.019 kg/Mg. Factors from reference cited below.

SOURCE OPERATION: Source dries phosphate rock in #6 oil-fired rotary dryer. During these tests, source operated at 69% of rated dryer capacity of 350 tons/day, and processed coarse pebble rock.

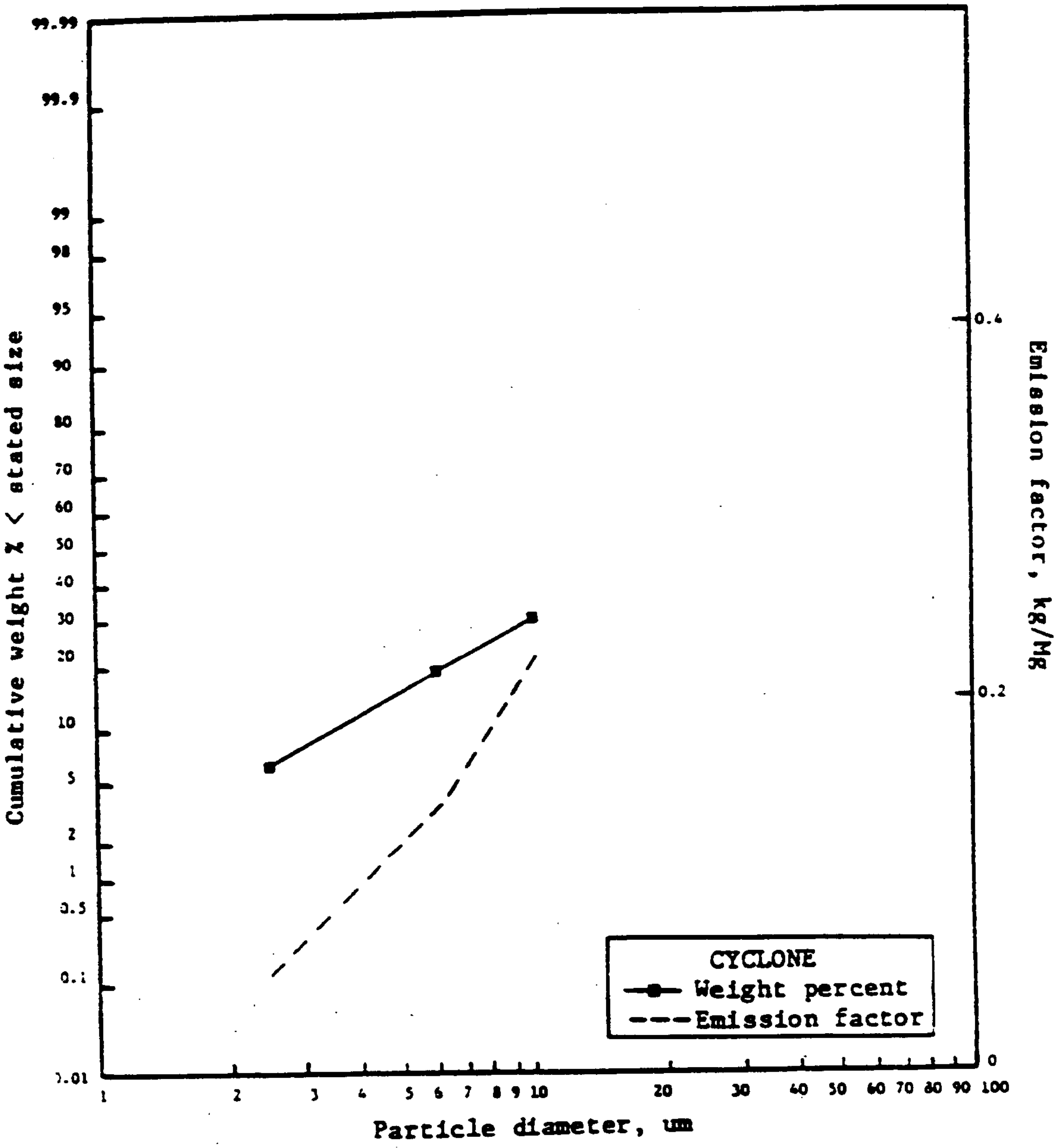
SAMPLING TECHNIQUE: (a) Brinks Cascade Impactor
(b) Andersen Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Air Pollution Emission Test, Mobil Chemical, Nichols, FL, EMB-75-PRP-3, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1976.

11.21 PHOSPHATE ROCK PROCESSING: BALL MILL



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	After cyclone[a]	After cyclone[a]
2.5	6.5	0.05
6.0	19.0	0.14
10.0	30.8	0.22

[a] Cyclones are typically used in phosphate rock processing as product collectors. Uncontrolled emissions are emissions in the air exhausted from such cyclones.

11.21 PHOSPHATE ROCK PROCESSING: BALL MILL

NUMBER OF TESTS: 4, conducted after cyclone

STATISTICS:			
Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	6.5	19.0	30.8
Standard deviation (Cum. %):	3.5	0.9	2.6
Min (Cum. %):	3	18	28
Max (Cum. %):	11	20	33

Impactor cutpoints were small, and most data points were extrapolated.

TOTAL PARTICULATE EMISSION FACTOR: 0.73 kg particulate/Mg of phosphate rock milled, after collection of airborne product in cyclone. Factor from reference cited below.

SOURCE OPERATION: Source mills western phosphate rock. During testing source was operating at 101% of rated capacity, producing 80 tons/hr.

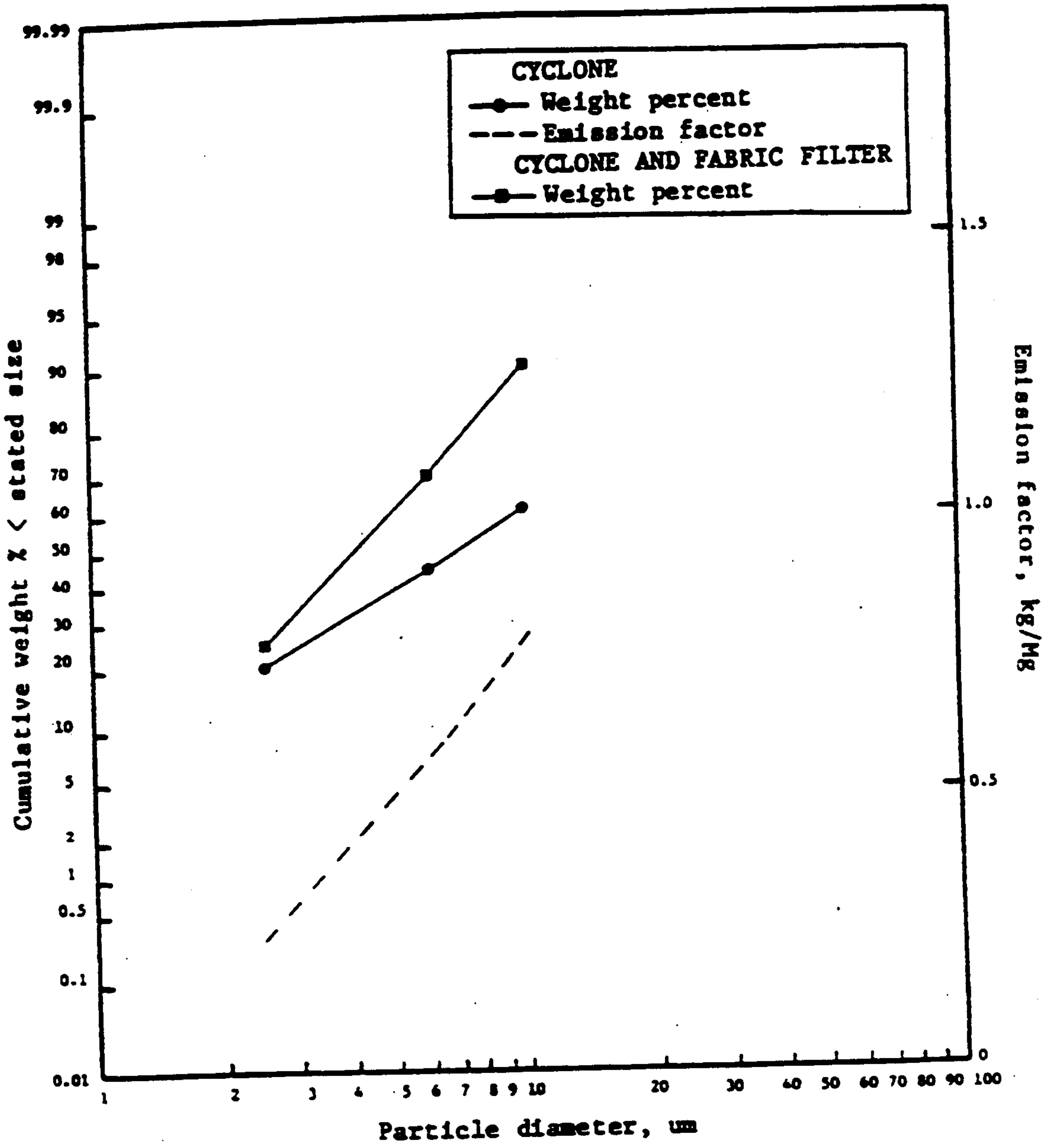
SAMPLING TECHNIQUE: Brink Impactor

EMISSION FACTOR RATING: C

REFERENCE:

Air Pollution Emission Test, Beker Industries, Inc., Conda, ID, EMB-75-PRP-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, November 1975.

11.21 PHOSPHATE ROCK PROCESSING: ROLLER MILL AND BOWL MILL GRINDING



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission factor, kg/Mg	
	After cyclone[a]	After fabric filter	After cyclone[a]	After fabric filter
2.5	21	25	0.27	Negligible
6.0	45	70	0.58	Negligible
10.0	62	90	0.79	Negligible

[a] Cyclones are typically used in phosphate rock processing as product collectors. Uncontrolled emissions are emissions in the air exhausted from such cyclones.

11.21 PHOSPHATE ROCK PROCESSING: ROLLER MILL AND BOWL MILL GRINDING

NUMBER OF TESTS: (a) 2, conducted after cyclone
(b) 1, conducted after fabric filter control

STATISTICS:

(a)	Aerodynamic particle diameter (µm):	2.5	6.0	10.0
	Mean (Cum. %):	21.0	45.0	62.0
	Standard deviation (Cum. %):	1.0	1.0	0
	Min (Cum. %):	20.0	44.0	62.0
	Max (Cum. %):	22.0	46.0	62.0
(b)	Aerodynamic particle diamter (µm):	2.5	6.0	10.0
	Mean (Cum. %):	25	70	90
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR. 0.73 kg particulate/Mg of rock processed, after collection of airborne product in a cyclone. After fabric filter control, 0.001 kg particulate/Mg rock processed. Factors calculated from data in reference cited below. See Table 11.21-3 for guidance.

SOURCE OPERATION: During testing, source was operating at 100% of design process rate. Source operates 1 roller mill with a rated capacity of 25 tons/hr of feed, and 1 bowl mill with a rated capacity of 50 tons/hr of feed. After product has been collected in cyclones, emissions from each mill are vented to a coin baghouse. Source operates 6 days/week, and processes Florida rock.

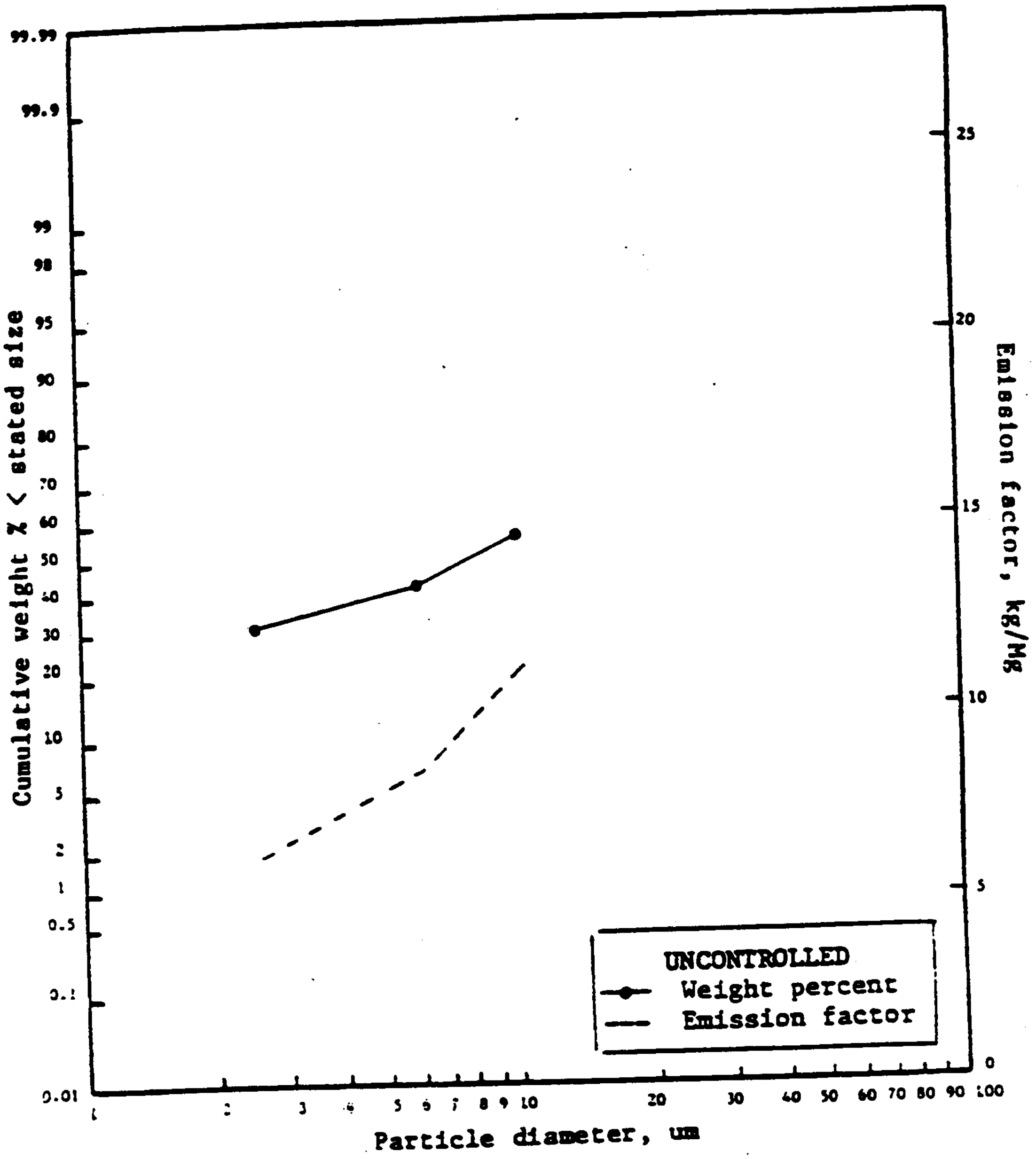
SAMPLING TECHNIQUE: (a) Brink Cascade Impactor
(b) Andersen Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Air Pollution Emission Test, The Royster Company, Mulberry, FL, EMB-75-PRP-2, U. S. Environmental Protection Agency, Research Triangle Park, NC, January 1976.

11.26 NONMETALLIC MINERALS: TALC PEBBLE MILL



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Before controls	Before controls
2.5	30.1	5.9
6.0	42.4	8.3
10.0	56.4	11.1

11.26 NONMETALLIC MINERALS: TALC PEBBLE MILL

NUMBER OF TESTS: 2, conducted before controls

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	30.1	42.4	56.4
	Standard deviation (Cum. %):	0.8	0.2	0.4
	Min (Cum. %):	29.5	42.2	56.1
	Max (Cum. %):	30.6	42.5	56.6

TOTAL PARTICULATE EMISSION FACTOR: 19.6 kg particulate/Mg ore processed. Calculated from data in reference.

SOURCE OPERATION: Source crushes talc ore then grinds crushed ore in a pebble mill. During testing, source operation was normal according to the operators. An addendum to the reference indicates throughput varied between 2.8 and 4.4 tons/hr during these tests.

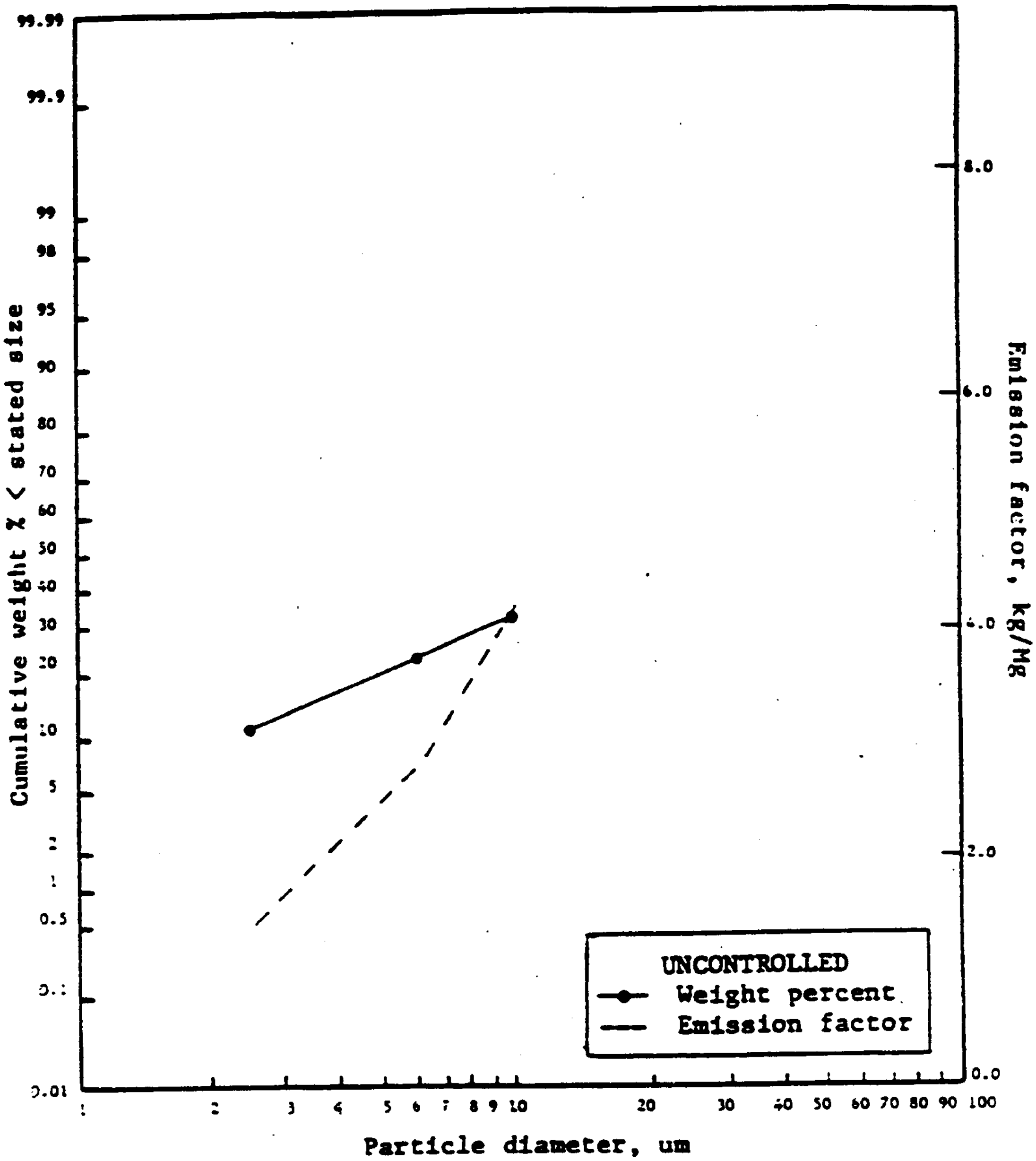
SAMPLING TECHNIQUE: Sample was collected in an alundum thimble and analyzed with a Spectrex Prototron Particle Counter Model ILI 1000.

