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DOE HANDBOOK

NUCLEAR AIR CLEANING HANDBOOK

U.S. Department of Energy
Washington, DC 20585

FOREWORD
TO
THIRD EDITION

This handbook is a revision of ORNL/NSIC-65, *Design, Construction, and Testing of High-Efficiency Air Filtration Systems for Nuclear Application*, which was issued in January 1970. For simplification, the title has been shortened to *Nuclear Air Cleaning Handbook*, and the report has been issued under an ERDA number.

The new edition updates the information of the original volume, corrects some errors that appeared in it, and adds some new material, particularly in the areas of sand filters, deep-bed glass fiber filters, and requirements for plutonium and reprocessing plants. Although A. B. Fuller was unable to contribute directly to this edition, his earlier material on single-filter installation and glove boxes has been largely retained, though rewritten and updated. With this issue, J. E. Kahn of the Union Carbide Corporation Nuclear Division's (UCCND) Engineering staff joins the writing team, contributing particularly in updating the material on glove boxes and writing the sections on sand filters and deep-bed glass fiber filters in Chapter 9. Others who have contributed to this edition include J. C. Little, UCCND Engineering, and a host of reviewers who provided technical evaluation of the draft. Particular thanks are due Dr. M. W. First of the Harvard University School of Public Health, and Mr. Humphrey Gilbert, consultant to the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission (NRC) and former safety engineer with the U.S. Atomic Energy Commission, for their detailed and thorough review of the complete draft. Others who reviewed the complete draft were J. F. Fish, chairman of ANSI Committee N45-8; J. C. Little, UCCND Engineering; J. C. Dempsey, ERDA Division of Nuclear Fuel Cycle and Production; A. B. Fuller, president of Fuller Engineering; and J. T. Collins of NRC. Thanks are also due to the members of ANSI Committee N45-8 who, perhaps unknowingly, supplied certain data and served as a sounding board for some of the concepts presented in the handbook. We wish to thank the many vendors and ERDA contractors who supplied drawings and photographs used in the book. We also acknowledge the work of Oak Ridge National Laboratory's Technical Publications Department, particularly that of the Composition and Makeup groups, that of R. H. Powell who provided editorial assistance, and especially that of P. J. Patton who edited and coordinated publication of this handbook.

Reviewers who contributed in the technical review of particular sections of the handbook include:

R. L. Alley	American Warming and Ventilating Company
J. E. Beavers	Union Carbide Corporation Nuclear Division
R. R. Bellamy	Nuclear Regulatory Commission
R. E. Blanco	Oak Ridge National Laboratory
P. J. Breman	Union Carbide Corporation Nuclear Division
C. L. Cheever	Argonne National Laboratory
J. C. Elder	Los Alamos Scientific Laboratory
A. G. Evans	Savannah River Laboratory
H. F. Farquhar	Lau Blower Company
S. S. Freeman	Mound Laboratory
R. T. Goulet	Cambridge Filter Corporation
R. K. Hilliard	Hanford Engineering Development Laboratory
D. J. Keigher	Los Alamos Scientific Laboratory

C. Lambert	Bechtel Power Corporation
F. D. Leckie	Nuclear Containment Systems, Inc.
H. A. Lee	Atlantic Richfield Hanford Company
J. Lipera	Lawrence Livermore Laboratory
R. A. Lorenz	Oak Ridge National Laboratory
W. Ng	Lawrence Livermore Laboratory
W. C. Schimdt	Atlantic Richfield Hanford Company
F. R. Schwartz, Jr.	North American Carbon Company
A. Shacter	U.S. Army Aberdeen Proving Ground-EA
A. A. Weintraub	Energy Research and Development Administration
R. E. Yoder	Rocky Flats Plant
D. P. Zippler	Savannah River Plant

Sheet Metal and Air Conditioning Contractors' National Association

C. A. Burchsted

Oak Ridge, Tennessee
March 31, 1976

FOREWORD TO SECOND EDITION

This handbook fills a large gap in the literature concerning air cleaning and filtration, the gap that encompasses design, construction, and testing of very high-efficiency air cleaning systems. The project was originally conceived by Mr. Humphrey Gilbert of the USAEC and was sponsored by the Division of Reactor Development and Technology of the USAEC. In preparing for the project we surveyed air-cleaning systems at atomic energy facilities and industrial installations throughout the United States and Canada. We visited AEC production reactors, commercial power reactors, laboratories, radiochemical plants, reactor fuel manufacturers, clean rooms, equipment manufacturers, and one chemical-biological warfare installation. The purposes of these visits were to review current practices in high efficiency air cleaning and to define the problems in operating, maintaining, and controlling contamination release from very high-efficiency air-cleaning systems from experienced people who were dealing with such problems daily. The handbook reflects a consensus of our findings in these travels, in addition to information gleaned from the available literature.

The handbook is addressed primarily to designers and architect-engineers. We frequently observed a lack of communication and feedback from people with problems in the field to designers. Our intention is to bring to the attention of designers of future systems the kind of problems that an operator faces and what he, the designer, must do to preclude or alleviate them. We have purposely pointed out some poor practices in current design in addition to our recommendations in the hope that such practices will go no further. To give "do's" without "don'ts" may encourage some designers to offer a poor design because he mistakenly believes that "it worked before."

Those who have contributed to the handbook number literally in the hundreds and include those we consulted with and those who have given of their time in reviewing drafts or have supplied specific bits and pieces of information. We take this opportunity to thank the many friends we have made in the course of this project, particularly for their candidness in discussing problems and ways of solving those problems, and for their help in supplying photographs and information. In particular we want to thank Mr. Humphrey Gilbert and I. Craig Roberts of the USAEC for their guidance, W. B. Cottrell of ORNL for his help in getting the book published, T. F. Davis of the USAEC's Division of Technical Information for his assistance in indexing the material, J. H. Waggoner of ORNL for doing the illustrations, and Dr. M. W. First of Harvard University for his meticulous page-by-page review of the draft and suggestions for this final issue.

C. A. Burchsted
A. B. Fuller

Oak Ridge, Tennessee
July 10, 1969

FOREWORD TO FIRST EDITION

This review presents the latest developments in the trapping of airborne radioactive materials encountered in reactor operations, fuel fabrication and processing plants, and radiochemical plants of all types. The containment of these radioactive aerosols and gases is essential to the safe operation of such installations. Research and development is directed toward increases in containment reliability under adverse conditions, as well as lowered costs and increased efficiencies.

Air cleaning problems and their solutions are related to the physical and chemical properties of the materials to be retained. For example, until recently radioactive iodine was caught on unimpregnated activated charcoal, but recent investigations indicate that the iodine exists in several chemical forms, one of them being methyl iodide, which must be caught on impregnated charcoal.

High-efficiency particulate air (HEPA) filters of fire-resistant fiber glass are now required in the trapping of fine particles in USAEC installations. New HEPA filters for nuclear installations in the United States must show a minimum efficiency of 99.97% for the retention of monodisperse 0.3-μ dioctyl phthalate particles in the standard USAEC Quality Assurance test. A difference of 0.02% is allowed between the rating of new filters by the Quality Assurance test and the rating of filter systems (including single installed filters) by the in-place test. To qualify as high-efficiency, the system or installed filter must have an efficiency of 99.95% in the in-place test.

Radioactive noble gases from high-velocity gas streams must be diluted to permissible concentrations before release to the atmosphere. Noble gases can be removed near the source, but only if treated in small volumes or if low-velocity gas streams are used.