EMISSION FACTOR RATING: E

REFERENCE:

Air Pollution Emission Test, Pfizer, Inc., Victorville, CA, EMB-77-NMM-5, U. S. Environmental Protection Agency, Research Triangle Park, NC, July 1977.

11.xx NONMETALLIC MINERALS: FELDSPAR BALL MILL



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Before controls	Before controls
2.5	11.5	1.5
6.0	22.8	2.9
10.0	32.3	4.2

11.xx NONMETALLIC MINERALS: FELDSPAR BALL MILL

NUMBER OF TESTS: 2, conducted before controls

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	11.5	22.8	32.3
	Standard deviation (Cum. %):	6.4	7.4	6.7
	Min (Cum. %):	7.0	17.5	27.5
	Max (Cum. %):	16.0	28.0	37.0

TOTAL PARTICULATE EMISSION FACTOR: 12.9 kg particulate/Mg feldspar produced. Calculated from data in reference and related documents.

SOURCE OPERATION: After crushing and grinding of feldspar ore, source produces feldspar powder in a ball mill.

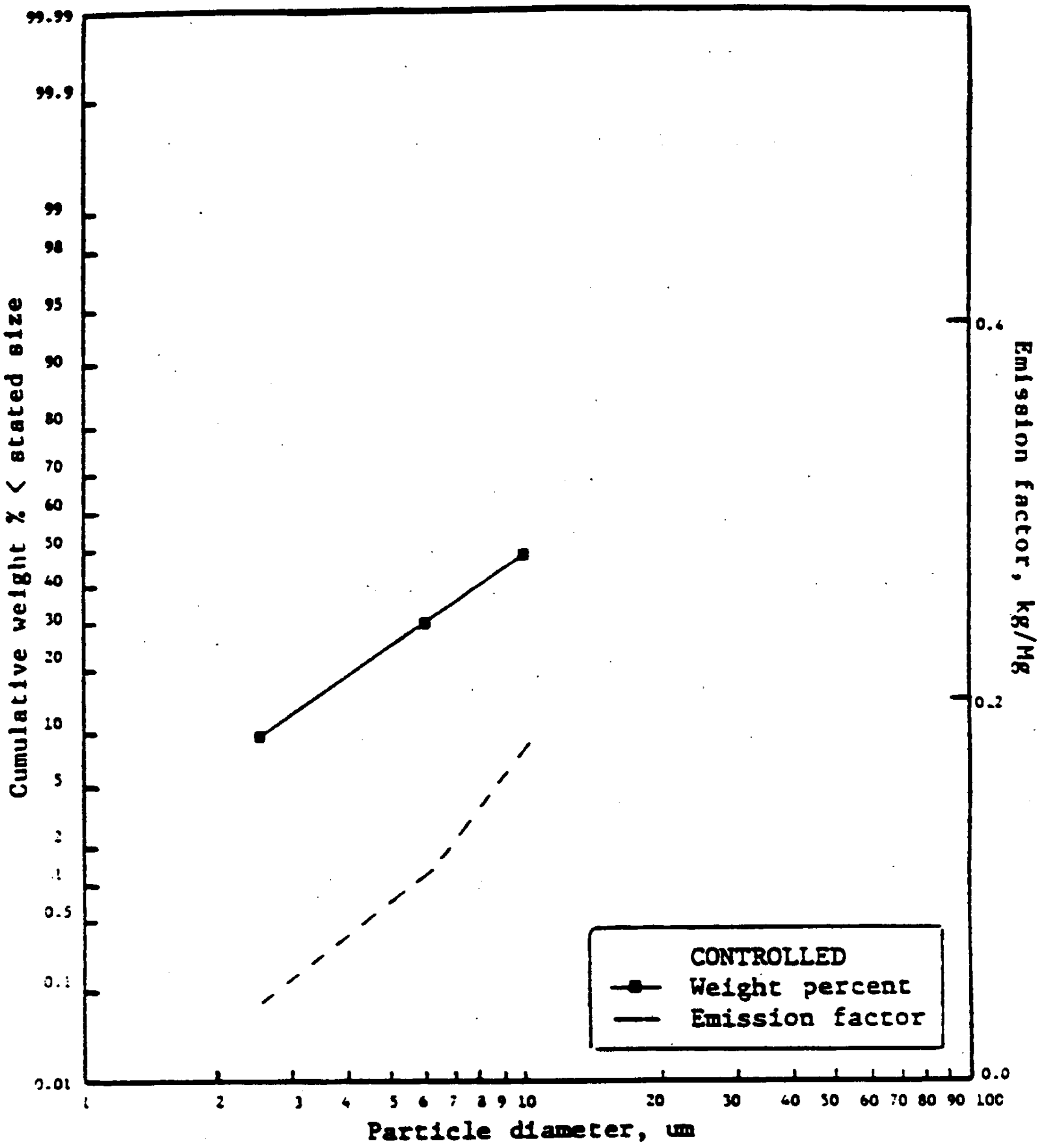
SAMPLING TECHNIQUE: Alundum thimble followed by 12-inch section of stainless steel probe followed by 47-mm type SGA filter contained in a stainless steel Gelman filter holder. Laboratory analysis methods: microsieve and electronic particle counter.

EMISSION FACTOR RATING: D

REFERENCE:

Air Pollution Emission Test, International Minerals and Chemical Company, Spruce Pine, NC, EMB-76-NMM-1, U. S. Environmental Protection Agency, Research Triangle Park, NC, September 1976.

11.xx NONMETALLIC MINERALS: FLUORSPAR ORE ROTARY DRUM DRYER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	After fabric filter control	After fabric filter control
2.5	10	0.04
6.0	30	0.11
10.0	48	0.18

11.xx NONMETALLIC MINERALS: FLUORSPAR ORE ROTARY DRUM DRYER

NUMBER OF TESTS: 1, conducted after fabric filter control

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	10	30	48
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.375 kg particulate/Mg ore dried, after fabric filter control. Factors from reference.

SOURCE OPERATION: Source dries fluorspar ore in a rotary drum dryer at a feed rate of 2 tons/hr.

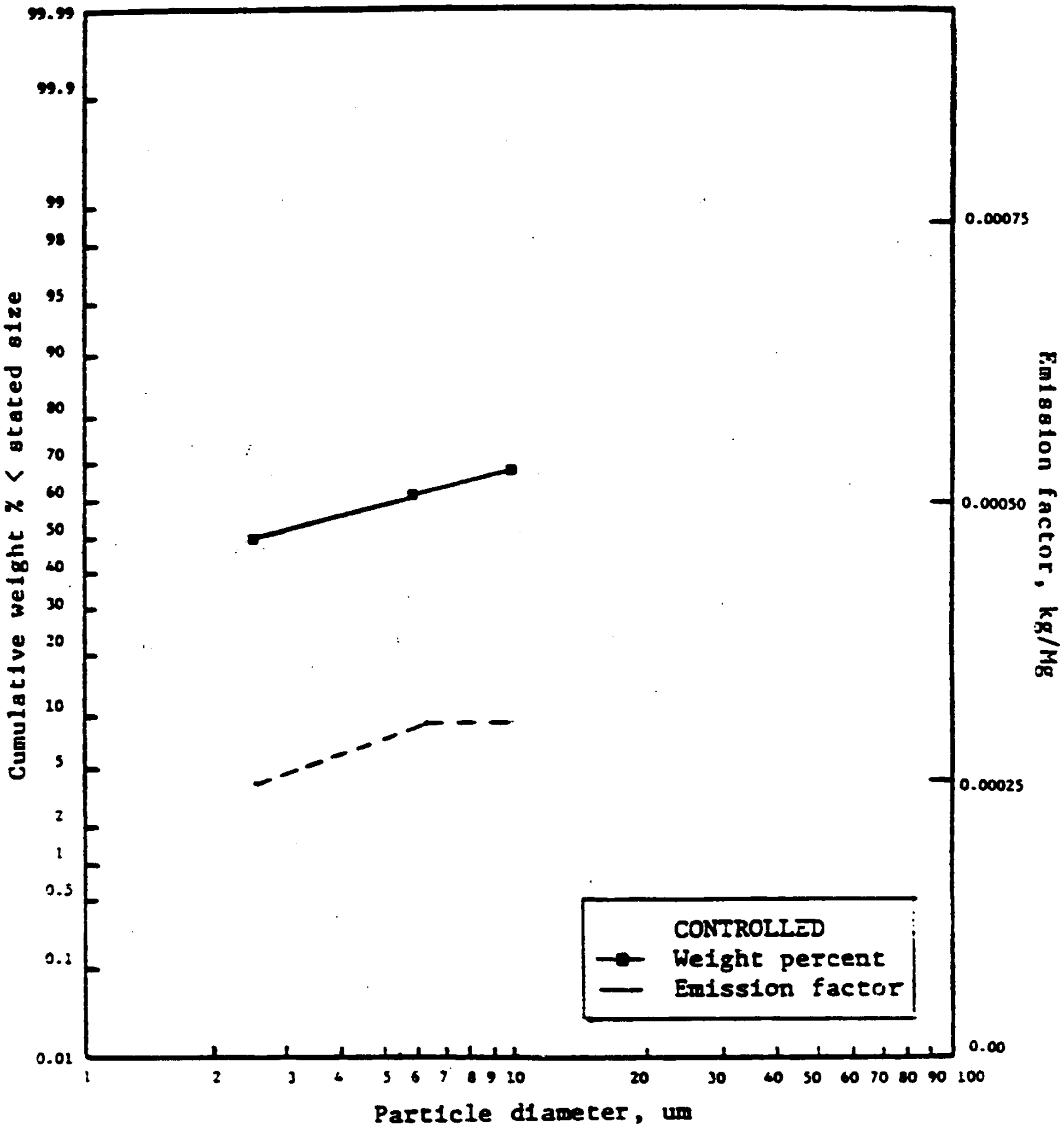
SAMPLING TECHNIQUE: Andersen Mark III Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Confidential test data from a major fluorspar ore processor, PEI Associates, Inc., Golden, CO, January 1985.

12.1 PRIMARY ALUMINUM PRODUCTION: BAUXITE PROCESSING - FINE ORE STORAGE



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Fabric filter controlled	Fabric filter controlled
2.5	50.0	0.00025
6.0	62.0	0.0003
10.0	68.0	0.0003

12.1 PRIMARY ALUMINUM PRODUCTION: BAUXITE PROCESSING - FINE ORE STORAGE

NUMBER OF TESTS: 2, after fabric filter control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	50.0	62.0	68.0
	Standard deviation (Cum. %):	15.0	19.0	20.0
	Min (Cum. %):	35.0	43.0	48.0
	Max (Cum. %):	65.0	81.0	88.0

TOTAL PARTICULATE EMISSION FACTOR: 0.0005 kg particulate/Mg of ore filled, with fabric filter control. Factor calculated from emission and process data in reference.

SOURCE OPERATION: The facility purifies bauxite to alumina. Bauxite ore, unloaded from ships, is conveyed to storage bins from which it is fed to the alumina refining process. These tests measured the emissions from the bauxite ore storage bin filling operation (the ore drop from the conveyer into the bin), after fabric filter control. Normal bin filling rate is between 425 and 475 tons per hour.

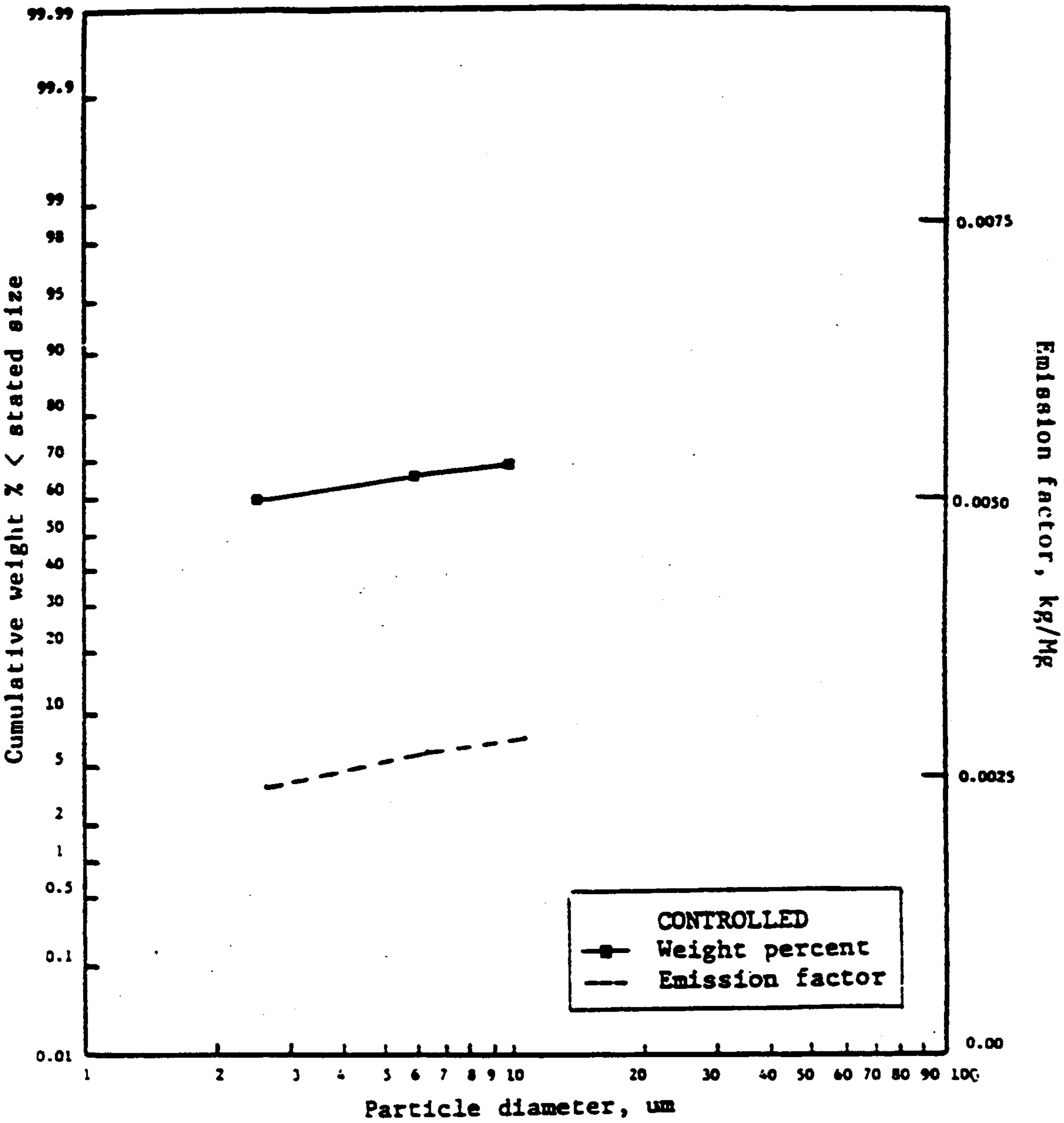
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Emission Test Report, Reynolds Metals Company, Corpus Christi, TX, EMB-80-MET-9, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1980.

12.1 PRIMARY ALUMINUM PRODUCTION: BAUXITE PROCESSING - UNLOADING ORE FROM SHIP



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Wet scrubber controlled	Wet scrubber controlled
2.5	60.5	0.0024
6.0	67.0	0.0027
10.0	70.0	0.0028

12.1 PRIMARY ALUMINUM PRODUCTION: BAUXITE PROCESSING - UNLOADING ORE FROM SHIP

NUMBER OF TESTS: 1, after venturi scrubber control

STATISTICS:

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	60.5	67.0	70.0
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 0.004 kg particulate/Mg bauxite ore unloaded after scrubber control. Factor calculated from emission and process data contained in reference.

SOURCE OPERATION: The facility purifies bauxite to alumina. Ship unloading facility normally operates at 1500-1700 tons/hr, using a self-contained extendable boom conveyor that interfaces with a dockside conveyor belt through an accordion chute. The emissions originate at the point of transfer of the bauxite ore from the ship's boom conveyer as the ore drops through the chute onto the dockside conveyer. Emissions are ducted to a dry cyclone.and then to a Venturi scrubber. Design pressure drop across scrubber is 15 inches, and efficiency during test was 98.4%.