Siting of nuclear power reactors is influenced by the potential hazard of released fission products. Fortunately, a number of transport phenomena, such as agglomeration, absorption, adsorption, deposition, and steam condensation within the containment vessel, serve to reduce the amounts of fission products available for release to the environment. Nevertheless, reactor designers depend on gas cleaning systems as an engineered safeguard to reduce the fission product concentration in the containment system in the event of a reactor accident resulting in fission product release. Clearly, it is important that the effectiveness of various air cleaning systems for removing radioactivity of the types and forms expected in the event of accidents to reactors, nuclear fuel processing plants, or radiochemical plants be demonstrated.

Efforts toward greater reactor safety by the use of engineered safeguards are encouraged by the AEC. However, only limited credit for engineered safeguards is presently allowed in establishing reactor site criteria. Furthermore, the dependability of such systems under accident conditions must be demonstrated beforehand.

Engineered safeguards, in addition to the containment enclosure, are classified into four general types: (1) emergency coolant to prevent melting of the fuel materials, (2) air cleaning systems for removing fission products from the containment enclosure, (3) methods, such as pressure suppression, for reducing the internal pressure, which in turn reduces leakage to the atmosphere, and (4) provision for two or more barriers around the primary system, which will prevent a major leak of fission product activity.

Air cleaning systems are provided to clean the containment atmosphere either during recirculation or by treatment before the air is released to the environment. Several nuclear power companies have installed filter systems in the newer plants, and some credit will be taken in calculating the effects of the maximum accident.

A number of the systems have been tested and show >99.99% iodine retention. However, generally only 95% efficiency has been assumed for an installed filter system until detailed behavior of iodine is better established for accident conditions.

The air cleaning system is usually within the containment envelope, where blowers induce air movement through the filter system. Two important considerations are the general reliability of the blowers, filters, filter housings, seals, etc., and the relative vulnerability of the system to damage from particles, missiles, chemical reagents, vapors, etc. This report does not cover engineering design or specifications for filter units or high-efficiency air cleaning systems. An engineering manual, addressed primarily to architects and engineers who are not familiar with the special requirements of such systems, is being prepared for the USAEC by the Oak Ridge National Laboratory and is expected to be available in 1967. The manual will contain design criteria, drawings, and specifications for HEPA filter units and systems in which they are used and will discuss problem areas concerned with the selection and installation of HEPA and activated charcoal filter units.

The methods for trapping radioactive aerosols (including solids and mists) and gases generated in nuclear installations are presented in three parts.

Part I, Fibrous Filters, is concerned with the high-efficiency removal of particles. Here, we review the properties of aerosols, filtration theory, aerosol sampling, analysis of particles, filter media, testing filter efficiency, and the generation of test aerosols for use in testing filters.

Part II, Sorbents, reviews the mechanisms for the sorption of gases and vapors, with particular emphasis on the trapping of fission product iodine and the noble gases.

Part III, Air Cleaning Systems, includes the design of air cleaning systems, in-place testing, filter failures and their prevention, with emphasis on the reduction of fire hazards, and typical engineered safeguard systems applicable to the containment of fission products, including pressure-suppression containment.

At present standard equipment in gas cleaning systems for reactors includes the following: a prefilter unit to remove most of the radioactivity and reduce the fission product decay heat load on later units; next, an HEPA filter to remove very small particles (submicron range); then, a solid adsorber to remove specific gases and vapors. These may be followed by another HEPA filter to protect against any dusting from the solid adsorber. Finally, a high off-gas stack to the atmosphere is required, since nonadsorbable and noncondensable radioactive gases that cannot be removed by the gas cleaning system must be diluted to permissible levels of radioactivity before their release to the environment.

INTRODUCTION

The 4th edition of the Nuclear Air Cleaning Handbook succeeds three previous editions: ERDA 76-21, *Nuclear Air Cleaning Handbook* (1976); ORNL/NSIC-65, *Design, Construction and Testing of High-Efficiency Air Filtration Systems for Nuclear Applications* (1970); and NSIC-13, *Filters, Sorbents, and Air Cleaning Systems as Engineered Safeguards in Nuclear Installations* (1966). It benefits from over 25 years of industry experience since the previous edition was published.

Along with U.S. Nuclear Regulatory Commission documents and consensus standards such as the American Society of Mechanical Engineers (ASME) *Code On Nuclear Air and Gas Treatment* (ASME AG-1), this handbook addresses systems and equipment used in nuclear facilities to capture and control radioactive aerosols and gases. It differs from other documents in that it is intended to be specific for U.S. Department of Energy (DOE) and National Nuclear Security Administration (NNSA) nuclear applications. This handbook is not intended for application to commercial systems other than for general historical information and discussions of basic air cleaning theory. DOE handbooks are nonmandatory documents unless invoked by DOE policy or Order, DOE-approved contractor document, or by contract.

This revision updates the information provided in ERDA 76-21 and incorporates current thinking as provided by manufacturers, subject matter experts from the DOE complex and members of the ASME Committee on Nuclear Air and Gas Treatment (ASME AG-1 Committee). Chapters have been added on History, Fire Protection, and Occupational Safety and Health.

This handbook draws from many special technical areas, each of which requires years of education and practice to master. The authors do not intend to make the reader an "instant expert" in the overall subject or in any of the disciplines of the contributors. For example, reading the chapter on fire protection will not make the reader a fire protection engineer, nor will reading the chapter on gloveboxes make one a glovebox expert. This handbook is intended to provide a very brief overview of the subjects discussed and identify potential issues. Qualified subject matter experts should be contacted for the areas discussed in this handbook.

While this handbook is written for nuclear applications, it is recognized that these systems have shared engineering characteristics that may, with professional discretion exercised by trained engineering and public health professionals, be applicable to nonradiological toxic materials. Such materials include, but are not limited to, asbestos and other particulate carcinogens, beryllium, and biological agents.

We would like to acknowledge the contributions of Humphrey Gilbert, who from the days of the Manhattan Project, was responsible for the initial development of the technology discussed in this handbook. He played a significant role in the development, writing, and technical review of this and previous editions. We wish to express our appreciation to Melvin First, Harvard School of Public Health, who provided a draft that was used in the development of this document; and to Richard C. Crowe, Department Manager for Environment, Safety, and Health (NNSA Service Center), without whose continued support this handbook would not have been possible.

James W. Slawski, NNSA
Project Manager

WRITERS AND REVIEWERS

David Anglen	National Nuclear Security Administration
Eric Banks*	NUCON International
Werner Bergman	Lawrence Livermore National Laboratory
William Boyce	U.S. Department of Energy
Edward Branagan	U.S. Department of Energy
Randy Brinkley*	Westinghouse Savannah River Company
John Cherry	Camfil Farr, Inc.
Matt Cole	U.S. Department of Energy
David Crosby*	Air Techniques International
Julie Davis	Air Techniques International
Leo Derderian	U.S. Department of Energy
Maynor Dykes*	Flanders Filters, Inc.
Melvin First*	Harvard University School of Public Health
Jan Fretthold*	Rocky Flats/Hukari Tech Services
Harry Frisby	Science Applications International Corporation
Humphrey Gilbert*	Atomic Energy Commission, Retired; Consultant
Gurinder Grewal*	Los Alamos National Laboratory
Robert Hamby	BWXT Y-12
Matt Hargan*	Hargan Engineering; Vice Chair, ASME Committee on Nuclear Air and Gas Treatment
John Hayes*	U.S. Nuclear Regulatory Commission
Cathy Haupt	Science Applications International Corporation
David Holiday	Oak Ridge National Laboratory
Russell Krainiak	Flanders Filters, Inc.
Dennis Kubicki	U.S. Department of Energy
Steven Mixon	Science Applications International Corporation
Glen W. Moore*	CSC/Flanders
John Pearson	NCS Corporation
Robin Phillips	Science Applications International Corporation
Richard Porco*	Ellis and Watts International; Chair, ASME Committee on Nuclear Air and Gas Treatment, ASME Board of Nuclear Codes and Standards
Joel Rabovsky	U.S. Department of Energy
Jacques Read	U.S. Department of Energy
Jerome Roberts	Westinghouse Savannah River Company
Scott Salisbury	Los Alamos National Laboratory
Ronald Scripsick*	Los Alamos National Laboratory