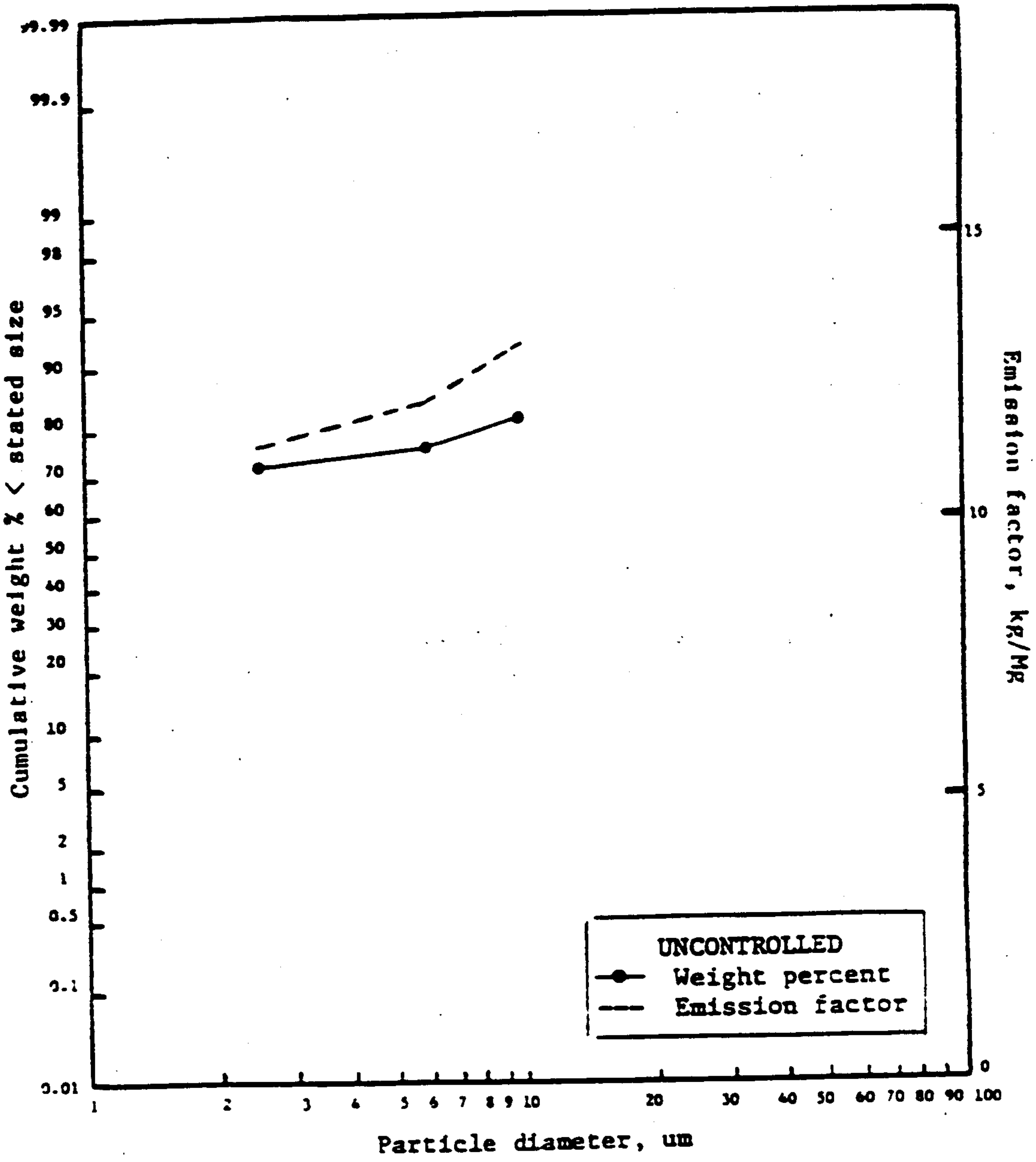
SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Emission Test Report, Reynolds Metals Company, Corpus Christi, TX, EMB-80-MET-9, U. S. Environmental Protection Agency, Research Triangle Park, NC, May 1980.

12.13 STEEL FOUNDRIES: CASTINGS SHAKEOUT



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	72.2	11.6
6.0	76.3	12.2
10.0	82.0	13.1

12.13 STEEL FOUNDRIES: CASTINGS SHAKEOUT

NUMBER OF TESTS: 2, conducted at castings shakeout exhaust hood before controls

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	72.2	76.3	82.0
	Standard deviation (Cum. %):	5.4	6.9	4.3
	Min (Cum. %):	66.7	69.5	77.7
	Max (Cum. %):	77.6	83.1	86.3

TOTAL PARTICULATE EMISSION FACTOR: 16 kg particulate/Mg metal melted, without controls. Although no nonfurnace emission factors are available for steel foundries, emissions are presumed to be similar to those in iron foundries. Nonfurnace emission factors for iron foundries are presented in AP-42, Section 12.13.

SOURCE OPERATION: Source is a steel foundry casting steel pipe. Pipe molds are broken up at the castings shakeout operation. No additional information is available.

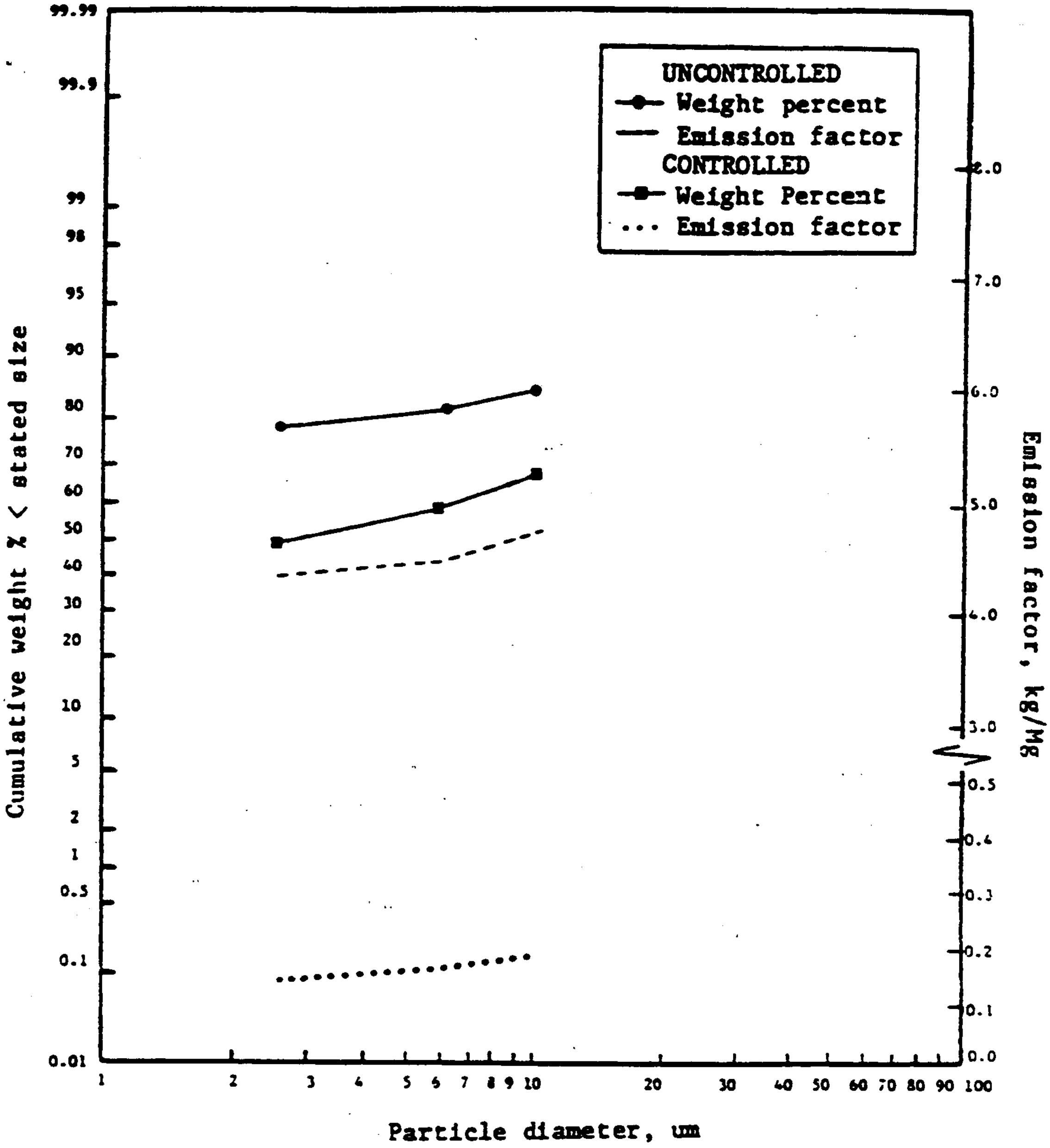
SAMPLING TECHNIQUE: Brink Model BMS-11 Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 117, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

12.13 STEEL FOUNDRIES: OPEN HEARTH EXHAUST



Aerodynamic particle diameter, um	Cumulative wt. % < stated size		Emission Factor (kg/Mg)	
	Uncontrolled	ESP	Uncontrolled	ESP
2.5	79.6	49.3	4.4	0.14
6.0	82.8	58.6	4.5	0.16
10.0	85.4	66.8	4.7	0.18

12.13 STEEL FOUNDRIES: OPEN HEARTH EXHAUST

NUMBER OF TESTS: (a) 1, conducted before control
(b) 1, conducted after ESP control

STATISTICS:

(a)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	79.6	82.8	85.4
	Standard Deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

(b)	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	49.3	58.6	66.8
	Standard Deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 5.5 kg particulate/Mg metal processed, before control. Emission factor from AP-42, Section 12.13. AP-42 gives an ESP control efficiency of 95 to 98.5%. At 95% efficiency, factor after ESP control is 0.275 kg particulate/Mg metal processed.

SOURCE OPERATION: Source produces steel castings by melting, alloying, and casting pig iron and steel scrap. During these tests, source was operating at 100% of rated capacity of 8260 kg metal scrap feed/hour, fuel oil-fired, and 8-hour heats.

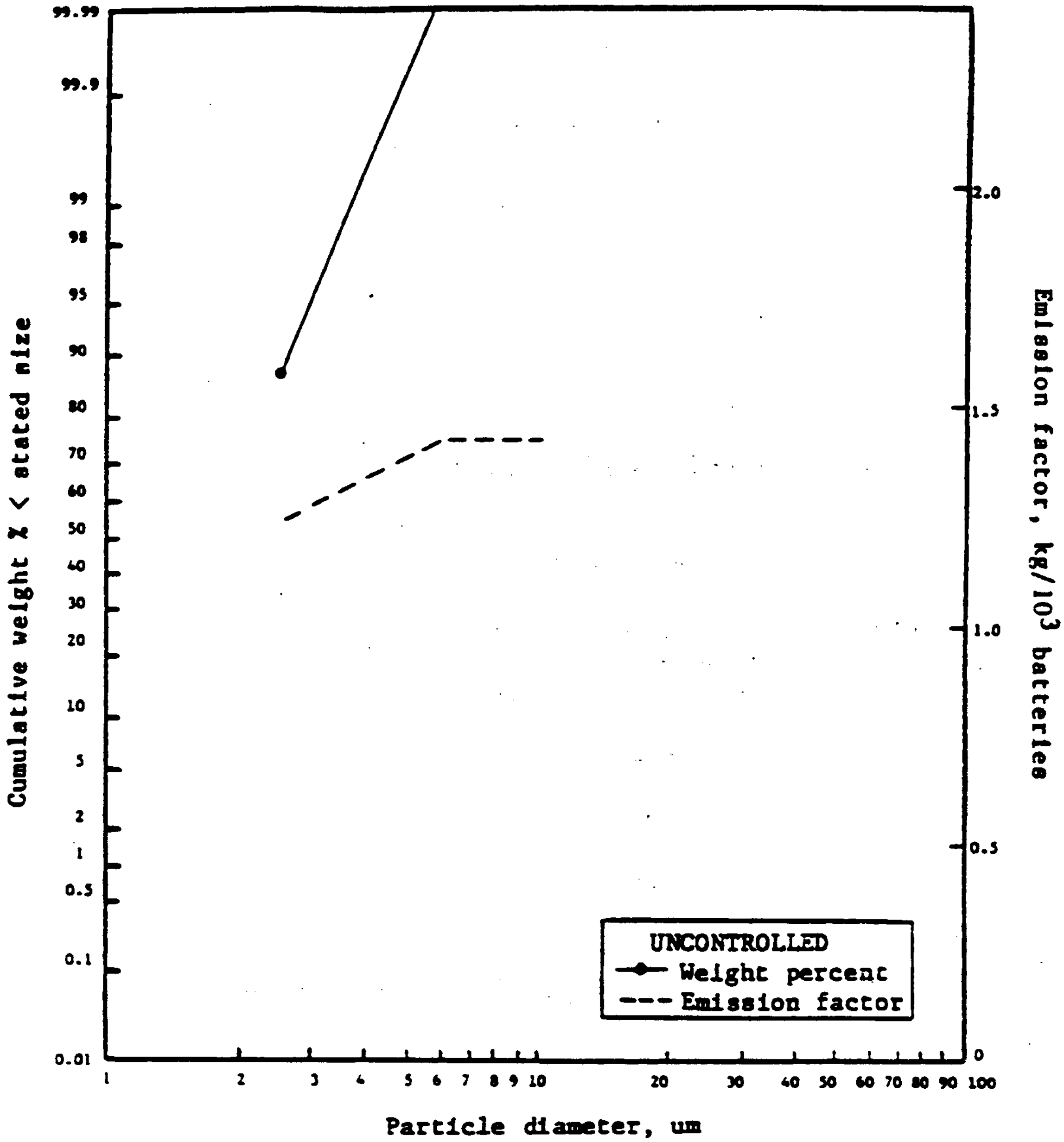
SAMPLING TECHNIQUE: (a) Joy train with 3 cyclones
(b) SASS train with cyclones

EMISSION FACTOR RATING: E

REFERENCE:

Emission test data from Environmental Assessment Data Systems, Fine Particle Emission Information System, Series Report No. 233, U. S. Environmental Protection Agency, Research Triangle Park, NC, June 1983.

12.15 STORAGE BATTERY PRODUCTION: GRID CASTING



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size	Emission factor (kg/10^3 batteries)
	Uncontrolled	Uncontrolled
2.5	87.8	1.25
6.0	100	1.42
10.0	100	1.42

12.15 STORAGE BATTERY PRODUCTION: GRID CASTING

NUMBER OF TESTS: 3, conducted before control

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	87.8	100	100
Standard deviation (Cum. %):	10.3	—	—
Min (Cum. %):	75.4	100	100
Max (Cum. %):	100	100	100

Impactor cut points were so small that most data points had to be extrapolated.

TOTAL PARTICULATE EMISSION FACTOR: 1.42 kg particulate/10^3 batteries produced, without controls. Factor from AP-42, Section 12.15.

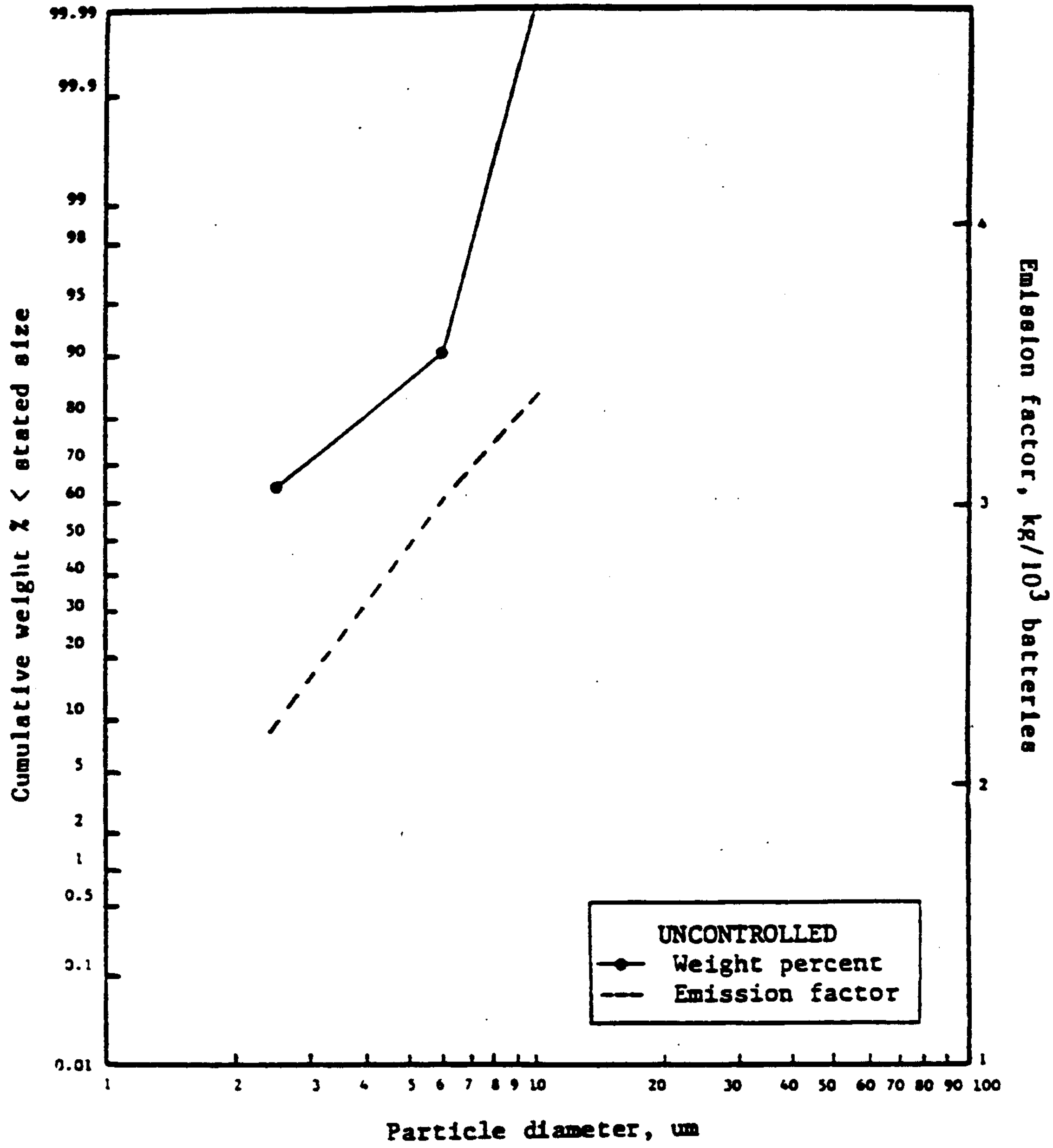
SOURCE OPERATION: During tests, plant was operated at 39% of design process rate. Six of nine of the grid casting machines were operating during the test. Typically, 26,500 to 30,000 pounds of lead per 24-hour day are charged to the grid casting operation.

SAMPLING TECHNIQUE: Brink Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Air Pollution Emission Test, Globe Union, Inc., Canby, OR, EMB-76-BAT-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1976.



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size	Emission factor (kg/10^3 batteries)
	Uncontrolled	Uncontrolled
2.5	65.1	2.20
6.0	90.4	3.05
10.0	100	3.38

12.15 STORAGE BATTERY PRODUCTION: GRID CASTING AND PASTE MIXING

NUMBER OF TESTS: 3, conducted before control

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	65.1	90.4	100
	Standard deviation (Cum. %):	24.8	7.4	—
	Min (Cum. %):	44.1	81.9	100
	Max (Cum. %):	100	100	100

TOTAL PARTICULATE EMISSION FACTOR: 3.38 kg particulate/10^3 batteries, without controls. Factor is from AP-42, Section 12.15, and is the sum of the individual factors for grid casting and paste mixing.

SOURCE OPERATION: During tests, plant was operated at 39% of the design process rate. Grid casting operation consists of 4 machines. Each 2,000 lb/hr paste mixer is controlled for product recovery by a separate low-energy, impingement-type wet collector designed for an 8 - 10 inch w. g. pressure drop at 2,000 acfm.

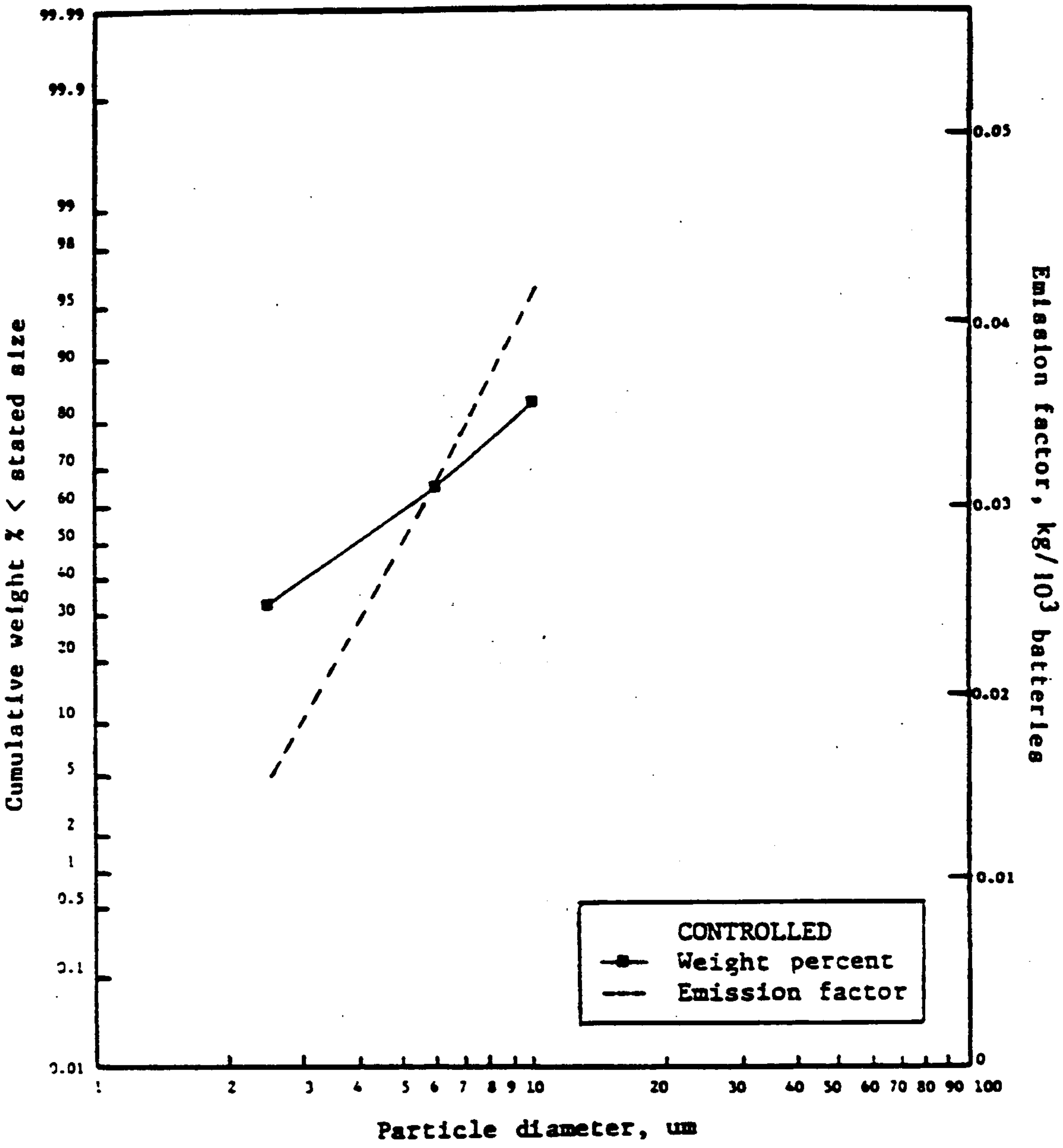
SAMPLING TECHNIQUE: Brink Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Air Pollution Emission Test, Globe Union, Inc., Canby, OR, EMB-76-BAT-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1976.

12.15 STORAGE BATTERY PRODUCTION: LEAD OXIDE MILL



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size	Emission factor (kg/10^3 batteries)
	After fabric filter	After fabric filter
2.5	32.8	0.016
6.0	64.7	0.032
10.0	83.8	0.042

12.15 STORAGE BATTERY PRODUCTION: LEAD OXIDE MILL

NUMBER OF TESTS: 3, conducted after fabric filter

STATISTICS: Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	32.8	64.7	83.8
Standard deviation (Cum. %):	14.1	29.8	19.5
Min (Cum. %):	17.8	38.2	61.6
Max (Cum. %):	45.9	97.0	100

TOTAL PARTICULATE EMISSION FACTOR: 0.05 kg particulate/10^3 batteries, after typical fabric filter control (oil-to-cloth ratio of 4:1). Emissions from a well-controlled facility (fabric filters with an average air-to-cloth ratio of 3:1) were 0.025 kg/10^3 batteries (Table 12.15-1 of AP-42).

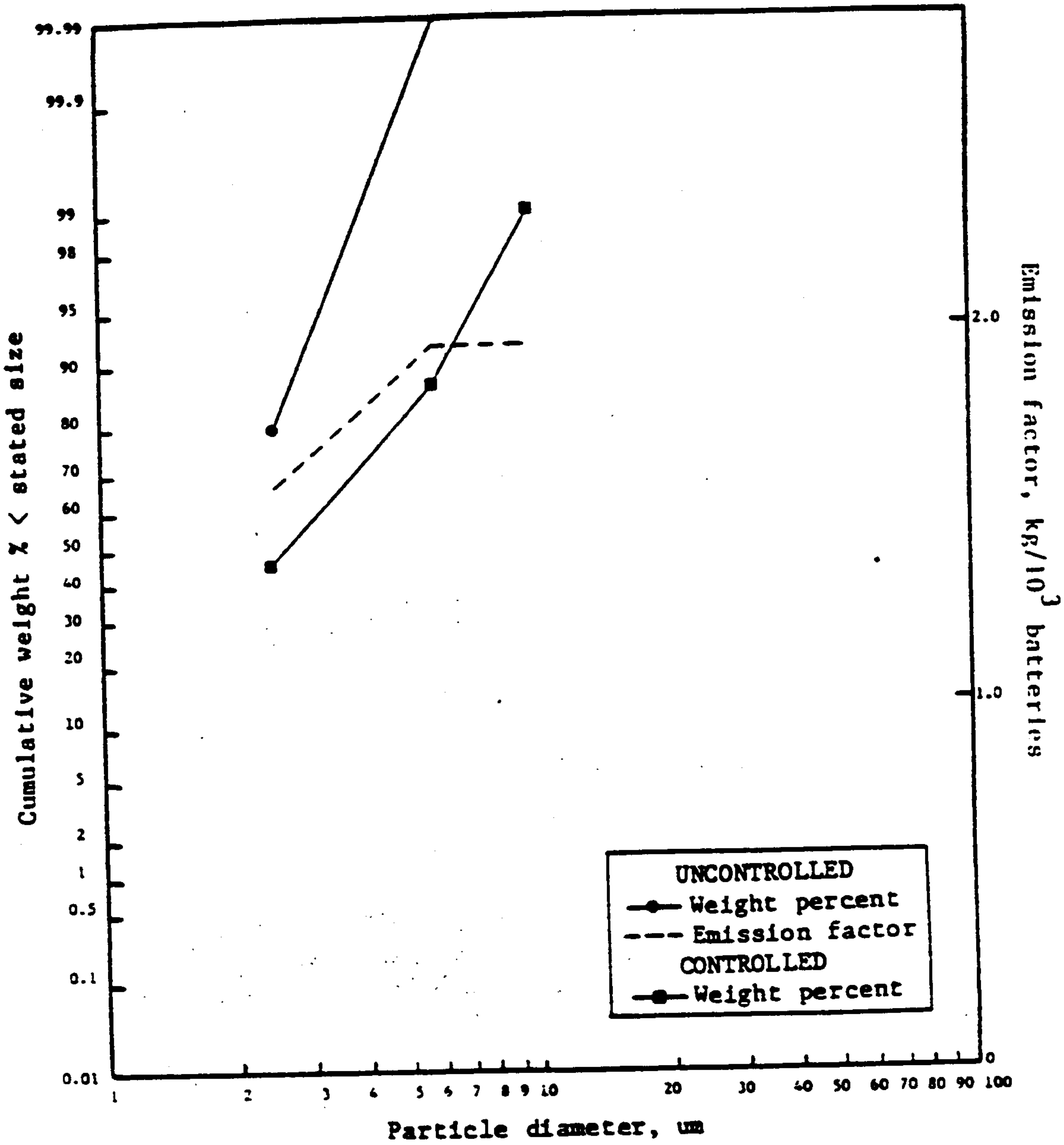
SOURCE OPERATION: Plant receives metallic lead and manufactures lead oxide by the ball mill process. There are 2 lead oxide production lines, each with a typical feed rate of 15 100-pound lead pigs per hour. Product is collected with a cyclone and baghouses with 4:1 air-to-cloth ratios.

SAMPLING TECHNIQUE: Andersen Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Air Pollution Emission Test, ESB Canada Limited, Mississouga, Ontario, EMB-76-BAT-3, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1976.



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size		Emission factor (kg/10^3 batteries)
	Uncontrolled	Fabric filter	Uncontrolled
2.5	80	47	1.58
6.0	100	87	1.96
10.0	100	99	1.96

12.15 STORAGE BATTERY PRODUCTION: PASTE MIXING AND LEAD OXIDE CHARGING

NUMBER OF TESTS: (a) 1, conducted before control
(b) 4, conducted after fabric filter control

STATISTICS: (a)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	80	100	100
Standard deviation (Cum. %):			
Min (Cum. %):			
Max (Cum. %):			

(b)

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %.):	47	87	99
Standard deviation (Cum. %):	33.4	14.5	0.9
Min (Cum. %):	36	65	98
Max (Cum. %):	100	100	100

Impactor cut points were so small that many data points had to be extrapolated. Reliability of particle size distributions based on a single test is questionable.

TOTAL PARTICULATE EMISSION FACTOR: 1.96 kg. particulate/10^3 batteries, without controls. Factor from AP-42, Section 12.15.

SOURCE OPERATION: During test, plant was operated at 39% of the design process rate. Plant has normal production rate of 2,400 batteries per day and maximum capacity of 4,000 batteries per day. Typical amount of lead oxide charged to the mixer is 29,850 lb/8-hour shift. Plant produces wet batteries, except formation is carried out at another plant.

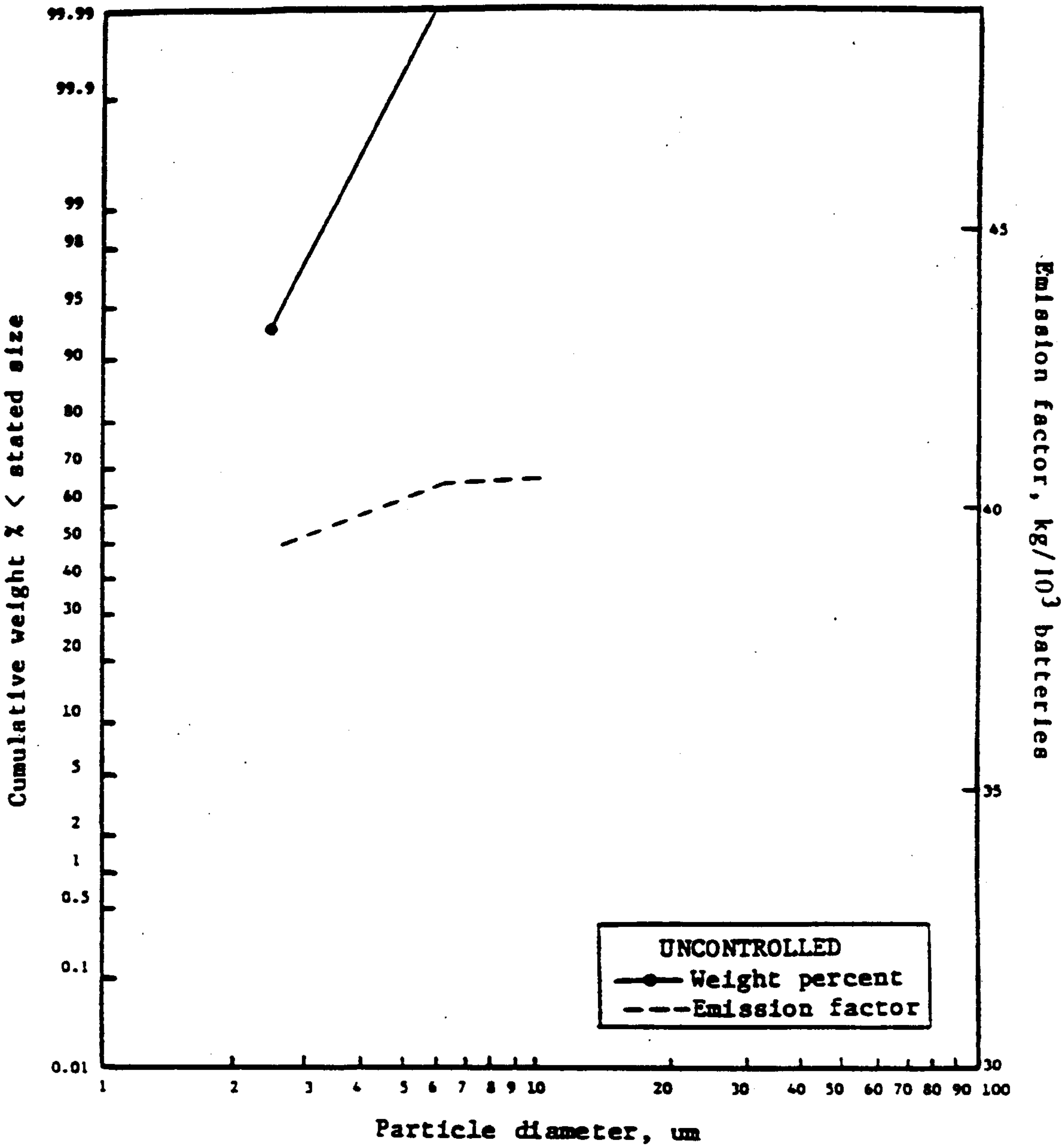
SAMPLING TECHNIQUE: (a) Brink Impactor
(b) Andersen Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Air Pollution Emission Test, Globe Union, Inc., Canby, OR, EMB-76-BAT-4, U. S. Environmental Protection Agency, Research Triangle Park, NC, October 1976.

12.15 STORAGE BATTERY PRODUCTION: THREE-PROCESS OPERATION



Aerodynamic particle diameter (um)	Cumulative wt. % < stated size	Emission factor ($kg/10^3$ batteries)
	Uncontrolled	Uncontrolled
2.5	93.4	39.3
6.0	100	42
10.0	100	42

12.15 STORAGE BATTERY PRODUCTION: THREE-PROCESS OPERATION

NUMBER OF TESTS: 3, conducted before control

STATISTICS:

Aerodynamic particle diameter (μm):	2.5	6.0	10.0
Mean (Cum. %):	93.4	100	100
Standard deviation (Cum. %):	6.43		
Min (Cum. %):	84.7		
Max (Cum. %):	100		

Impactor cut points were so small that data points had to be extrapolated.

TOTAL PARTICULATE EMISSION FACTOR: 42 kg particulate/10^3 batteries, before controls. Factor from AP-42, Section 12.15.

SOURCE OPERATION: Plant representative stated that the plant usually operated at 35% of design capacity. Typical production rate is 3,500 batteries per day (dry and wet), but up to 4,500 batteries per day can be produced. This is equivalent to normal and maximum daily element production of 21,000 and 27,000 battery elements, respectively.

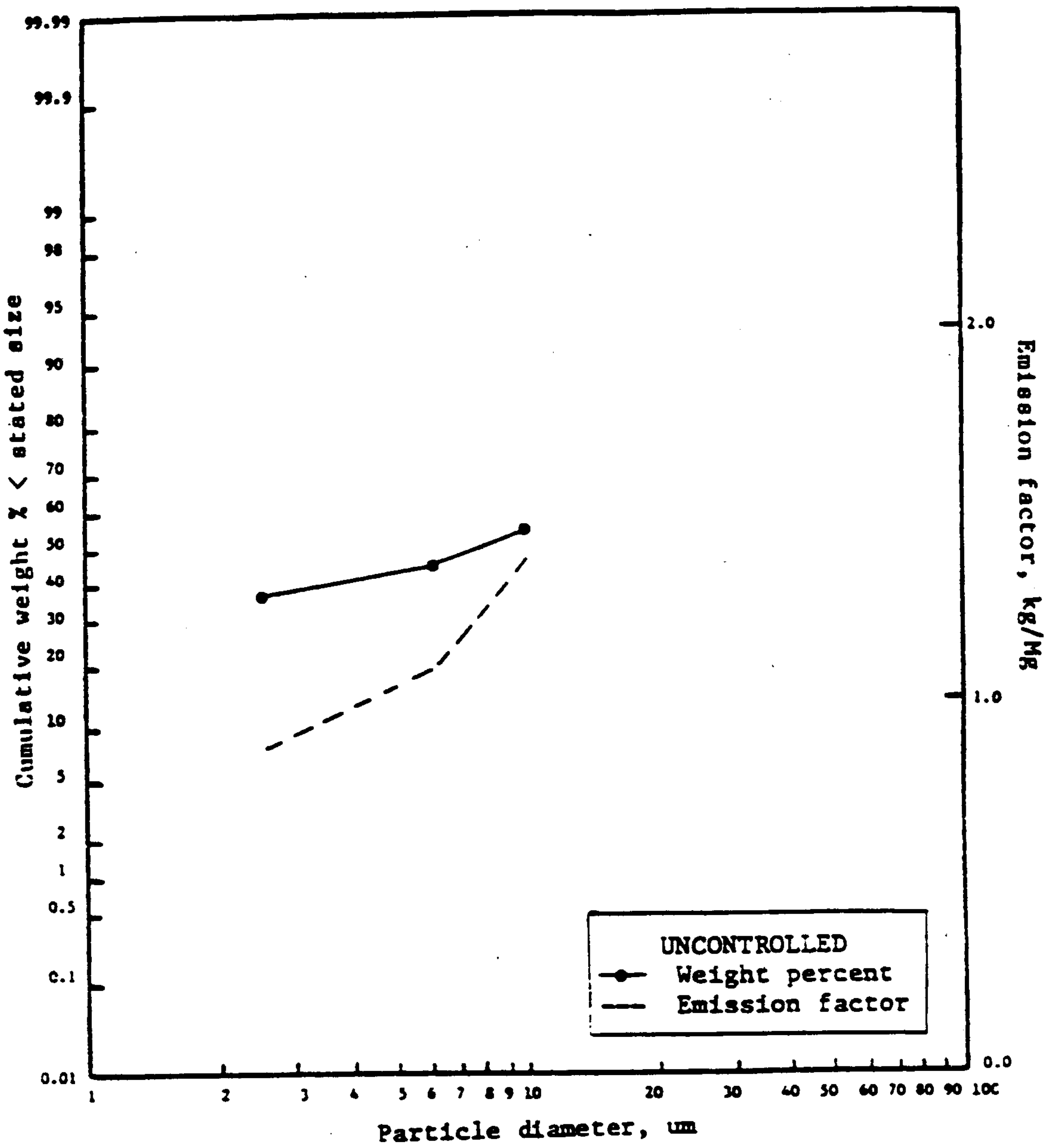
SAMPLING TECHNIQUE: Brink Impactor

EMISSION FACTOR RATING: E

REFERENCE:

Air Pollution Emission Test, ESB Canada Limited, Mississouga, Ontario, EMB-76-BAT-3, U. S. Environmental Protection Agency, Research Triangle Park, NC, August 1976.