James Slawski*	National Nuclear Security Administration
Rodney B. Smith	BWXT Y-12
Wander ter Kuile*	Vokes BTR Environmental
Bhasker Tripathi	Science Applications International Corporation
Raymond Weidler*	Consultant; Past Chair, ASME Committee on Nuclear Air and Gas Treatment; ASME Board of Nuclear Codes of Standards
Roger Zavadoski*	Defense Nuclear Facilities Safety Board

** ASME Committee on Nuclear Air and Gas Treatment*

EDITORS

James W. Slawski

Jan K. Fretthold

Matt R. Hargan

Roger W. Zavadoski

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ACRONYMS, ABBREVIATIONS, AND CONVERSION CHARTS

ACGIH	American Conference of Governmental Industrial Hygienists
ACI	American Concrete Institute
ADC	Air Diffusion Council
ADL	Additional Dynamic Loads
AEC	U.S. Atomic Energy Commission (predecessor of ERDA, DOE, and NRC)
AFI	Air Filter Institute
AGS	American Glovebox Society
AgX	silver-exchanged zeolite
AHJ	Authority Having Jurisdiction
AISI	American Iron and Steel Institute
AISC	American Institute of Steel Construction
ALAP	as low as practicable (obsolete term for ALARA)
ALARA	as low as reasonably achievable
AMCA	Air Moving and Conditioning Association
AMD	aerodynamic mean diameter (of particles)
ANS	American Nuclear Society
ANSI	American National Standards Institute
APA	American Plywood Association
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AWS	American Welding Society
BET	Brunauer, Emmett, and Teller (test for surface area of adsorbents)
BWR	boiling water reactor
CAM	continuous air monitors
CBR	chemical, biological, and radiological (filter)
CFD	continuous fire detector
CFR	Code of Federal Regulations
CG	concentration guide
CH_3I	Methyl iodide
CONAGT	Committee on Nuclear Air and Gas Treatment (a subcommittee of ASME)
CRSI	Concrete Reinforced Steel Institute
CVS	Confinement Ventilation System
CWS	U.S. Army Chemical Warfare Service Laboratories
DAC	derived air concentration

DBA	design basis accident
DBE	design basis earthquake
DBS	deep-bed sand (filter)
DBGF	deep-bed glass fiber (filter)
DF	decontamination factor
DoD	Department of Defense
DOE	U.S. Department of Energy
DOP	dioctyl phthalate
DP	differential pressure
DNFSB	Defense Nuclear Facilities Safety Board
DPD	design pressure differential
DSA	Documented Safety Analysis (replaces the term SAR)
ECCS	Emergency Core Cooling System
EL	external loads
ERDA	Energy Research and Development Administration
ES	equipment specification
ESF	engineered safety feature
ESP	electrostatic Precipitator (prefilter)
FHA	Fire Hazard Analysis
FML	Fluid Momentum Loads
FRP	fiber-reinforced plastic
FTF	Filter Test Facility
GFRP	Glass-Fiber-Reinforced Plastic
HEMF	high-efficiency metal filter
HEPA	high-efficiency particulate air (filter)
HEPA-Vac	HEPA Vacuum Cleaning Systems/Units
HF	hydrogen fluoride
HFATS	High Flow Alternative Test System
HVAC	heating, ventilating, and air conditioning
HWESF	Hanford Waste Encapsulation and Storage Facility
IAEA	International Atomic Energy Agency
IBC	International Building Code
IEEE	Institute of Electrical and Electronic Engineers
IEST	Institute of Environmental Sciences and Technology
IPF	Iodine Protection Factor
KI	potassium iodide
Kr	Krypton
LANL	Los Alamos National Laboratory
LCO	limiting conditions for operation
LEL	lower explosive limit
LER	Licensee Event Report
LMD	light scattering mean diameter

LMFBR	liquid-metal fast breeder reactor
LOCA	loss-of-coolant accident
LWR	light water reactor
MCE	maximum considered earthquake
MCFL	Maximum Credible Fire Loss
MERV	Minimum Efficiency Reporting Value
MMD	mass median diameter (of particles)
MPC	maximum permissible concentration
MPFL	maximum possible fire loss
MPPS	Most Penetrating Particle Size
NACE	National Association of Corrosion Engineers
NBS	National Bureau of Standards
NCIG	Nuclear Construction Issues Group
NDRC	National Defense Research Council
NEC	Nuclear Air Cleaning Conference
NEMA	National Electrical Manufactures Association
NFPA	National Fire Protection Association
NIST	National Institutes of Science and Technology
NMD	number mean diameter (of particles)
NOPD	normal operating pressure differential
NPH	natural phenomena hazards
NQA	Nuclear Quality Assurance
NRC	U.S. Nuclear Regulatory Commission
NRL	U.S. Naval Research Laboratory
NRR	noise reduction rating
NSIC	Nuclear Safety Information Center
NSSS	Nuclear Steam Supply System
OBE	operating basis earthquake
ORFTF	Oak Ridge Filter Test Facility
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
PAO	Polyalphaolefin
PC	performance category
PEL	permissible exposure limit
PHFS	portable HEPA filtration system
PPE	personal protective equipment
PPH	Precipitation Hardening (grade of stainless steel)
PSHA	Probabilistic Seismic Hazard Analysis
PSL	Polystyrene Latex
PSS	Passive Safe Shutdown
PVC	polyvinyl chloride

PWR	pressurized water reactor
QA	quality assurance
QAS	quality assurance station
QC	quality control
QPL	qualified product list
RFETS	Rocky Flats Environmental Technology Site
RFFTF	Rocky Flats Filter Test Facility
RG	Regulatory Guide
RH	relative humidity
RPP	radiation protection program
RSCV	removable surface contamination value
RSIC	Reactor Shielding Information Center
RTP	Rapid-Transfer Port
RTV	room temperature vulcanizing
RWP	radiological work permit
SBMS	Standards Based Management Systems
SMACNA	Sheet Metal and Air Conditioning Contractors' National Association
SMP	Size of Maximum Penetration
SOP	standard operating procedure
SOPD	System Operating Pressure Differential
SRL	Savannah River Laboratory
SRP	Standard Review Plan
SRS	Savannah River Site
SSC	Structures, Systems, and Components
SSE	safe shutdown earthquake
SSPC	Steel Structures Painting Council (now the Society of Protective Coating)
TAPPI	Technical Association of the Pulp and Paper Industry
TEDA	triethylene diamine
TEFC	totally enclosed fan cooled
TLV	threshold limit value
TMI	Three Mile Island
TURF	Thorium-Uranium Recycle Facility
UL	Underwriters Laboratories, Inc.
ULPA	ultra low penetration air (filter)
VLSI	Very Large-Scale Integrated
VOC	volatile organic chemical
WESF	Waste Encapsulation and Storage Facility (Hanford B-Plant)
WWII	World War II
Xe	Xenon

UNITS OF MEASURE AND METRIC EQUIVALENTS USED IN THIS HANDBOOK

acfm	actual cubic feet per minute		
BTU	British thermal unit		
cfm	cubic feet per minute	x 0.000472 = m^3/sec	cubic meters per second
Ci	curies		
dBA	decibel A-weighted		
fpm	feet per minute	x 0.00508 = m/sec	meters per second
ft	feet	x 0.3048 = m	meters
ft^2	square feet	x 0.09290 = m^2	square meters
ft^3	cubic feet	x 28.32 = L	Liter
		x 0.02832 = m^3	cubic meters
gpm	gallons per minute		
Hz	Hertz		
in.	inch	x 2.54 = cm	centimeters
in.wc	inches water column		
in.wg	inches water gauge	x 0.24836 = kPa	kilopascals
kPa	kilopascals		
mCi	millicuries		
mm	millimeter, 0.001 inch		
m^3/hr	cubic meters per hour		
mmwg	millimeter water gauge		
m/s^2	meters per seconds squared		
pH	percent hydrogen (measure of acidity/alkalinity), power of the hydrogen ion		
ppm	parts per million		
psi	pounds per square inch		
psia	pounds per square inch absolute		
psig	pounds per square inch in gauge		
rem/hr	rems (roentgen equivalent man) per hour		
scfm	standard cubic feet per minute		
µCi	microcuries		
µg	micrograms		
µin	microinch		
µm	micrometer		
vpm	volume parts per million		

GLOSSARY

Absolute, AEC, or CWS Filter—Obsolete terms for HEPA filters.

Acceptance Test—A test made upon completion of fabrication, installation, repair, or modification of a system unit, component or part to verify to the user or owner that the item meets specified requirements.

Adsorber—A device for removing gases or vapors from air by means of preferential physical condensation and retention of molecules on a solid surface. Adsorbers used in nuclear applications are often impregnated with chemicals to increase their activity for organic radioactive iodine compounds.

Adsorber Cell—A modular replaceable adsorber element.

Aerosol—A dispersion of very small particles and/or droplets in air.

Air Cleaning Stage—An Air cleaning stage is a single component or a bank of identical components in an air cleaning unit or an air cleaning system. A system that has one bank of components (e.g., HEPA filters) in each of three air cleaning units, arranged in parallel, is a single stage system. A multistage unit or system has two or more stages in tandem.

Air Cleaning System—An air cleaning system is an assembly of one or more air cleaning units plus all external components needed to convey air or gases from one or more intake points, through the air cleaning units, to one or more points of discharge. The system may be either recirculating or once through.

Air Cleanup System—A system provided to decontaminate the air in, or exhausted from, a contained space following s system upset or prior to personnel access to the contained space.

Air Cleaning Unit—An air cleaning unit is an assembly of components, which comprises a single subdivision of a complete air cleaning system, including all components necessary to perform the air cleaning function of that subdivision.

ALARA—As Low As Reasonably Achievable. The design philosophy used to determine the need for, or extent of, air cleaning and off-gas facilities, based on their cost effectiveness in reducing adverse impact with respect to offsite and onsite dose criteria. Formerly known as ALAP.

Array—An array is the arrangement of internal components in a bank, expressed as the number of components across the width of a bank times the number high (e.g., a 4 by 3 array of HEPA filters).

Bag-in/Bag-out—A method of introducing and removing items from a contaminated enclosure that prevents the spread of contamination or opening of the contaminated space to the atmosphere through the use of plastic bagging material.

Blinding—Water vapor or droplets that interfere with particulate capture.

Case, Casing—The frame or cell sides of a modular filter element.

Clean-Air Device—A clean bench, clean workstation, downflow module, or other equipment designed to control air cleanness (particle count) in a localized working area and incorporating, as a minimum, a HEPA filter and a fan.

Clean Room—An occupied room designed to maintain a defined level of air cleanness under operating conditions; inlet and recirculated air is cleaned by HEPA filters.

Coating—Paint or other protective surface treatment applied by brushing, spraying, or dipping (does not include electro plating).

Combustible—A material that will ignite and burn in the form that it is used.

Combustible Liquid—A liquid with a high flash point, greater than 100 degrees F. The flash point is the temperature of the liquid above which vapors will be released that can be ignited by a flame source.

Component—A component is a filter, adsorber cell, fan, damper, or other basic element of an air cleaning system which cannot be disassembled without nullifying the capability of performing its designed task.

Confinement (contained volume)—A building, building space, room, cell, glovebox, or other enclosed volume in which air supply and exhaust are controlled, and typically filtered.

Confined Space—A space that: (1) is large enough and so configured that an employee can bodily enter and perform assigned work; (2) has limited or restricted means for entry or exit (e.g., tanks, vessels, silos, storage bins, hoppers, vaults, and pits); and (3) is not designed for continuous employee occupancy. Also, an enclosure that contains an oxygen deficiency, where oxygen concentration is less than 19.5 percent.

Containment (containment vessel or building)—A gastight enclosure around a nuclear reactor or other nuclear facility designed to prevent fission products from escaping to the atmosphere. Typically, when a containment vessel or building is exhausted, it occurs through an engineered filtration system.

Contamination—Any unwanted material in the air, in process fluids, or on surfaces. For the purposes of this handbook, contamination is usually assumed to be radioactive.

Contamination Zone—An isolable area which is, or which could become, contaminated and which is designed to facilitate decontamination.

Controlled Area—An area to which access is restricted.

Cover Gas—An inert gas, under pressure, provided in a contained space or process equipment item to prevent inleakage of air.

Criticality—The state of sustaining a chain reaction, as in a nuclear reactor. When fissionable materials are handled or processed, they must be kept in a subcritical geometry, configuration, or mass to avoid accidental criticality.

Critical System, Unit, or Item—One that is essential for adequate or safe operation, failure of which would cause loss of function.

Decay Heat—The heat produced by radioactive materials as nuclides spontaneously transform into other nuclides or into different energy states. Each decay process has a definite half-life.

Decontamination—The removal of unwanted substances from personnel, rooms, building surfaces, equipment, etc.

Decontamination Factor—A measure of air cleaning effectiveness; the ratio of the concentration of a contaminant in the untreated air or gas to the concentration in the treated air or gas.

Demister—A device designed to collect and divert moisture away from downstream filters (i.e., prefilters, HEPAs, and adsorbers). Demisters are installed in final filter plenums upstream of the first stage HEPA filters to prevent water damage to the filters.

Design Basis Accident (DBA)—The most serious accident that can be hypothesized from an adverse combination of equipment malfunction, operating errors, and other unforeseen causes.

Design Pressure—The pressure that is used for the structural design of a unit, component, or system, and which includes allowance for forces encountered under system upset conditions.

Monodisperse Aerosol—An aerosol generated by controlled vaporization and condensation of liquid test agent to give a cloud of droplets with diameters of approximately 0.3 micrometers.

Polydisperse Aerosol—An aerosol generated by blowing compressed air through liquid test agent and exhausting through special nozzles under controlled conditions to produce a cloud of droplets with a light-scattering mean diameter of approximately 0.7 micrometers.

Dose—The amount of ionizing radiation energy absorbed per unit mass of irradiated material at a specific location. In the human body, it is measured in Roentgen equivalent man (rems); in inanimate bodies, it is measured in radiation absorbed dose (rad).

Efficiency—Is defined as treated air concentration ÷ untreated air concentration x 100.

Enclosed Filter—A filter that is completely enclosed on all sides and both faces except for reduced end connections or nipples for direct connection into a duct system. Enclosed filters are installed individually because there is a separate run of duct to each filter unit.