12.xx BATCH TINNER



Aerodynamic particle diameter, um	Cumulative wt. % < stated size	Emission factor, kg/Mg
	Uncontrolled	Uncontrolled
2.5	37.2	0.93
6.0	45.9	1.15
10.0	55.9	1.40

12.xx BATCH TINNER

NUMBER OF TESTS: 2, conducted before controls

STATISTICS:	Aerodynamic particle diameter (μm):	2.5	6.0	10.0
	Mean (Cum. %):	37.2	45.9	55.9
	Standard deviation (Cum. %):			
	Min (Cum. %):			
	Max (Cum. %):			

TOTAL PARTICULATE EMISSION FACTOR: 2.5 kg particulate/Mg tin consumed, without controls. Factor from AP-42, Section 12.14.

SOURCE OPERATION: Source is a batch operation applying a lead/tin coating to tubing. No further source operating information is available.

SAMPLING TECHNIQUE: Andersen Mark III Impactor

EMISSION FACTOR RATING: D

REFERENCE:

Confidential test data, PEI Associates, Inc., Golden, CO, January 1985.

APPENDIX B.2

GENERALIZED PARTICLE SIZE DISTRIBUTIONS

CONTENTS

Page

B.2.1 Rationale For Developing Generalized Particle Size Distributions B.2-3

B.2.2 How to Use The Generalized Particle Size Distributions for Uncontrolled Processes . B.2-3

B.2.3 How to Use The Generalized Particle Size Distributions for Controlled Processes . . . B.2-16

B.2.4 Example Calculation B.2-16

References B.2-18

Appendix B.2

Generalized Particle Size Distributions

B.2.1 Rationale For Developing Generalized Particle Size Distributions

The preparation of size-specific particulate emission inventories requires size distribution information for each process. Particle size distributions for many processes are contained in appropriate industry sections of this document. Because particle size information for many processes of local impact and concern are unavailable, this appendix provides "generic" particle size distributions applicable to these processes. The concept of the "generic" particle size distribution is based on categorizing measured particle size data from similar processes generating emissions from similar materials. These generic distributions have been developed from sampled size distributions from about 200 sources.

Generic particle size distributions are approximations. They should be used only in the absence of source-specific particle size distributions for areawide emission inventories.

B.2.2 How To Use The Generalized Particle Size Distributions For Uncontrolled Processes

Figure B.2-1 provides an example calculation to assist the analyst in preparing particle size-specific emission estimates using generic size distributions.

The following instructions for the calculation apply to each particulate emission source for which a particle size distribution is desired and for which no source specific particle size information is given elsewhere in this document:

1. Identify and review the AP-42 section dealing with that process.
2. Obtain the uncontrolled particulate emission factor for the process from the main text of AP-42, and calculate uncontrolled total particulate emissions.
3. Obtain the category number of the appropriate generic particle size distribution from Table B.2-1.
4. Obtain the particle size distribution for the appropriate category from Table B.2-2. Apply the particle size distribution to the uncontrolled particulate emissions.

Instructions for calculating the controlled size-specific emissions are given in Table B.2-3 and illustrated in Figure B.2-1.

Figure B.2-1. Example calculation for determining uncontrolled and controlled particle size-specific emissions.

SOURCE IDENTIFICATION

Source name and address: ABC Brick Manufacturing
24 Dusty Way
Anywhere, USA

Process description: Dryers/Grinders
AP-42 Section: 8.3, Bricks And Related Clay Products
Uncontrolled AP-42 emission factor: 96 lbs/ton (units)
Activity parameter: 63,700 tons/year (units)
Uncontrolled emissions: 3057.6 tons/year (units)

UNCONTROLLED SIZE EMISSIONS

Category name: Mechanically Generated/Aggregated, Unprocessed Ores
Category number: 3

	Particle size (μm)		
	≤ 2.5	≤ 6	≤ 10
Generic distribution, Cumulative percent equal to or less than the size:	15	34	51
Cumulative mass ≤ particle size emissions (tons/year):	458.6	1039.6	1559.4

CONTROLLED SIZE EMISSIONS*

Type of control device: Fabric Filter

	Particle size (μm)		
	0 - 2.5	2.5 - 6	6 - 10
Collection efficiency (Table B.2-3):	99.0	99.5	99.5
Mass in size range** before control (tons/year):	458.6	581.0	519.8
Mass in size range after control (tons/year):	4.59	2.91	2.60
Cumulative mass (tons/year):	4.59	7.50	10.10

* These data do not include results for the greater than 10 μm particle size range.

** Uncontrolled size data are cumulative percent equal to or less than the size. Control efficiency data apply only to size range and are not cumulative.

Table B.2-1. PARTICLE SIZE CATEGORY BY AP-42 SECTION

AP-42 Section	Source Category	Category Number*
	External combustion	
1.1	Bituminous and subbituminous coal combustion	a
1.2	Anthracite coal combustion	a
1.3	Fuel oil combustion	
	Residual oil	
	Utility	a
	Commercial	a
	Distillate oil	
	Utility	a
	Commercial	a
	Residential	a
1.4	Natural gas combustion	a
1.5	Liquefied petroleum gas	a
1.6	Wood waste combustion in boilers	a
1.7	Lignite combustion	a
1.8	Bagasse combustion	b
1.9	Residential fireplaces	a
1.10	Residential wood stoves	a
1.11	Waste oil combustion	a
	Solid waste disposal	
2.1	Refuse combustion	a
2.2	Sewage sludge incineration	a
2.7	Conical burners (wood waste)	2
	Internal combustion engines	
	Highway vehicles	c
3.2	Off highway vehicles	1
	Organic chemical processes	
6.4	Paint and varnish	4
6.5	Phthalic anhydride	9
6.8	Soap and detergents	a
	Inorganic chemical processes	
8.2	Urea	a
8.3	Ammonium nitrate fertilizers	a
8.4	Ammonium sulfate	
	Rotary dryer	b
	Fluidized bed dryer	b
8.5	Phosphate fertilizers	3
8.5.3	Ammonium phosphates	
	Reactor/ammoniator-granulator	4
	Dryer/cooler	4
8.7	Hydrofluoric acid	
	Spar drying	3
	Spar handling	3
	Transfer	3
8.9	Phosphoric acid (thermal process)	a
8.10	Sulfuric acid	b
8.12	Sodium carbonate	a
	Food and agricultural	
9.3.1	Defoliation and harvesting of cotton	
	Trailer loading	6
	Transport	6
9.3.2	Harvesting of grain	
	Harvesting machine	6
	Truck loading	6
	Field transport	6
9.5.2	Meat smokehouses	9
9.7	Cotton ginning	b
9.9.1	Grain elevators and processing plants	a
9.9.4	Alfalfa dehydrating	
	Primary cyclone	b
	Meal collector cyclone	7
	Pellet cooler cyclone	7
	Pellet regrind cyclone	7
9.9.7	Starch manufacturing	7
9.12	Fermentation	6,7
9.13.2	Coffee roasting	6
	Wood products	
10.2	Chemical wood pulping	a
10.7	Charcoal	9
	Mineral products	
11.1	Hot mix asphalt plants	a
11.3	Bricks and related clay products	
	Raw materials handling	
	Dryers, grinders, etc.	b

Table B.2-1 (cont.).

AP-42 Section	Source Category	Category Number*
	Tunnel/periodic kilns	
	Gas fired	a
	Oil fired	a
	Coal fired	a
11.5	Refractory manufacturing	
	Raw material dryer	3
	Raw material crushing and screening	3
	Electric arc melting	8
	Curing oven	3
11.6	Portland cement manufacturing	
	Dry process	
	Kilns	a
	Dryers, grinders, etc.	4
	Wet process	
	Kilns	a
	Dryers, grinders, etc.	4
11.7	Ceramic clay manufacturing	
	Drying	3
	Grinding	4
	Storage	3
11.8	Clay and fly ash sintering	
	Fly ash sintering, crushing, screening, yard storage	5
	Clay mixed with coke	
	Crushing, screening, yard storage	3
11.9	Western surface coal mining	a
11.10	Coal cleaning	3
11.12	Concrete batching	3
11.13	Glass fiber manufacturing	
	Unloading and conveying	3
	Storage bins	3
	Mixing and weighing	3
	Glass furnace - wool	a
	Glass furnace - textile	a
11.15	Glass manufacturing	a
11.16	Gypsum manufacturing	
	Rotary ore dryer	a
	Roller mill	4
	Impact mill	4
	Flash calciner	a
	Continuous kettle calciner	a
11.17	Lime manufacturing	a
11.18	Mineral wool manufacturing	
	Cupola	8
	Reverberatory furnace	8
	Blow chamber	8
	Curing oven	9
	Cooler	9
11.19.1	Sand and gravel processing	
	Continuous drop	
	Transfer station	a
	Pile formation - stacker	a
	Batch drop	a
	Active storage piles	a
	Vehicle traffic on unpaved road	a
11.19.2	Crushed stone processing	
	Dry crushing	
	Primary crushing	a
	Secondary crushing and screening	a
	Tertiary crushing and screening	3
	Recrushing and screening	4
	Fines mill	4
	Screening, conveying, handling	a
11.21	Phosphate rock processing	
	Drying	a
	Calcining	a
	Grinding	b
	Transfer and storage	3
11.23	Taconite ore processing	
	Fine crushing	4

Table B.2-1 (cont.).

AP-42 Section	Source Category	Category Number*
	Waste gas	a
	Pellet handling	4
	Grate discharge	5
	Grate feed	4
	Bentonite blending	4
	Coarse crushing	3
	Ore transfer	3
	Bentonite transfer	4
	Unpaved roads	a
11.24	Metallic minerals processing	a
	Metallurgical	
12.1	Primary aluminum production	
	Bauxite grinding	4
	Aluminum hydroxide calcining	5
	Anode baking furnace	9
	Prebake cell	a
	Vertical Soderberg	8
	Horizontal Soderberg	a
12.2	Coke manufacturing	a
12.3	Primary copper smelting	a
12.4	Ferroalloy production	a
12.5	Iron and steel production	
	Blast furnace	
	Slips	a
	Cast house	a
	Sintering	
	Windbox	a
	Sinter discharge	a
	Basic oxygen furnace	a
	Electric arc furnace	a
12.6	Primary lead smelting	a

AP-42 Section	Source Category	Category Number*
12.7	Zinc smelting	8
12.8	Secondary aluminum operations	
	Sweating furnace	8
	Smelting	
	Crucible furnace	8
	Reverberatory furnace	a
12.9	Secondary copper smelting and alloying	8
12.10	Gray iron foundries	a
12.11	Secondary lead processing	a
12.12	Secondary magnesium smelting	8
12.13	Steel foundries - melting	b
12.14	Secondary zinc processing	8
12.15	Storage battery production	b
12.18	Leadbearing ore crushing and grinding	4
	Miscellaneous sources	
13.1	Wildfires and prescribed burning	a
13.2	Fugitive dust	a

---

* Data for numbered categories are given Table B.2-2. Particle size data on "a" categories are found in the AP-42 text; for "b" categories, in Appendix B.1; and for "c" categories, in AP-42 *Volume II: Mobile Sources*.

Figure B.2-2. CALCULATION SHEET

SOURCE IDENTIFICATION

Source name and address: ____________________

____

____

Process description: ____________________
AP-42 Section: ____________________
Uncontrolled AP-42 emission factor: ____________________ (units)
Activity parameter: ____________________ (units)
Uncontrolled emissions: ____________________ (units)

UNCONTROLLED SIZE EMISSIONS

Category name: ____________________
Category number: ____

	Particle size (μm)		
	≤ 2.5	≤ 6	≤ 10
Generic distribution, Cumulative percent equal to or less than the size:			
Cumulative mass ≤ particle size emissions (tons/year):			

CONTROLLED SIZE EMISSIONS*

Type of control device: ____________________

	Particle size (μm)		
	0 - 2.5	2.5 - 6	6 - 10
Collection efficiency (Table B.2-3):			
Mass in size range** before control (tons/year):			
Mass in size range after control (tons/year):			
Cumulative mass (tons/year):			

* These data do not include results for the greater than 10 μm particle size range.

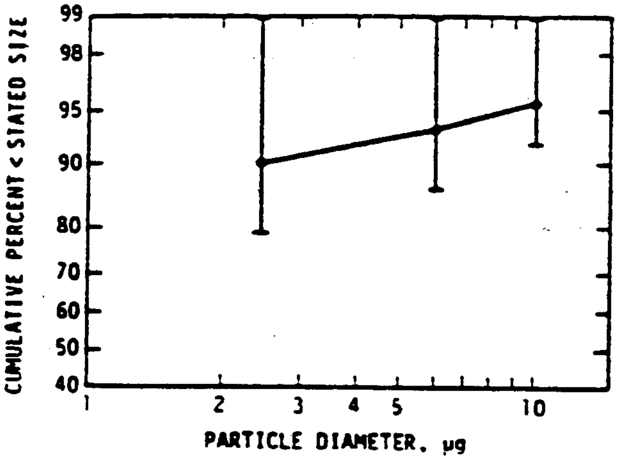
** Uncontrolled size data are cumulative percent equal to or less than the size. Control efficiency data apply only to size range and are not cumulative.

Table B.2-2. DESCRIPTION OF PARTICLE SIZE CATEGORIES

Category:	1
Process:	Stationary Internal Combustion Engines
Material:	Gasoline and Diesel Fuel

Category 1 covers size-specific emissions from stationary internal combustion engines. The particulate emissions are generated from fuel combustion.

REFERENCES: 1,9



Particle Size, μm	Cumulative % ≤ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	82			
2.0[a]	88			
2.5	90	78	99	11
3.0[a]	90			
4.0[a]	92			
5.0[a]	93			
6.0	93	86	99	7
10.0	96	92	99	4

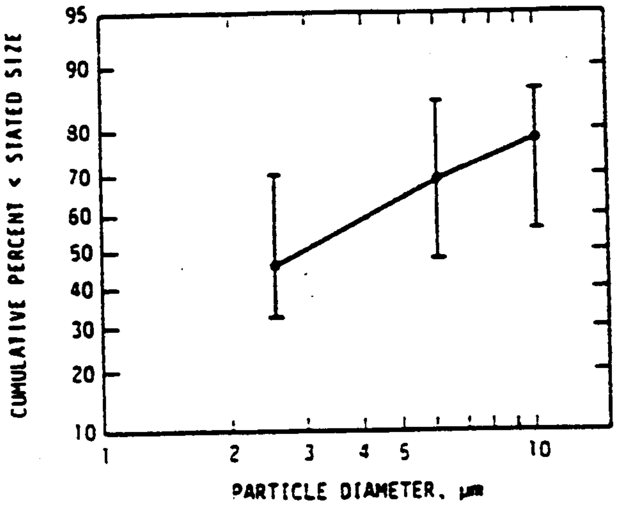
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category: 2
Process: Combustion
Material: Mixed Fuels

Category 2 covers boilers firing a mixture of fuels, regardless of the fuel combination. The fuels include gas, coal, coke, and petroleum. Particulate emissions are generated by firing these miscellaneous fuels.

REFERENCE: 1



Particle Size, μm	Cumulative % $\leq$ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	23			
2.0[a]	40			
2.5	45	32	70	17
3.0[a]	50			
4.0[a]	58			
5.0[a]	64			
6.0	70	49	84	14
10.0	79	56	87	12

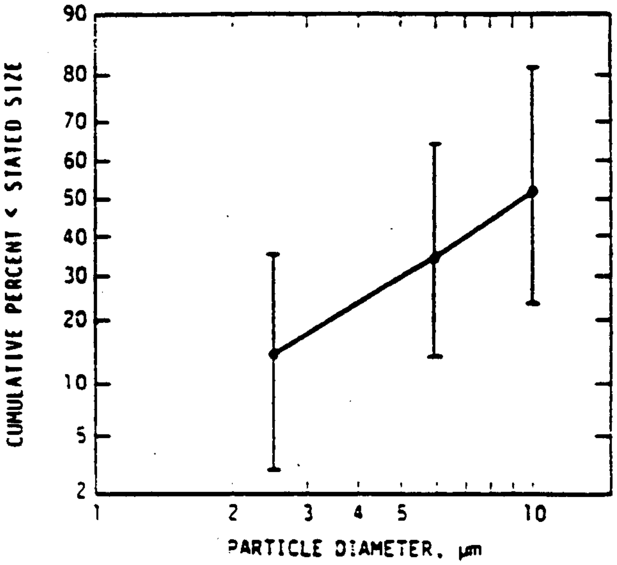
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category: 3
Process: Mechanically Generated
Material: Aggregate, Unprocessed Ores

Category 3 covers material handling and processing of aggregate and unprocessed ore. This broad category includes emissions from milling, grinding, crushing, screening, conveying, cooling, and drying of material. Emissions are generated through either the movement of the material or the interaction of the material with mechanical devices.