Engineered Safety Feature (ESF)—A unit or system that is provided to directly mitigate the consequences of a DBA.

Extended-Medium Filter—A filter having a pleated medium or a medium in the form of bags, socks, or other shape to increase the surface area relative to the frontal area of the filter.

Face Guard—A screen, usually made from 4-mesh galvanized hardware cloth, permanently affixed to the face of a filter unit to protect it against damage caused by mishandling.

Face Shield—A screen or protective grille placed over a filter unit after it is installed to protect it from damage that might be caused from operations carried on in the vicinity of the filter.

Fail Safe—A design to give equipment the capability to fail without producing an unsafe condition.

Filter—A device having a porous or fibrous medium for removing suspended particles from air or gas that is passed through the medium.

Filter/Adsorber Bank—A parallel arrangement of filters/adsorbers on a common mounting frame installed within a single housing.

Final Filter—The last filter unit in a set of filters arranged in series.

Fire Resistance Rating—A term associated with the qualification of fire barriers. Fire barriers are tested to a standard fire exposure detailed in ASTM E-119, *Standard Method of Fire Tests of Building Construction and Materials.*

Flammable Liquid—A liquid with a low flashpoint, less than 100° F. These liquids are a greater fire hazard than combustible liquids, because they will readily burn at room temperature or below.

Flame Spread Rating—A term associated with the qualification of exposed interior finish materials. Materials are tested to determine their flame spread rating by a standard test in ASTM E-84, *Standard Test Method for Surface Burning Characteristics of Building Materials.*

Functional Design—The establishment of airflow rates, airflow capacities, types of components to be employed, general system layout, operational objectives and criteria, decontamination factors and rates, space allocations, and other overall features of a system.

Gallons per Minute (gpm)—This is a measurement of the quantity of water flowing through a pipe. The design specifications of water spray and sprinkler systems are based on the quantity of water flowing through the pipes and out of the nozzles.

Gas Chromatograph—An analytical instrument used for quantitative analysis of extremely small quantities of organic compounds whose operation is based upon the absorption and partitioning of a gaseous phase within a column of granular material.

Gas Residence Time—The calculated time that a contaminant or test agent theoretically remains in contact with an adsorbent, based on active volume of adsorbent and air or gas velocity through the adsorber bed.

High-Efficiency Particulate Air Filter or HEPA Filter—A throw-away extended-pleated-medium dry-type filter with: (1) a rigid casing enclosing the full depth of the pleats, (2) a minimum particle removal efficiency of 99.97 percent for particles with a diameter of 0.3 micrometers, and (3) a maximum pressure drop of 1.0 in.wg. or 1.3 in.wg. when clean and operated at its rated airflow capacity.

Hot cell—A heavily shielded and environmentally controlled enclosure in which radioactive materials can be handled remotely with manipulators and viewed through shielding windows to limit danger to operating personnel.

In-place Leakage Test—A system or bank test for leakage of filter units or charcoal adsorbers made after they are installed.

Ionizing Radiation—Any radiation (alpha, beta, or gamma) that directly or indirectly displaces electrons from the outer domains of atoms.

Isotope—One of several forms or nuclides of the same chemical element that have the same number of protons in the nucleus and therefore have the same chemical properties, but have differing numbers of neutrons and differing nuclear properties.

Leaktightness—The condition of a system unit or component where leakage through its pressure boundary is less than a specified maximum value at a specified pressure differential across the pressure boundary.

Lower Flammable Limit (LFL)—The least amount of a flammable vapor or gas that will support combustion when mixed with air. The LFL is usually expressed in volume per cent. Mixtures that contain less than the LFL of a material are too lean to burn.

Medium (plural, media)**—**The filtering material in a filter.

Mounting Frame—The structure to which a filter unit is clamped and sealed.

Noncombustible Materials—Materials that under ordinary conditions will not burn. Composite materials are determined to be noncombustible if they successfully pass the test criteria contained in ASTM E-136, *Test for Behavior of Materials in a Vertical Tube Furnace at 750 Degrees C*.

Nuclear Reactor—An apparatus in which a chain reaction of fissionable material is initiated and controlled.

Off-gas—The gaseous effluent from a process or operation.

Open-Face Filter—A filter with no restrictions over the ends or faces of the unit, as opposed to the enclosed filter with reduced-size end connections.

Operating Pressure—The desired pressure corresponding to any single condition of operation.

Overpressure—Pressure in excess of the design or operating pressure.

Particle, Particulate—A minute piece of solid matter having measurable dimensions.

Penetration—The measure of the quantity of a test agent that leaks through or around an air cleaning device when the device is tested with an agent of known characteristics under specified conditions.

Poison—Any material that tends to decrease the effectiveness of an adsorbent by occupying adsorption sites on the surface of the adsorbent or by reacting with the impregnants in the adsorbent.

Prefilter—Prefilters are throwaway type filters that are located upstream of HEPA filters. Prefilters are intended to collect and hold the larger airborne particles that are in the passing airstream. Prefilters are sometimes called roughing filters.

Production Test—Test made on each item or a sample of items or product from a production run to verify that the item meets specification requirements.

Permanent Single-Unit (PSU) Adsorber—An adsorber that is permanently installed in a system and that can be emptied of and refilled with adsorbent without removing it from the system.

Pyrophoric Material—Materials or compounds in a form that will ignite in air at a temperature of 150° C or below in the absence of external heat, shock, or friction.

Qualification/Proof of Design Test—A periodic test made on a product or equipment item when it is proposed as a candidate to meet certain service requirements, which will verify to the user or owner that the item can meet his requirements (see production test).

Rad—Radiation Absorbed Dose, the basic unit of ionizing radiation. One rad is equal to the absorption of 100 ergs of radiation energy per gram of matter.

Radiation—The propagation of energy through matter or space in the form of electromagnetic waves or fast-moving particles (alpha and beta particles, neutrons, etc).

Radioactivity—The spontaneous decay or disintegration of an unstable atomic nucleus accompanied by the emission of radiation.

Rated Airflow—The manufacturer's assigned design airflow capacity of a HEPA filter at a "not to exceed" designated clean filter resistance. With a media velocity limit of 5 feet per minute, the rated airflow is obtained by multiplying the filtration velocity of 5 feet per minute by the effective area of filter media.

Recirculation Air Cleanup System—An air cleaning system that recirculates the air of a contained space.

Redundant Unit or System—An additional and independent unit or system, which is capable of achieving the objectives of the basic system and is brought online in the event of failure of the basic system.

Rem—Roentgen Equivalent Man. The unit of absorbed radiation dose in rads multiplied by the relative biological effectiveness of the radiation.

Roughing Filter—A prefilter with high efficiency for large particles and fibers but low efficiency for small particles; usually of the panel type.

Safety-class Structures, Systems, and Components (SC SSCs)—Structures, systems, or components including portions of process systems, whose preventive and mitigative function is necessary to limit radioactive hazardous material exposure to the public, as determined from the safety analyses.

Safety-significant Structures, Systems, and Components (SC SSCs)—Structures, systems, and components which are not designed as safety-class SSCs but whose preventive or mitigative function is a major contributor to defense in depth and/or worker safety as determined from safety analyses.

Scrubber—A device in which the gas stream is brought into contact with a liquid so that undesirable components in the gas stream are removed by reacting with or dissolving in the liquid.

Separators—Corrugated foil (usually aluminum) used to separate the folds of a pleated filter medium and to provide air channels between them.

Service Environment—The aggregate of conditions (temperature, pressure, humidity, radioactivity, chemical contaminants, etc) to which the components of a system are exposed.

Shielding—A mass of absorbing material placed around a radioactive source to reduce ionizing radiation to levels.

Shock Overpressure—The pressure over and above atmospheric or operating pressure produced by a shock wave from an explosion, a suddenly closed damper, or other event.

Single-Component Air Cleaning Unit—A single-component air cleaning unit is one in which there is only one component (HEPA filter, prefilter, etc.) per stage, as opposed to a bank installation in which there are two or more components per stage.

Smoke Developed Rating—The numerical value assigned a material tested to the ASTM E-84 flame spread test method.

Specific Radioactivity—Radioactivity per unit weight of a material with an isotope.

Surveillance Test—A test made periodically to establish the current condition of a system, unit, component, or part.

Test Program—A formalized schedule of tests, which specify the test sequence, the procedures to be employed, and the acceptance criteria.

Train—A set of components arranged in series.

Treatment—The process of removing all or a part of one or more chemical components, particulate components, or radionuclides from an off-gas stream.

Ventilation System—The ventilation system includes the total facilities required to supply air to, circulate air within, and remove air from a building or building space by natural or by mechanical means.

CHAPTER 1

HISTORY OF THE DEVELOPMENT OF AIR CLEANING TECHNOLOGY IN THE NUCLEAR INDUSTRY

1.1 Brief History of Nuclear Aerosol Filtration

1.1.1 Early High-Efficiency Filter Paper Development for Military Gas Mask Use

In the early days of World War II, the British sent filter paper extracted from captured German gas mask canisters to the U.S. Army Chemical Warfare Service Laboratories (CWS) in Edgewood, Maryland.[1] The German filter paper was made of fine asbestos dispersed in esparto grass and had unusually high particle retention characteristics, acceptable resistance to airflow, good dust storage, and resistance to plugging from oil-type screening smokes (a deficiency of the resin-wool filters then used by the British forces). The CWS and the U.S. Naval Research Laboratory (NRL) reproduced the German-designed filter paper and had it manufactured in large quantities on conventional papermaking machinery by the Hollingsworth and Vose Company in Massachusetts. The first successful paper produced for the U.S. Navy contained Bolivian crocidolite and was called H-60. The paper produced for the U.S. Army also contained Bolivian crocidolite and was first designated H-64, but later renamed CWS Type 6. It was formulated from northern spruce sulfite and sulfate pulp (approximately 76 percent), cotton waste (approximately 15 percent), and Bolivian Blue crocidolite asbestos (approximately 14 percent). Penetration was 0.025-0.04 percent based on a methylene blue stain-intensity test procedure.[2]

The National Defense Research Council (NDRC), acting for the Armed Services, solicited the assistance of a number of university and industrial scientists in the search for better smoke filters. This effort resulted in important U.S. advances in the theory and technology of aerosol filtration. Up to this time, aerosol filtration theory had developed almost exclusively as an offshoot of water filtration knowledge. To meet then-current military requirements, however, researchers such as Nobel Laureate Irving Langmuir examined the physical basis for particle retention on fibers or small granules. Langmuir concluded that the principal mechanisms involved were: (1) interception, which affected suspended particles of sizes substantially greater than 1.0 micrometer (µm) in diameter when moving through a devious flow path in a bed of porous material; and (2) diffusion, which affected suspended particles with diameters substantially smaller than 1.0 µm.[3] His analysis, later modified by Ramskill and Anderson[4] to include inertia, indicated that the combined effects of these forces on a particle would be minimal when the particle was 0.3 µm in diameter. Langmuir advised testing gas mask filters with smoke of this particle size to determine their minimum retention efficiency and indicated that, when particles with diameters greater or smaller than 0.3 µm were present during field use of the gas mask, they would be removed at higher efficiencies than the test particles.

After the war, Victor LaMer[5] of Columbia University performed many experiments to further examine Langmuir's theory of a minimum filterable particle size, concluding that efficiency declined as particle size decreased below 0.3 µm. Other research results confirmed a minimum filterable particle size, but not necessarily a diameter of 0.3 µm. This is understandable, as subsequent studies showed that forces not taken into account by Langmuir (particle inertia, flow rate, naturally occurring electrostatic charges on particles and filter media) can also affect collection efficiency. However history may judge the accuracy of Langmuir's theory, it profoundly affected U.S. filter technology and directly led to LaMer and Sinclair's development of the filter test used by the NDRC from 1942 through 1945. This filter test became the standard U.S. method for rating ultra-high-efficiency (i.e., absolute) filters.[6] Before this standard, the U.S. Army Chemical Corps had been using a test aerosol generated from methylene blue dye (dispersed from a water solution and dried). In 1963, W. H. Walton[7] developed a sodium flame test to speed up testing of gas mask canisters because of the relative slowness of the methylene blue test procedure. This sodium flame test became the basis for the British standard test for high-efficiency filters.[8, 9]

1.1.2 Development of the High-Efficiency Particulate Air (HEPA) Filter

Protection against chemical warfare agents is required for operational headquarters, where wearing of an individual gas mask is impractical. To address this type of problem, the U.S. Army Chemical Corps developed a mechanical blower and air purifier known as a “collective protector” filter unit. Because relatively large air volume flow rates are required for effective use, the gas mask canister smoke filter (which uses CWS Type 6 filter paper) was refabricated into a filter constructed of deep pleats separated by a spacer panel and sealed into a rigid rectangular frame using rubber cement. The spaces between the teeth of the comb-shaped separators provided air passages to the depths of the pleats and were inserted front and back in alternate folds to direct contaminated air in and clean air out. The collective protector units were designed for use at the particulate removal stage by a combined chemical, biological, and radiological purification unit of the U.S. Armed Services. This development was highly fortunate, as later activities associated with the Manhattan Project created potential air pollution problems that could be solved only by using air filters with characteristics similar to those of the CWS filter. The U.S. Army Chemical Corps became the sole supplier of high-performance filters to the Manhattan Project, and later to the U.S. Atomic Energy Commission (AEC). In the late 1940s, the AEC adopted this type of filter to confine airborne radioactive particles in the exhaust ventilation systems of experimental reactors, as well as for most other areas of nuclear research. In this application, they were known as AEC filters or simply nuclear filters.

In recognition of their unusually high retention efficiency for very small particles, the U.S. Army Chemical Corps collective protector filters were also known as absolute, super-interception, and super-efficiency filters. The most widely used name, however, was HEPA filters, an acronym coined by Humphrey Gilbert, a former Manhattan Project safety engineer, from the title of a 1961 AEC report called *High-Efficiency Particulate Air Filter Units, Inspection, Handling, Installation*.[10] A HEPA filter was defined as a throwaway, extended-medium, dry-type filter with: (1) a minimum particle removal efficiency of 99.95 percent (later raised to 99.97 percent) for a 0.3-µm monodisperse particle cloud; (2) a maximum resistance (when clean) of 1 inches water gauge (in.wg) when operated at rated airflow capacity; and (3) a rigid frame [now called “casing” in American Society of Mechanical Engineers (ASME) AG-1, *Code On Nuclear Air and Gas Treatment*].[11] extending the full depth of the medium (see **Figure 1.1**). HEPA filters have proven to be extraordinarily effective, reliable, and economical devices for removing radioactive and nonradioactive submicrometer-sized particles at a high rate of collection efficiency.