REFERENCES: 1-2,4,7



Particle Size, μm	Cumulative % $\leq$ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	4			
2.0[a]	11			
2.5	15	3	35	7
3.0[a]	18			
4.0[a]	25			
5.0[a]	30			
6.0	34	15	65	13
10.0	51	23	81	14

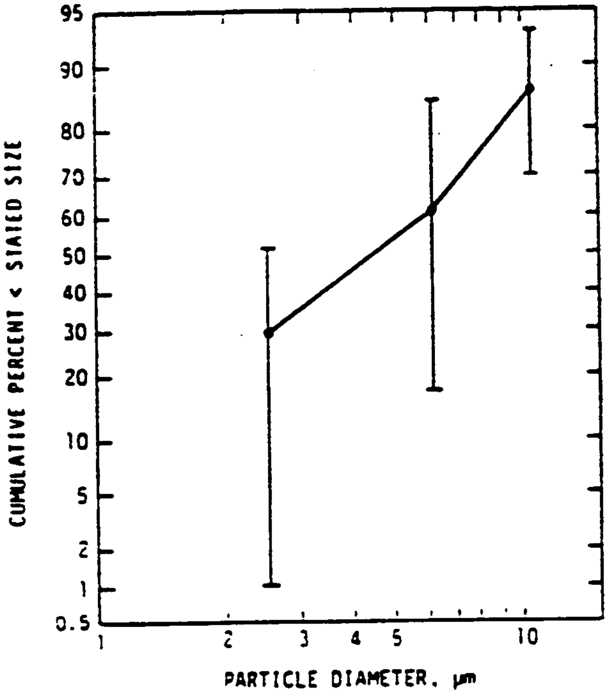
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category: 4
Process: Mechanically Generated
Material: Processed Ores and Nonmetallic Minerals

Category 4 covers material handling and processing of processed ores and minerals. While similar to Category 3, processed ores can be expected to have a greater size consistency than unprocessed ores. Particulate emissions are a result of agitating the materials by screening or transfer during size reduction and beneficiation of the materials by grinding and fine milling and by drying.

REFERENCE: 1



Particle Size, µm	Cumulative % ≤ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	6			
2.0[a]	21			
2.5	30	1	51	19
3.0[a]	36			
4.0[a]	48			
5.0[a]	58			
6.0	62	17	83	17
10.0	85	70	93	7

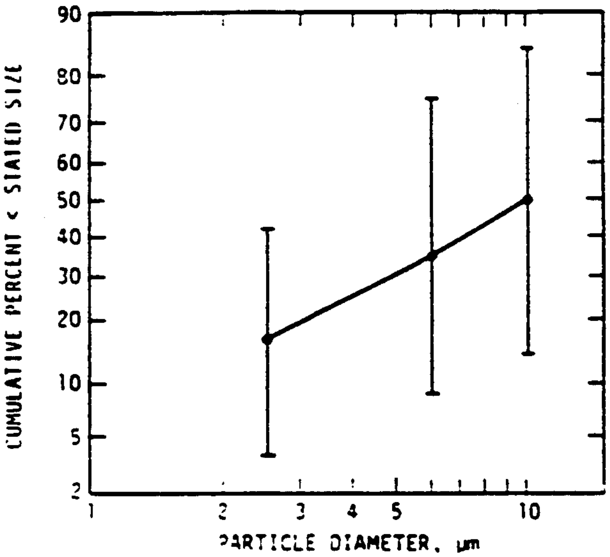
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 µm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category:	5
Process:	Calcining and Other Heat Reaction Processes
Material:	Aggregate, Unprocessed Ores

Category 5 covers the use of calciners and kilns in processing a variety of aggregates and unprocessed ores. Emissions are a result of these high temperature operations.

REFERENCES: 1-2,8



Particle Size, μm	Cumulative % $\leq$ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	6			
2.0[a]	13			
2.5	18	3	42	11
3.0[a]	21			
4.0[a]	28			
5.0[a]	33			
6.0	37	13	74	19
10.0	53	25	84	19

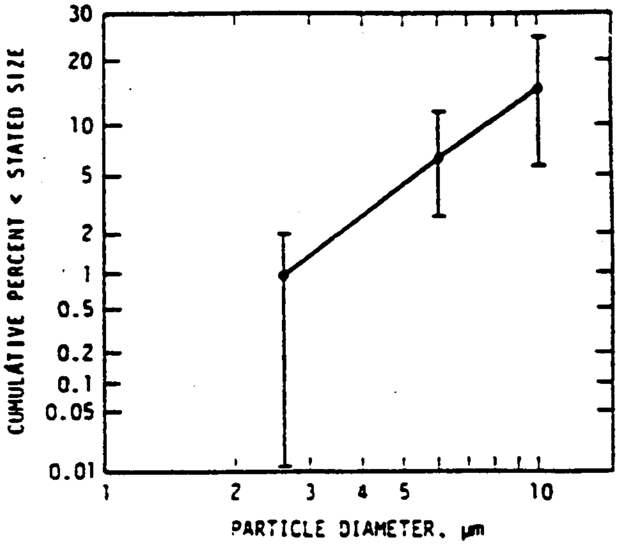
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category: 6
Process: Grain Handling
Material: Grain

Category 6 covers various grain handling (versus grain processing) operations. These processes could include material transfer, ginning and other miscellaneous handling of grain. Emissions are generated by mechanical agitation of the material.

REFERENCES: 1,5



Particle Size, μm	Cumulative % $\leq$ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	0.07			
2.0[a]	0.60			
2.5	1	0	2	1
3.0[a]	2			
4.0[a]	3			
5.0[a]	5			
6.0	7	3	12	3
10.0	15	6	25	7

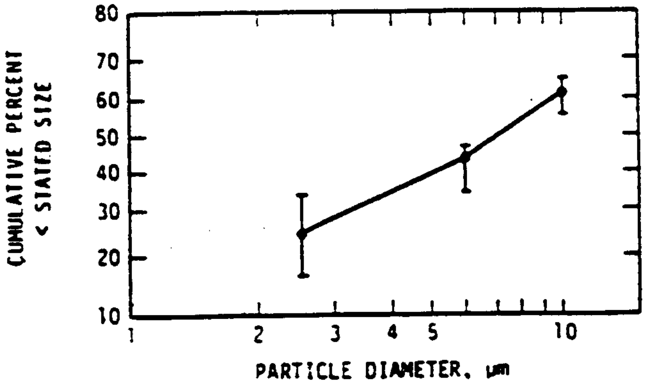
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category:	7
Process:	Grain Processing
Material:	Grain

Category 7 covers grain processing operations such as drying, screening, grinding, and milling. The particulate emissions are generated during forced air flow, separation, or size reduction.

REFERENCES: 1-2



Particle Size, μm	Cumulative % $\leq$ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	8			
2.0[a]	18			
2.5	23	17	34	9
3.0[a]	27			
4.0[a]	34			
5.0[a]	40			
6.0	43	35	48	7
10.0	61	56	65	5

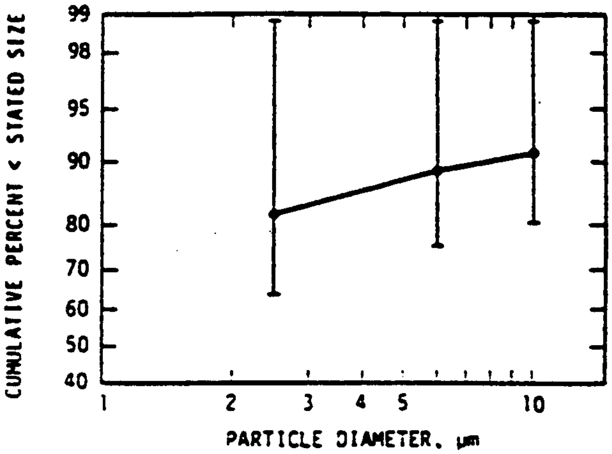
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category: 8
Process: Melting, Smelting, Refining
Material: Metals, except Aluminum

Category 8 covers the melting, smelting, and refining of metals (including glass) other than aluminum. All primary and secondary production processes for these materials which involve a physical or chemical change are included in this category. Materials handling and transfer are not included. Particulate emissions are a result of high temperature melting, smelting, and refining.

REFERENCES: 1-2



Particle Size, μm	Cumulative % $\leq$ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	72			
2.0[a]	80			
2.5	82	63	99	12
3.0[a]	84			
4.0[a]	86			
5.0[a]	88			
6.0	89	75	99	9
10.0	92	80	99	7

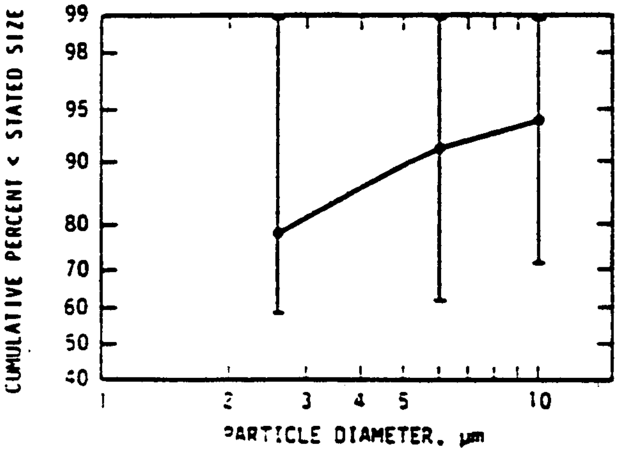
[a] Value calculated from data reported at 2.5, 6.0, and 10.0 μm. No statistical parameters are given for the calculated value.

Table B.2.2 (cont.).

Category: 9
Process: Condensation, Hydration, Absorption, Prilling, and Distillation
Material: All

Category 9 covers condensation, hydration, absorption, prilling, and distillation of all materials. These processes involve the physical separation or combination of a wide variety of materials such as sulfuric acid and ammonium nitrate fertilizer. (Coke ovens are included since they can be considered a distillation process which separates the volatile matter from coal to produce coke.)

REFERENCES: 1,3



Particle Size, µm	Cumulative % ≤ Stated Size (Uncontrolled)	Minimum Value	Maximum Value	Standard Deviation
1.0[a]	60			
2.0[a]	74			
2.5	78	59	99	17
3.0[a]	81			
4.0[a]	85			
5.0[a]	88			
6.0	91	61	99	12
10.0	94	71	99	9

[a] Value calculated from data reported at 2.5, 6.0, and 10.0 µm. No statistical parameters are given for the calculated value.

B.2.3 How To Use The Generalized Particle Size Distributions For Controlled Processes

To calculate the size distribution and the size-specific emissions for a source with a particulate control device, the user first calculates the uncontrolled size-specific emissions. Next, the fractional control efficiency for the control device is estimated using Table B.2-3. The Calculation Sheet provided (Figure B.2-2) allows the user to record the type of control device and the collection efficiencies from Table B.2-3, the mass in the size range before and after control, and the cumulative mass. The user will note that the uncontrolled size data are expressed in cumulative fraction less than the stated size. The control efficiency data apply only to the size range indicated and are not cumulative. These data do not include results for the greater than 10 μm particle size range. In order to account for the total controlled emissions, particles greater than 10 μm in size must be included.

B.2.4 Example Calculation

An example calculation of uncontrolled total particulate emissions, uncontrolled size-specific emissions, and controlled size specific emission is shown in Figure B.2-1. A blank Calculation Sheet is provided in Figure B.2-2.

Table B.2-3. TYPICAL COLLECTION EFFICIENCIES OF VARIOUS PARTICULATE CONTROL DEVICES[a]
(%)

AIRS Code[b]	Type Of Collector	Particle Size (μm)		
		0 - 2.5	2.5 - 6	6 - 10
001	Wet scrubber - hi-efficiency	90	95	99
002	Wet scrubber - med-efficiency	25	85	95
003	Wet scrubber - low-efficiency	20	80	90
004	Gravity collector - hi-efficiency	3.6	5	6
005	Gravity collector - med-efficiency	2.9	4	4.8
006	Gravity collector - low-efficiency	1.5	3.2	3.7
007	Centrifugal collector - hi-efficiency	80	95	95
008	Centrifugal collector - med-efficiency	50	75	85
009	Centrifugal collector - low-efficiency	10	35	50
010	Electrostatic precipitator - hi-efficiency	95	99	99.5
011	Electrostatic precipitator - med-efficiency			
	boilers	50	80	94
	other	80	90	97
012	Electrostatic precipitator - low-efficiency			
	boilers	40	70	90
	other	70	80	90
014	Mist eliminator - high velocity >250 FPM	10	75	90
015	Mist eliminator - low velocity <250 FPM	5	40	75

Table B.2-3 (cont.).

AIRS Code[b]	Type Of Collector	Particle Size (μm)		
		0 - 2.5	2.5 - 6	6 - 10
016	Fabric filter - high temperature	99	99.5	99.5
017	Fabric filter - med temperature	99	99.5	99.5
018	Fabric filter - low temperature	99	99.5	99.5
046	Process change	NA	NA	NA
049	Liquid filtration system	50	75	85
050	Packed-gas absorption column	90	95	99
051	Tray-type gas absorption column	25	85	95
052	Spray tower	20	80	90
053	Venturi scrubber	90	95	99
054	Process enclosed	1.5	3.2	3.7
055	Impingement plate scrubber	25	95	99
056	Dynamic separator (dry)	90	95	99
057	Dynamic separator (wet)	50	75	85
058	Mat or panel filter - mist collector	92	94	97
059	Metal fabric filter screen	10	15	20
061	Dust suppression by water sprays	40	65	90
062	Dust suppression by chemical stabilizer or wetting agents	40	65	90
063	Gravel bed filter	0	5	80
064	Annular ring filter	80	90	97
071	Fluid bed dry scrubber	10	20	90
075	Single cyclone	10	35	50
076	Multiple cyclone w/o fly ash reinjection	80	95	95
077	Multiple cyclone w/fly ash reinjection	50	75	85
085	Wet cyclonic separator	50	75	85
086	Water curtain	10	45	90

[a] Data represent an average of actual efficiencies. Efficiencies are representative of well designed and well operated control equipment. Site-specific factors (e. g., type of particulate being collected, varying pressure drops across scrubbers, maintenance of equipment, etc.) will affect collection efficiencies. Efficiencies shown are intended to provide guidance for estimating control equipment performance when source-specific data are not available. NA = not applicable.

[b] Control codes in Aerometric Information Retrieval System (AIRS), formerly National Emissions Data Systems.

References For Appendix B.2

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5. I. W. Kirk, "Air Quality In Saw And Roller Gin Plants", *Transactions Of The ASAE*, 20:5, 1977.

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9. H. J. Taback, *et al.*, *Fine Particulate Emissions From Stationary Sources In The South Coast Air Basin*, KVB, Inc., Tustin, CA, 1979.

10. K. Rosbury, *Generalized Particle Size Distributions For Use In Preparing Particle Size-Specific Emission Inventories*, U. S. EPA Contract No. 68-02-3890, PEI Associates, Inc., Golden, CO, 1985.

APPENDIX C.1

PROCEDURES FOR SAMPLING SURFACE/BULK DUST LOADING

Appendix C.1

Procedures For Sampling Surface/Bulk Dust Loading

This appendix presents procedures recommended for the collection of material samples from paved and unpaved roads and from bulk storage piles. (AP-42, Appendix C.2, "Procedures For Laboratory Analysis Of Surface/Bulk Dust Loading Samples", presents analogous information for the analysis of the samples.) These recommended procedures are based on a review of American Society For Testing And Materials (ASTM) methods, such as C-136 (sieve analysis) and D-2216 (moisture content). The recommendations follow ASTM standards where practical, and where not, an effort has been made to develop procedures consistent with the intent of the pertinent ASTM standards.

This appendix emphasizes that, before starting any field sampling program, one must first define the study area of interest and then determine the number of samples that can be collected and analyzed within the constraints of time, labor, and money available. For example, the study area could be defined as an individual industrial plant with its network of paved/unpaved roadways and material piles. In that instance, it is advantageous to collect a separate sample for each major dust source in the plant. This level of resolution is useful in developing cost-effective emission reduction plans. On the other hand, if the area of interest is geographically large (say a city or county, with a network of public roads), collecting at least 1 sample from each source would be highly impractical. However, in such an area, it is important to obtain samples representative of different source types within the area.

C.1.1 Samples From Unpaved Roads

Objective -

The overall objective in an unpaved road sampling program is to inventory the mass of particulate matter (PM) emissions from the roads. This is typically done by:

1. Collecting "representative" samples of the loose surface material from the road;
2. Analyzing the samples to determine silt fractions; and
3. Using the results in the predictive emission factor model given in AP-42, Section 13.2.2, Unpaved Roads, together with traffic data (e. g., number of vehicles traveling the road each day).

Before any field sampling program, it is necessary to define the study area of interest and to determine the number of unpaved road samples that can be collected and analyzed within the constraints of time, labor, and money available. For example, the study area could be defined as a very specific industrial plant having a network of roadways. Here it is advantageous to collect a separate sample for each major unpaved road in the plant. This level of resolution is useful in developing cost-effective emission reduction plans involving dust suppressants or traffic rerouting. On the other hand, the area of interest may be geographically large, and well-defined traffic information may not be easily obtained. In this case, resolution of the PM emission inventory to specific road segments would not be feasible, and it would be more important to obtain representative road-type samples within the area by aggregating several sample increments.

Procedure -

For a network consisting of many relatively short roads contained in a *well-defined study area* (as would be the case at an industrial plant), it is recommended that one collect a sample for each 0.8 kilometers (km) (0.5 miles [mi]) length, or portion thereof, for each major road segment. Here, the term "road segment" refers to the length of road between intersections (the nodes of the network) with other paved or unpaved roads. Thus, for a major segment 1 km (0.6 mi) long, 2 samples are recommended.

For longer roads in *study areas that are spatially diverse*, it is recommended that one collect a sample for each 4.8 km (3 mi) length of the road. Composite a sample from a minimum of 3 incremental samples. Collect the first sample increment at a random location within the first 0.8 km (0.5 mi), with additional increments taken from each remaining 0.8 km (0.5 mi) of the road, up to a maximum length of 4.8 km (3 mi). For a road less than 1.5 mi in length, an acceptable method for selecting sites for the increments is based on drawing 3 random numbers (x1, x2, x3) between zero and the length. Random numbers may be obtained from tabulations in statistical reference books, or scientific calculators may be used to generate pseudorandom numbers. See Figure C.1-1.

The following steps describe the collection method for samples (increments).

1. Ensure that the site offers an unobstructed view of traffic and that sampling personnel are visible to drivers. If the road is heavily traveled, use 1 person to "spot" and route traffic safely around another person collecting the surface sample (increment).

2. Using string or other suitable markers, mark a 0.3 meters (m) (1 foot [ft]) wide portion across the road. (WARNING: *Do not mark the collection area with a chalk line or in any other method likely to introduce fine material into the sample.*)

3. With a whisk broom and dustpan, remove the loose surface material from the hard road base. Do not abrade the base during sweeping. Sweeping should be performed slowly so that fine surface material is not injected into the air. NOTE: *Collect material only from the portion of the road over which the wheels and carriages routinely travel* (i. e., not from berms or any "mounds" along the road centerline).