1.1.3 Early Nuclear Filter Developments in the United States

The U.S. Government was disturbed by the fact that components of the filter medium used in the CWS filters [Bolivian or African crocidolite (Blue Bolivian asbestos) and African esparto grass] had to be imported and could be difficult to obtain. After a variety of domestic cellulose fibers (yucca, Kraft, viscose) were used successfully by the NRL and the Hollingsworth and Vose Company as a replacement for esparto in trial runs, the AEC contracted Arthur D. Little, Inc. to develop a paper with equal or better filtration performance characteristics that could be manufactured entirely from fibers obtainable on the North American continent. Their investigations led them to examine coarse glass fibers as a substitute for cellulose, Canadian asbestos as a substitute for Bolivian Blue, and resin-stiffened, corrugated Kraft paper separators as a substitute for the comb-like separators in the CWS filter that had proved to be a significant obstruction to airflow.[12] The search for domestic sources of filter materials concluded successfully in 1951 with the development (partly sponsored by the NRL) of an all-glass-fiber paper made partly from super-fine glass fibers with diameters substantially less than 1.0 µm. As the domestic industry was able to produce unlimited quantities of glass

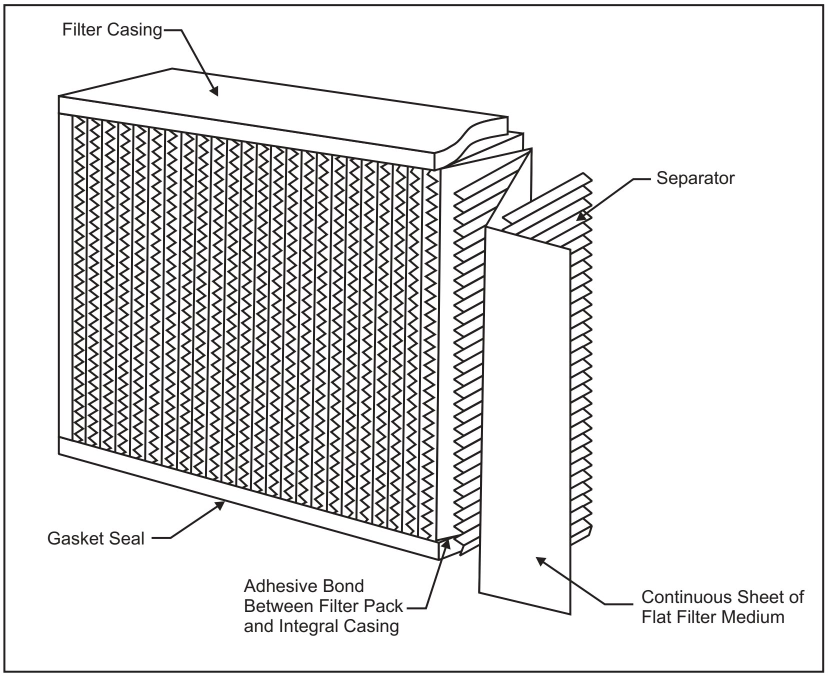

Figure 1.1 – HEPA Filter Design

fibers as small as 0.25 µm, asbestos was no longer needed. Abandonment of asbestos, which is difficult to disperse, allowed much greater control of manufacturing procedures and production of better, more uniform papers.

Because inclusion of some asbestos fibers in absolute (HEPA) filter papers containing glass fiber increases resistance to hydrogen fluoride and results in a slight cost reduction, some use of asbestos continued for a number of years after it was known that the papers could be made without asbestos. International concern about the toxic properties of inhaled asbestos fibers ultimately resulted in total abandonment of the commercial use of asbestos-containing filter papers, as well as the use of corrugated asbestos paper for separators. Other materials were found that provided both improved resistance to chemical attack and fire resistance. Fires at the AEC's Rocky Flats Plant and in the Windscale graphite-moderated, air-cooled reactor in 1957 revealed the need for noncombustible effluent filters. The ability to make all-glass-fiber paper was a step in the right direction; but the separators, frames, and rubber cement used to seal the filter packs into the frames were all combustible. To overcome this problem, Arthur D. Little, Inc. was asked to develop a noncombustible absolute filter.[13] They designed a prototype filter constructed from the glass-fiber filter paper prepared by NRL, corrugated asbestos paper separators stiffened by a water glass treatment, a perforated steel frame, and a refractory furnace cement for sealing the filter pack to the steel frame. The filter was completely fire-resistant, but it was heavy and the refractory furnace cement adhesive made the filter paper brittle, produced air leaks, and created a distressing tendency for the filter pack to separate from the steel frame. This filter assembly became obsolete after high chlorine- or bromine-content, self-extinguishing, flexible organic adhesives were introduced and Arthur D. Little, Inc. developed a fiber blanket seal that was compressed between the filter pack and metal frame.

The Hurlbut Paper Company and the Hollingsworth and Vose Company produced an air filter paper in the mid-1950s that was made from Fiberfrax fibers produced by the Carborundum Corporation. The Fiberfrax fibers were comprised of silicon oxide-aluminum hydroxide and could withstand temperatures up to 2,000 degrees Fahrenheit for long periods and in excess of 3,000 degrees Fahrenheit for shorter periods. Using this filter paper combined with loose Fiberfrax fibers of various grades, Flanders Filters, Inc., fabricated an all-ceramic filter (i.e., Fiberfrax paper, separators, filter-frame, and sealant) that was capable of performing satisfactorily at temperatures in excess of 2,000 degrees Fahrenheit and had extraordinary resistance to heat shock.[14] However, it proved impossible to produce Fiberfrax fibers fine enough to provide filter efficiencies equal to those available with all-glass-fiber papers, and interest in Fiberfrax filters waned.

1.1.4 Commercial Development

After development of the absolute filter by Arthur D. Little Company, a manufacturing capability was installed at the Army Chemical Center in Edgewood, Maryland. Arthur D. Little also started the first commercial filter manufacturing company, the Cambridge Filter Company, which they sold shortly thereafter when they decided to restrict their efforts to research.

By 1957, three firms were fabricating absolute filters. Following allegations that defective filters were being delivered to its facilities, the AEC requested that sample filters from each of the three filter manufacturers be removed from AEC facility stocks and sent to Edgewood for inspection and testing. Seven of the 12 filters received by Edgewood had obvious defects upon removal from their shipping cartons.[15] AEC facilities were advised to open and inspect the filters held in their stocks, and facility responses indicated a similar proportion of defects.

Based on these findings, the AEC initiated quality assurance (QA) inspection and testing of filter deliveries; installation of a test facility at Richland, Washington; and an agreement for QA testing by Edgewood for the eastern half of the United States. Oak Ridge, Tennessee, replaced Edgewood after installation of testing equipment there in 1964. A QA facility was activated at the Rocky Flats Plant in Golden, Colorado, in 1970. Facilities at both the Rocky Flats and Richland sites have been decommissioned and dismantled.

A Government-Industry Filter Committee was established at about this same time with voluntary participation from representatives of filter manufacturers, filter medium makers, the sole supplier of glass fibers, users, and Government agencies and organizations, including the Army Chemical Center and the NRL. Discussion sessions were held before the biennial AEC Air Cleaning Conferences, and working sessions were convened at the Underwriters Laboratories (UL) in Chicago, Illinois. Topics ranged from the aging of glass fibers to the integrity of shipping cartons. The Committee provided guidance to the Army Chemical Center concerning military standards for fire-resistant filters and its glass fiber filter medium, and also advised UL in establishing their UL-586 standard for filter heat resistance.[16] The Committee was also responsible for considerable technology exchange (in view of the relative newness of the glass fiber filter medium and the undeveloped technology for its fabrication into filters).