4. Periodically deposit the swept material into a clean, labeled container of suitable size, such as a metal or plastic 19 liter (L) (5 gallon [gal]) bucket, having a sealable polyethylene liner. Increments may be mixed within this container.

5. Record the required information on the sample collection sheet (Figure C.1-2).

Sample Specifications -

For uncontrolled unpaved road surfaces, a gross sample of 5 kilograms (kg) (10 pounds [lb]) to 23 kg (50 lb) is desired. Samples of this size will require splitting to a size amenable for analysis (see Appendix C.2). For unpaved roads having been treated with chemical dust suppressants (such as petroleum resins, asphalt emulsions, etc.), the above goal may not be practical in well-defined study areas because a very large area would need to be swept. In general, a minimum of 400 grams (g) (1 lb) is required for silt and moisture analysis. Additional increments should be taken from heavily controlled unpaved surfaces, until the minimum sample mass has been achieved.

C.1.2 Samples From Paved Roads

Objective -

The overall objective in a paved road sampling program is to inventory the mass of particulate emissions from the roads. This is typically done by:

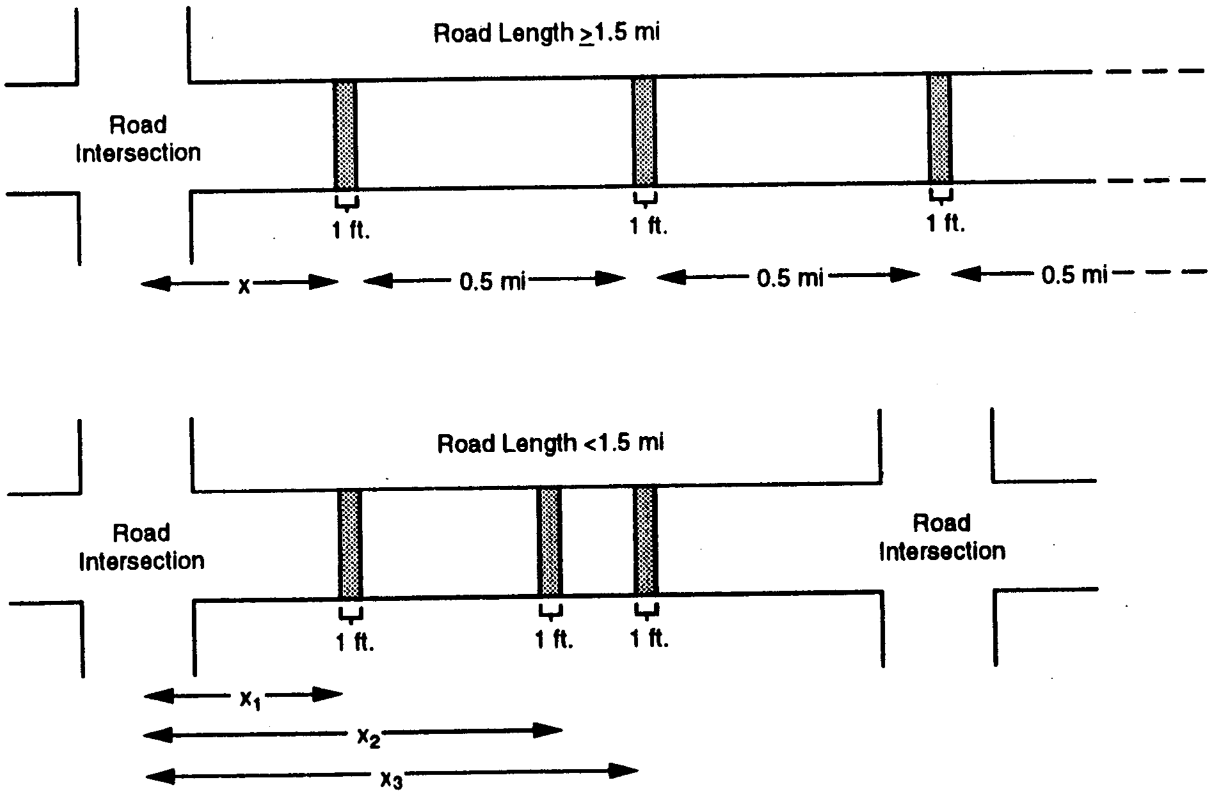


Figure C.1-1. Sampling locations for unpaved roads.

SAMPLING DATA FOR UNPAVED ROADS

Date Collected _________ Recorded by _________

Road Material (e.g., gravel, slag, dirt, etc.):* ______________________________

____

____

Site of Sampling: ______________________________

METHOD:

1. Sampling device: whisk broom and dustpan
2. Sampling depth: loose surface material (do not abrade road base)
3. Sample container: bucket with sealable liner
4. Gross sample specifications:
   a. Uncontrolled surfaces -- 5 kg (10 lb) to 23 kg (50 lb)
   b. Controlled surfaces -- minimum of 400 g (1 lb) is required for analysis

Refer to AP-42 Appendix B.1 for more detailed instructions.

Indicate any deviations from the above: ______________________________

____

____

SAMPLING DATA COLLECTED:

Sample No.	Time	Location +	Surf. Area	Depth	Mass of Sample

* Indicate and give details if roads are controlled.

\+ Use code given on plant or road map for segment identification. Indicate sampling location on map.

Figure C.1-2. Example data form for unpaved road samples.

1. Collecting "representative" samples of the loose surface material from the road;
2. Analyzing the sample to determine the silt fraction; and
3. Combining the results with traffic data in a predictive emission factor model.

The remarks above about definition of the study area and the appropriate level of resolution for sampling unpaved roads are equally applicable to paved roads. Before a field sampling program, it is necessary first to define the study area of interest and then to determine the number of paved road samples that can be collected and analyzed. For example, in a well-defined study area (e. g., an industrial plant), it is advantageous to collect a separate sample for each major paved road, because the resolution can be useful in developing cost-effective emission reduction plans. Similarly, in geographically large study areas, it may be more important to obtain samples representative of road types within the area by aggregating several sample increments.

Compared to unpaved road sampling, planning for a paved road sample collection exercise necessarily involves greater consideration as to types of equipment to be used. Specifically, provisions must be made to accommodate the characteristics of the vacuum cleaner chosen. For example, paved road samples are collected by cleaning the surface with a vacuum cleaner with "tared" (i. e., weighed before use) filter bags. Upright "stick broom" vacuums use relatively small, lightweight filter bags, while bags for industrial-type vacuums are bulky and heavy. Because the mass collected is usually several times greater than the bag tare weight, uprights are thus well suited for collecting samples from lightly loaded road surfaces. On the other hand, on heavily loaded roads, the larger industrial-type vacuum bags are easier to use and can be more readily used to aggregate incremental samples from all road surfaces. These features are discussed further below.

Procedure -

For a network of many relatively short roads *contained in a well-defined study area* (as would be the case at an industrial plant), it is recommended that one collect a sample for each 0.8 km (0.5 mi) length, or portion thereof, for each major road segment. For a 1 km long (0.6 mi) segment, then, 2 samples are recommended. As mentioned, the term "road segment" refers to the length of road between intersections with other paved or unpaved roads (the nodes of the network).

For longer roads *in spatially heterogeneous study areas*, it is recommended that one collect a sample for each 4.8 km (3 mi) of sampled road length. Create a composite sample from a minimum of 3 incremental samples. Collect the first increment at a random location within the first 0.8 km (0.5 mi), with additional increments taken from each remaining 0.8 km (0.5 mi) of the road, up to a maximum length of 4.8 km (3 mi.) For a road less than 2.4 km (1.5 mi) long, an acceptable method for selecting sites for the increments is based on drawing 3 random numbers (x1, x2, x3) between zero and the length (See Figure C.1-3). Random numbers may be obtained from tabulations in statistical reference books, or scientific calculators may be used to generate pseudorandom numbers.

The following steps describe the collection method for samples (increments).

1. Ensure that the site offers an unobstructed view of traffic and that sampling personnel are visible to drivers. If the road is heavily traveled, use 1 crew member to "spot" and route traffic safely around another person collecting the surface sample (increment).

2. Using string or other suitable markers, mark the sampling portion across the road. (WARNING: *Do not mark the collection area with a chalk line or in any other method likely to introduce fine material into the sample.*) The widths may be varied between 0.3 m (1 ft) for visibly dirty roads and 3 m (10 ft) for clean roads. When an industrial-

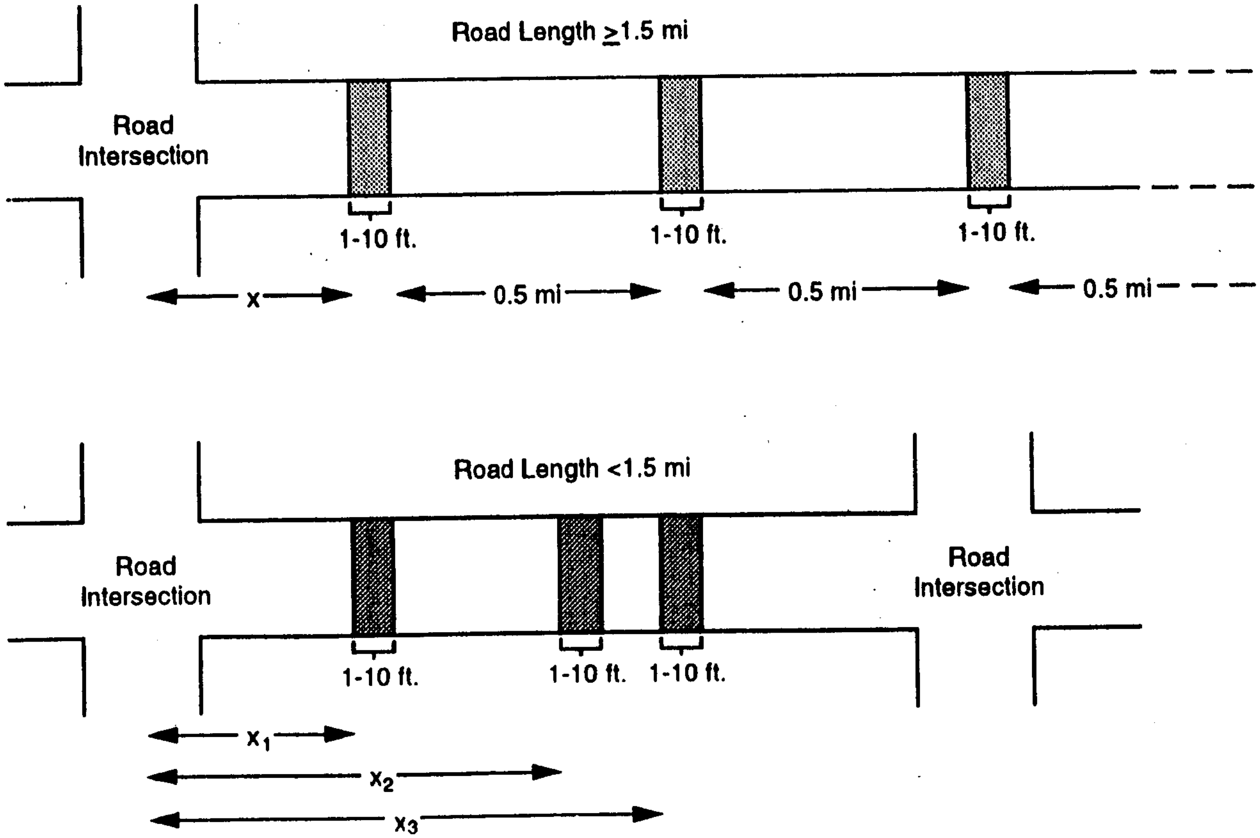


Figure C.1-3. Sampling locations for paved roads.

type vacuum is used to sample lightly loaded roads, a width greater than 3 m (10 ft) may be necessary to meet sample specifications, unless increments are being combined.

3. If large, loose material is present on the surface, it should be collected with a whisk broom and dustpan. NOTE: *Collect material only from the portion of the road over which the wheels and carriages routinely travel* (i. e., not from berms or any "mounds" along the road centerline). On roads with painted side markings, collect material "from white line to white line" (but avoid centerline mounds). Store the swept material in a clean, labeled container of suitable size, such as a metal or plastic 19 L (5 gal) bucket, with a sealable polyethylene liner. Increments for the same sample may be mixed within the container.

4. Vacuum the collection area using a portable vacuum cleaner fitted with an empty tared (preweighed) filter bag. NOTE: *Collect material only from the portion of the road over which the wheels and carriages routinely travel* (i. e., not from berms or any "mounds" along the road centerline). On roads with painted side markings, collect material "from white line to white line" (but avoid centerline mounds). The same filter bag may be used for different increments for 1 sample. For heavily loaded roads, more than 1 filter bag may be needed for a sample (increment).

5. Carefully remove the bag from the vacuum sweeper and check for tears or leaks. If necessary, reduce samples (using the procedure in Appendix C.2) from broom sweeping to a size amenable to analysis. Seal broom-swept material in a clean, labeled plastic jar for transport (alternatively, the swept material may be placed in the vacuum filter bag). Fold the unused portion of the filter bag, wrap a rubber band around the folded bag, and store the bag for transport.

6. Record the required information on the sample collection sheet (Figure C.1-4).

Sample Specifications -

When broom swept samples are collected, they should be at least 400 g (1 lb) for silt and moisture analysis. Vacuum swept samples should be at least 200 g (0.5 lb). Also, the weight of an "exposed" filter bag should be at least 3 to 5 times greater than when empty. Additional increments should be taken until these sample mass goals have been attained.

C.1.3 Samples From Storage Piles

Objective -

The overall objective of a storage pile sampling and analysis program is to inventory particulate matter emissions from the storage and handling of materials. This is done typically by:

1. Collecting "representative" samples of the material;
2. Analyzing the samples to determine moisture and silt contents; and
3. Combining analytical results with material throughput and meteorological information in an emission factor model.

As initial steps in storage pile sampling, it is necessary to decide (a) what emission mechanisms - material load-in to and load-out from the pile, wind erosion of the piles - are of interest, and (b) how many samples can be collected and analyzed, given time and monetary constraints. (In general, annual average PM emissions from material handling can be expected to be

SAMPLING DATA FOR PAVED ROADS

Date Collected ________ Recorded by ________

Sampling location* ______________________ No. of Lanes ________

Surface type (e.g., asphalt, concrete, etc.)____________________________

Surface condition (e.g., good, rutted, etc.) ____________________________

* Use code given on plant or road map for segment identification. Indication sampling location on map.

METHOD:

1. Sampling device: portable vacuum cleaner (whisk broom and dustpan if heavy loading present)
2. Sampling depth: loose surface material (do not sample curb areas or other untravelled portions of the road)
3. Sample container: tared and numbered vacuum cleaner bags (bucket with sealable liner if heavy loading present)
4. Gross sample specifications: Vacuum swept samples should be at least 200 g (0.5 lb), with the exposed filter bag weight should be at least 3 to 5 times greater than the empty bag tare weight.

Refer to AP-42 Appendix C.1 for more detailed instructions.

Indicate any deviations from the above: ____________________________

____

____

SAMPLING DATA COLLECTED:

Sample No.	Vacuum Bag ID	Vacuum Bag Tare Wgt (g)	Sampling Surface Dimensions (l x w)	Time	Mass of Broom-Swept Sample +

+ Enter "0" if no broom sweeping is performed.

Figure C.1-4. Example data form for paved roads.

much greater than those from wind erosion.) For an industrial plant, it is recommended that at least 1 sample be collected for each major type of material handled within the facility.

In a program to characterize load-in emissions, representative samples should be collected from material recently loaded into the pile. Similarly, representative samples for load-out emissions should be collected from areas that are worked by load-out equipment such as front end loaders or clamshells. For most "active" piles (i. e., those with frequent load-in and load-out operations), 1 sample may be considered representative of both loaded-in and loaded-out materials. Wind erosion material samples should be representative of the surfaces exposed to the wind.

In general, samples should consist of increments taken from all exposed areas of the pile (i. e., top, middle, and bottom). If the same material is stored in several piles, it is recommended that piles with at least 25 percent of the amount in storage be sampled. For large piles that are common in industrial settings (e. g., quarries, iron and steel plants), access to some portions may be impossible for the person collecting the sample. In that case, increments should be taken no higher than it is practical for a person to climb carrying a shovel and a pail.

Procedure -

The following steps describe the method for collecting samples from storage piles:

1. Sketch plan and elevation views of the pile. Indicate if any portion is not accessible. Use the sketch to plan where the N increments will be taken by dividing the perimeter into N-1 roughly equivalent segments.

    a. For a large pile, collect a minimum of 10 increments, as near to mid-height of the pile as practical.

    b. For a small pile, a sample should be a minimum of 6 increments, evenly distributed among the top, middle, and bottom.

    "Small" or "large" piles, for practical purposes, may be defined as those piles which can or cannot, respectively, be scaled by a person carrying a shovel and pail.

2. Collect material with a straight-point shovel or a small garden spade, and store the increments in a clean, labeled container of suitable size (such as a metal or plastic 19 L [5 gal] bucket) with a sealable polyethylene liner. Depending upon the ultimate goals of the sampling program, choose 1 of the following procedures:

    a. To characterize emissions from *material handling operations at an active pile*, take increments from the portions of the pile which most recently had material added and removed. Collect the material with a shovel to a depth of 10 to 15 centimeters (cm) (4 to 6 inches [in]). Do not deliberately avoid larger pieces of aggregate present on the surface.

    b. To characterize *handling emissions from an inactive pile*, obtain increments of the core material from a 1 m (3 ft) depth in the pile. A sampling tube 2 m (6 ft) long, with a diameter at least 10 times the diameter of the largest particle being sampled, is recommended for these samples. Note that, for piles containing large particles, the diameter recommendation may be impractical.

c. If characterization of *wind erosion*, rather than material handling is the goal of the sampling program, collect the increments by skimming the surface in an upwards direction. The depth of the sample should be 2.5 cm (1 in), or the diameter of the largest particle, whichever is less. Do not deliberately avoid collecting larger pieces of aggregate present on the surface.

In most instances, collection method "a" should be selected.

3. Record the required information on the sample collection sheet (Figure C.1-5). Note the space for deviations from the summarized method.

Sample Specifications -

For any of the procedures, the sample mass collected should be at least 5 kg (10 lb). When most materials are sampled with procedures 2a or 2b, 10 increments will normally result in a sample of at least 23 kg (50 lb). Note that storage pile samples usually require splitting to a size more amenable to laboratory analysis.

SAMPLING DATA FOR STORAGE PILES

Date Collected _________ Recorded by _________

Type of material sampled ____

Sampling location* ____

METHOD:

1. Sampling device: pointed shovel (hollow sampling tube if inactive pile is to be sampled)
2. Sampling depth:
   For material handling of active piles: 10-15 cm (4-6 in.)
   For material handling of inactive piles: 1 m (3 ft)
   For wind erosion samples: 2.5 cm (1 in.) or depth of the largest particle (whichever is less)
3. Sample container: bucket with sealable liner
4. Gross sample specifications:
   For material handling of active or inactive piles: minimum of 6 increments with total sample weight of 5 kg (10 lb) [10 increments totalling 23 kg (50 lb) are recommended]
   For wind erosion samples: minimum of 6 increments with total sample weight of 5 kg (10 lb)

Refer to AP-42 Appendix C.1 for more detailed instructions.

Indicate any deviations from the above: ____

____

____

SAMPLING DATA COLLECTED:

Sample No.	Time	Location* of Sample Collection	Device Used S/T **	Depth	Mass of Sample

* Use code given of plant or area map for pile/sample identification. Indicate each sampling location on map.

** Indicate whether shovel or tube.

Figure C.1-5. Example data form for storage piles.

APPENDIX C.2

PROCEDURES FOR LABORATORY ANALYSIS OF SURFACE/BULK DUST LOADING SAMPLES

Appendix C.2

Procedures For Laboratory Analysis Of Surface/Bulk Dust Loading Samples

This appendix discusses procedures recommended for the analysis of samples collected from paved and unpaved surfaces and from bulk storage piles. (AP-42 Appendix C.1, "Procedures For Sampling Surface/Bulk Dust Loading", presents procedures for the collection of these samples.) These recommended procedures are based on a review of American Society For Testing And Materials (ASTM) methods, such as C-136 (sieve analysis) or D-2216 (moisture content). The recommendations follow ASTM standards where practical, and where not, an effort has been made to develop procedures consistent with the intent of the pertinent ASTM standards.

C.2.1 Sample Splitting

Objective -

The collection procedures presented in Appendix C.1 can result in samples that need to be reduced in size before laboratory analysis. Samples are often unwieldy, and field splitting is advisable before transporting the samples.

The size of the laboratory sample is important. Too small a sample will not be representative, and too much sample will be unnecessary as well as unwieldy. Ideally, one would like to analyze the entire gross sample in batches, but that is not practical. While all ASTM standards acknowledge this impracticality, they disagree on the exact optimum size, as indicated by the range of recommended samples, extending from 0.05 to 27 kilograms (kg) (0.1 to 60 pounds [lb]).

Splitting a sample may be necessary before a proper analysis. The principle in sizing a laboratory sample for silt analysis is to have sufficient coarse and fine portions both to be representative of the material and to allow sufficient mass on each sieve to assure accurate weighing. A laboratory sample of 400 to 1,600 grams (g) is recommended because of the capacity of normally available scales (1.6 to 2.6 kg). A larger sample than this may produce "screen blinding" for the 20 centimeter (cm) (8 inch [in.]) diameter screens normally available for silt analysis. Screen blinding can also occur with small samples of finer texture. Finally, the sample mass should be such that it can be spread out in a reasonably sized drying pan to a depth of $<$ 2.5 cm (1 in.).

Two methods are recommended for sample splitting: riffles, and coning and quartering. Both procedures are described below.

Procedures -

Figure C.2-1 shows 2 riffles for sample division. Riffle slot widths should be at least 3 times the size of the largest aggregate in the material being divided. The following quote from ASTM Standard Method D2013-72 describes the use of the riffle.

Divide the gross sample by using a riffle. Riffles properly used will reduce sample variability but cannot eliminate it. Riffles are shown in Figure C.2-1. Pass the material through the riffle from a feed scoop, feed bucket, or riffle pan having a lip or opening the full length of the riffle. When using any of the above containers to feed the riffle, spread the material evenly in the container, raise the container, and hold it with its front edge resting on top of the feed chute, then slowly tilt it so that the material flows in a uniform stream through the hopper straight down over the center of the riffle into all the slots, thence into the riffle pans, one-half of the sample being collected in a pan.

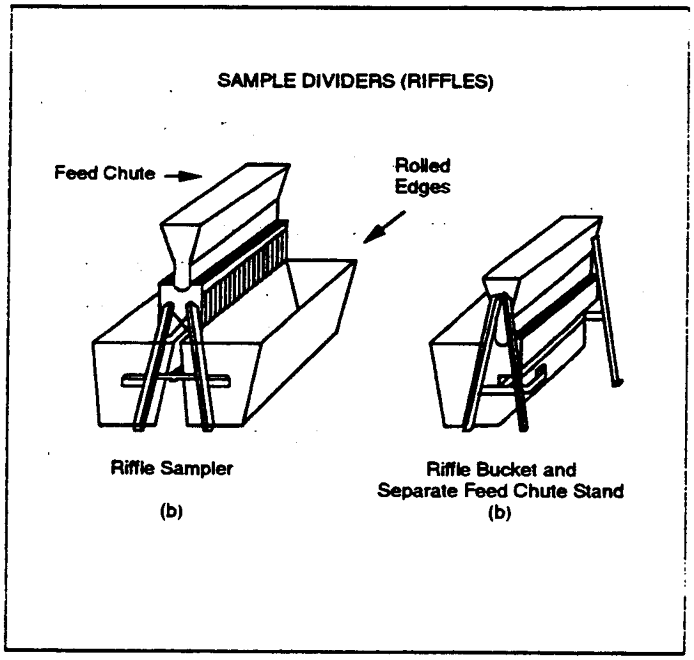


Figure C.2-1. Sample riffle dividers.

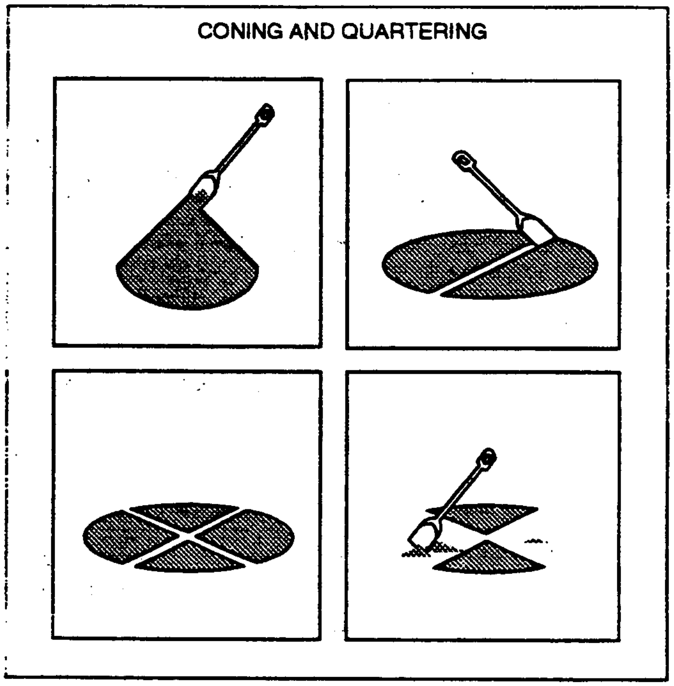


Figure C.2-2. Procedure for coning and quartering.

Under no circumstances shovel the sample into the riffle, or dribble into the riffle from a small-mouthed container. Do not allow the material to build up in or above the riffle slots. If it does not flow freely through the slots, shake or vibrate the riffle to facilitate even flow.[1]

Coning and quartering is a simple procedure useful with all powdered materials and with sample sizes ranging from a few grams to several hundred pounds.[2] Oversized material, defined as > 0.6 millimeters (mm) (3/8 in.) in diameter, should be removed before quartering and be weighed in a "tared" container (one for which its empty weight is known).

Preferably, perform the coning and quartering operation on a floor covered with clean 10 mil plastic. Take care that the material is not contaminated by anything on the floor or that any portion is not lost through cracks or holes. Samples likely affected by moisture or drying must be handled rapidly, preferably in a controlled atmosphere, and sealed in a container to prevent further changes during transportation and storage.

The procedure for coning and quartering is illustrated in Figure C.2-2. The following procedure should be used:

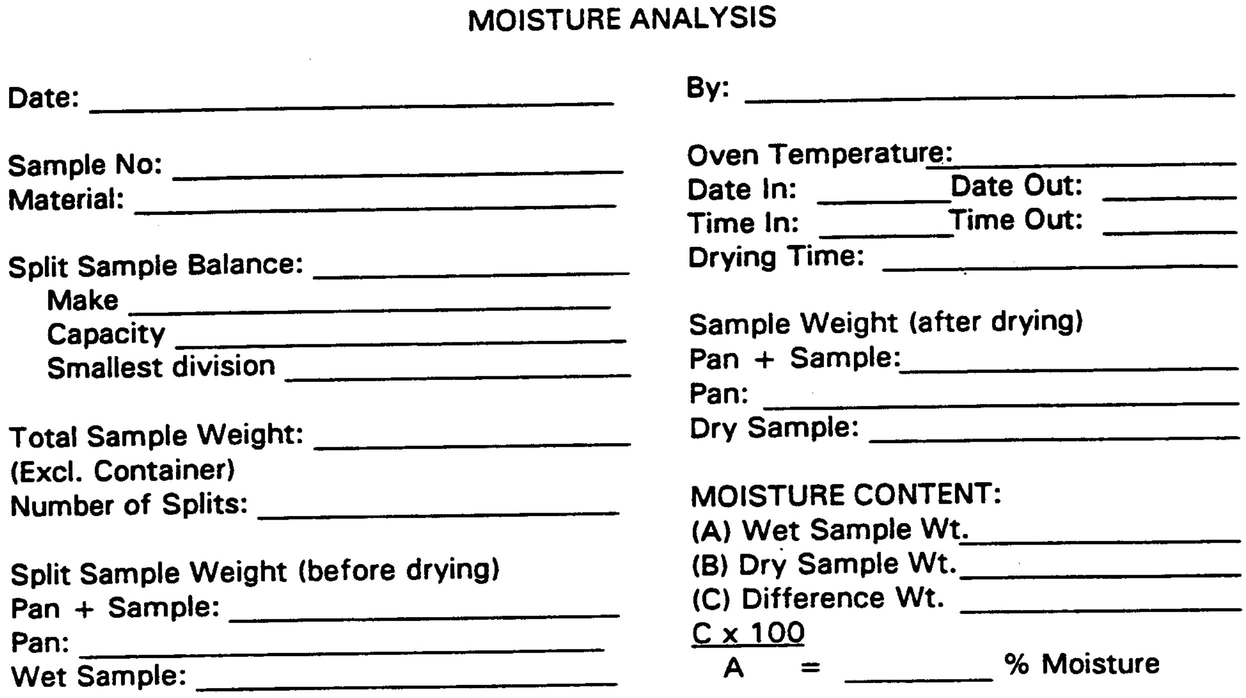
1. Mix the material and shovel it into a neat cone.
2. Flatten the cone by pressing the top without further mixing.
3. Divide the flat circular pile into equal quarters by cutting or scraping out 2 diameters at right angles.
4. Discard 2 opposite quarters.
5. Thoroughly mix the 2 remaining quarters, shovel them into a cone, and repeat the quartering and discarding procedures until the sample is reduced to 0.4 to 1.8 kg (1 to 4 lb).

C.2.2 Moisture Analysis

Paved road samples generally are not to be oven dried because vacuum filter bags are used to collect the samples. After a sample has been recovered by dissection of the bag, it is combined with any broom swept material for silt analysis. All other sample types are oven dried to determine moisture content before sieving.

Procedure -

1. Heat the oven to approximately 110°C (230°F). Record oven temperature. (See Figure C.2-3.)
2. Record the make, capacity, and smallest division of the scale.
3. Weigh the empty laboratory sample containers which will be placed in the oven to determine their tare weight. Weigh any lidded containers with the lids. Record the tare weight(s). Check zero before each weighing.
4. Weigh the laboratory sample(s) in the container(s). For materials with high moisture content, assure that any standing moisture is included in the laboratory sample container. Record the combined weight(s). Check zero before each weighing.



MOISTURE ANALYSIS

Date: ______________________

Sample No: ______________________
Material: ______________________

Split Sample Balance: ______________
Make ______________________
Capacity ______________________
Smallest division ______________

Total Sample Weight: ______________
(Excl. Container)
Number of Splits: ______________

Split Sample Weight (before drying)
Pan + Sample: ______________
Pan: ______________________
Wet Sample: ______________

By: ______________________

Oven Temperature: ______________
Date In: ________ Date Out: ________
Time In: ________ Time Out: ________
Drying Time: ______________

Sample Weight (after drying)
Pan + Sample: ______________
Pan: ______________________
Dry Sample: ______________

MOISTURE CONTENT:
(A) Wet Sample Wt. ______________
(B) Dry Sample Wt. ______________
(C) Difference Wt. ______________

$\frac{C \times 100}{A}$ = ________ % Moisture

Figure C.2-3. Example moisture analysis form.

5. Place sample in oven and dry overnight. Materials composed of hydrated minerals or organic material such as coal and certain soils should be dried for only 1.5 hours.

6. Remove sample container from oven and (a) weigh immediately if uncovered, being careful of the hot container; or (b) place a tight-fitting lid on the container and let it cool before weighing. Record the combined sample and container weight(s). Check zero before weighing.

7. Calculate the moisture, as the initial weight of the sample and container, minus the oven-dried weight of the sample and container, divided by the initial weight of the sample alone. Record the value.

8. Calculate the sample weight to be used in the silt analysis, as the oven-dried weight of the sample and container, minus the weight of the container. Record the value.

C.2.3 Silt Analysis

Objective -

Several open dust emission factors have been found to be correlated with the silt content (< 200 mesh) of the material being disturbed. The basic procedure for silt content determination is mechanical, dry sieving. For sources other than paved roads, the same sample which was oven-dried to determine moisture content is then mechanically sieved.

For paved road samples, the broom-swept particles and the vacuum-swept dust are individually weighed on a beam balance. The broom-swept particles are weighed in a container, and the vacuum-swept dust is weighed in the bag of the vacuum, which was tared before sample collection. After weighing the sample to calculate total surface dust loading on the traveled lanes, combine the broom-swept particles and the vacuumed dust. Such a composite sample is usually small and may not require splitting in preparation for sieving.

Procedure -

1. Select the appropriate 20-cm (8-in.) diameter, 5-cm (2-in.) deep sieve sizes. Recommended U. S. Standard Series sizes are 3/8 in., No. 4, No. 40, No. 100, No. 140, No. 200, and a pan. Comparable Tyler Series sizes can also be used. The No. 20 and the No. 200 are mandatory. The others can be varied if the recommended sieves are not available, or if buildup on 1 particulate sieve during sieving indicates that an intermediate sieve should be inserted.

2. Obtain a mechanical sieving device, such as a vibratory shaker or a Roto-Tap® without the tapping function.

3. Clean the sieves with compressed air and/or a soft brush. Any material lodged in the sieve openings or adhering to the sides of the sieve should be removed, without handling the screen roughly, if possible.

4. Obtain a scale (capacity of at least 1600 grams [g] or 3.5 lb) and record make, capacity, smallest division, date of last calibration, and accuracy. (See Figure C.2-4.)

5. Weigh the sieves and pan to determine tare weights. Check the zero before every weighing. Record the weights.

6. After nesting the sieves in decreasing order of size, and with pan at the bottom, dump dried laboratory sample (preferably immediately after moisture analysis) into the top sieve. The sample should weigh between ~ 400 and 1600 g (~ 0.9 and 3.5 lb). This amount will vary for finely textured materials, and 100 to 300 g may be sufficient when 90% of the sample passes a No. 8 (2.36 mm) sieve. Brush any fine material adhering to the sides of the container into the top sieve and cover the top sieve with a special lid normally purchased with the pan.

7. Place nested sieves into the mechanical sieving device and sieve for 10 minutes (min). Remove pan containing minus No. 200 and weigh. Repeat the sieving at 10-min intervals until the difference between 2 successive pan sample weighings (with the pan tare weight subtracted) is less than 3.0%. Do not sieve longer than 40 min.

8. Weigh each sieve and its contents and record the weight. Check the zero before every weighing.

9. Collect the laboratory sample. Place the sample in a separate container if further analysis is expected.

10. Calculate the percent of mass less than the 200 mesh screen (75 micrometers [μm]). This is the silt content.

SILT ANALYSIS

Date: ______________________

By: ______________________

Sample No: ______________________

Material: ______________________

Make ______________________

Smallest Division ______________________

Sample Weight (after drying)

Pan + Sample: ______________________

Pan: ______________________

Split Sample Balance: ______________________

Dry Sample: ______________________

Capacity: ______________________

Final Weight: ______________________

$$\% \text{ Silt} = \frac{\text{Net Weight} < 200 \text{ Mesh}}{\text{Total Net Weight}} \times 100 = \_\_\%$$

SIEVING

Time: Start:	Weight (Pan Only)
Initial (Tare):	
10 min:	
20 min:	
30 min:	
40 min:	

Screen	Tare Weight (Screen)	Final Weight (Screen + Sample)	Net Weight (Sample)	%
3/8 in.				
4 mesh				
10 mesh				
20 mesh				
40 mesh				
100 mesh				
140 mesh				
200 mesh				
Pan				

Figure C.2-4. Example silt analysis form.

References For Appendix C.2

1. "Standard Method Of Preparing Coal Samples For Analysis", *Annual Book Of ASTM Standards, 1977*, D2013-72, American Society For Testing And Materials, Philadelphia, PA, 1977.

2. L. Silverman, *et al.*, *Particle Size Analysis In Industrial Hygiene*, Academic Press, New York, 1971.

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(Please read Instructions on the reverse before completing)

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16. ABSTRACT

This document contains emission factors and process information for more than 200 air pollution source categories. These emission factors have been compiled from source test data, material balance studies, and engineering estimates, and they can be used judiciously in making emission estimations for various purposes. When specific source test data are available, such should be preferred over the generalized factors presented in this document.

This Fifth Edition addresses pollutant-generating activity from EXTERNAL COMBUSTION SOURCES, SOLID WASTE DISPOSAL, STATIONARY INTERNAL COMBUSTION SOURCES, EVAPORATION LOSS SOURCES, PETROLEUM INDUSTRY, ORGANIC CHEMICAL PROCESS INDUSTRY, LIQUID STORAGE TANKS, INORGANIC CHEMICAL INDUSTRY, FOOD AND AGRICULTURAL INDUSTRIES, WOOD PRODUCTS INDUSTRY, MINERAL PRODUCTS INDUSTRY, METALLURGICAL INDUSTRY, and MISCELLANEOUS SOURCES.

Also included are particle size distribution data and procedures for sampling and analyzing surface/bulk dust loading.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Emission Factors Emission Estimation Stationary Sources Point Sources Area Sources Criteria Pollutants Toxic Pollutants		

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