1.1.5 Development of HEPA Filter Standards

With the Army's issue of Military Specifications MIL-F-51068, *Filter, Particulates, High-Efficiency, Fire-Resistant*,[17] for the fire-resistant filter and MIL-F-51079, *Filter Medium, Fire-Resistant, High-Efficiency*,[18] for the glass fiber medium in the early 1960s, Edgewood abandoned its manufacture of the cellulose-asbestos filter and turned to commercial procurement. These standards documents remained in service until 1994, when due to changing requirements, the availability of new materials, improved instrumentation, advanced technology, and a U.S. Department of Defense emphasis on consensus standards, the U.S. Army announced it would no longer maintain MIL-F-51068 and MIL-F-51079 in active status. Both of these military standards were incorporated into ASME AG-1,[11] Section FC, which is administered by the Committee on Nuclear Air and Gas Treatment (CONAGT). Improvements were incorporated into the standards with the concurrence of the other military services and the U.S. Nuclear Regulatory Commission (NRC).

The HEPA filter design used by the U.S. nuclear industry is nearly identical to the one used in the United Kingdom and has been the mainstay of the nuclear industry for the past 5 decades. Additional progress was made in documenting and codifying standards for filter installation and testing with the AEC's issuance of the original Regulatory Guide 1.52, *Design, Testing and Maintenance Criteria for Engineered-Safety-Feature Atmospheric Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Reactors*,[19] in 1973. [Unknown to most, Mr. Humphrey Gilbert, mentioned in Section 1.1.2, and Dr. Roger Zavadoski were the primary authors of this Regulatory Guide.] Further progress was made with the American National Standards Institute's issuance of ANSI N509, *Nuclear Power Plant Air Cleaning Units and Components*,[20] and ANSI N510, *Testing of Nuclear Air Cleaning Systems*.[21] Although these two standards were intended to apply only to the construction and testing of engineered safety systems in U.S. civilian nuclear power plants, the major part of each standard can be and often has been applied with salutary results to air cleaning systems in all manner of nuclear facilities in the United States (including DOE facilities) and abroad. CONAGT has transferred many sections of the former ASME N509[22] and N510[23] into ASME AG-1.[11] The contents of the early editions of these two standards were substantially incorporated into NRC Regulatory Guide 1.52, Revision 1, *Design, Testing, and Maintenance Criteria for Engineered Safety Feature Atmospheric Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants*.[24] Some standard-setting agencies in other countries with a significant nuclear power establishment have prepared and issued similar standards that differ only in details. The principal modification to the military standards since 1968 focused on requirements for filter medium resistance to radiation (for prolonged filter effectiveness following a core-disruptive accident). For procurement ease, the military service (Edgewood Arsenal) qualified HEPA filter paper and assembled filters manufactured by a number of producers and published their names in a Qualified Products List (QPL).[25]

Table 1.1 lists important developments relating to filtration and the year of development.

Table 1.1 – Summary of Important Dates for Nuclear Air Cleaning Filtration

Year	*Publications/Actions*
1950	MIL-STD-282, *Filter Units, Protective Clothing, Gas-Mask Components and Related Products: Performance Test Methods*
1950	Stack Gas Committee
1950s	Arthur D. Little Co., *Fire Resistant Media*
1957	Air Cleaning Conference, "Filter Quality Problems"
1959	Air Cleaning Conference, "Filters Sent to Edgewood"
1959	Government/Industry Safety Committee
1959	UL-586, *High Efficiency, Particulate, Air Filter Units*
1961	High Efficiency Particulate Air Filter Units, TID 7023, Gilbert and Palmer
1962	Hanford (AEC/DOE) Filter Test Facility
1962	MIL-F-51068, *Filter, Particulates, High-Efficiency, Fire-Resistant*
1963	MIL-F-51079, Filter Medium, Fire-Resistant, High-Efficiency
1963	Flanders Inc. - Filter Media Production
1966	ORNL/NSIC-13, *Filters, Sorbets and Air Cleaning Systems as Engineered Safeguards in Nuclear Installations (Nuclear Air Cleaning Handbook*, 1st Edition)
1968	AACC CS-IT HEPA FILTER (IES), *Tentative Standard for HEPA Filters*
1968	ASHRAE 52.68, *Method of Testing Air Cleaning Devices Used in General Ventilation for Removing Particulate Matter*
1969	ORNL/NSIC-65, *Nuclear Air Cleaning Handbook*, 2nd Edition
1971	ANSI N-45.2, *Requirements for Quality Assurance Programs for Nuclear Power Plants*
1971	ANSI N-45.8 CONHET
1972	Flanders Inc. - Manufactures Glass F-700 Media
1973	REGULATORY GUIDE 1.52, *Design, Testing, and Maintenance Criteria for Engineered Safety Feature Atmospheric Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants*
1973	REGULATORY GUIDE 3.12, *General Design Guide for Ventilation Systems of Plutonium Processing and Fuel Fabrication Plants*
1975	ANSI N510, *Testing of Nuclear Air Treatment Systems*
1976	ASME CONHET
1976	ANSI/ASME N509, *Nuclear Power Plant Air Cleaning Units*
1976	ERDA 76-21, *Nuclear Air Cleaning Handbook*, 3rd Edition
1978	Flanders Inc. – Manufactures Last Glass/Asbestos Media

Year	***Publications/Actions***
1979	REGULATORY GUIDE 1.140, *Design, Inspection and Testing Criteria Air Filtration and Adsorption Units of Normal Atmosphere Cleanup Systems in Light-Water-Cooled Nuclear Power Plants*
1978	NE F3-41T, *In-Place Testing of HEPA Filter Systems by Single-Particle, Particle-Size Spectrometer Method*
1980	Flanders Inc. – Manufactures Last Asbestos Separators
1984	DOE HEPA FILTER/TEST STANDARDS NE F3-43, -44, -45, Nuclear Standards, *Nuclear Standard Quality Assurance Testing of HEPA Filters, DOE Filter Test Facilities Quality Program Plan,* and *Specifications for HEPA Filters Used by DOE Contractors*
1984	NE F3-42, Nuclear Standard, *Operating Policy of DOE Filter Test Program*
1984	ASME AG-1, *Code on Nuclear Air and Gas Treatment,* 1st Edition
1993	ASTM-F-1471-93, *Standard Test Method for Air Cleaning Performance for HEPA Filter Systems*
1997	DOE-STD-3020-97, Replaced NE F 3-45 HEPA Filter Standard, *Specification for HEPA Filters Used by DOE Contractors*
1999	ASHRAE 52.2, *Method of Testing General Ventilation Air Cleaning Devices for Removal Efficiency by Particle Size*
2003	ASME AG-1, *Code on Nuclear Air and Gas Treatment,* Update
2003	*Nuclear Air Cleaning Handbook*, 4th Edition

1.1.6 Further Development of the HEPA Filter

Thin, corrugated aluminum-alloy separators completely replaced asbestos, thermoplastics, and resin-treated Kraft paper to assure fire-resistance. Stainless steel is often selected because of its resistance to severe chemical attack, but aluminum-coated plastic is satisfactory for less corrosive service. Improved resistance to wetting, an issue of major importance for engineered safety system filters in water-cooled reactors, was developed by applying water-repellent chemicals to the filter paper. For such applications, it has become standard practice to install the filters with the paper folds in the vertical position so that any water droplets captured on the surface of the paper will drain to the bottom of the filter.

1.1.7 Introduction of HEPA Filters for Treating Reactor Effluent Gases

The first nuclear reactor fitted with effluent high-efficiency air filters is believed to have been the graphite-moderated, air-cooled unit at Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. The initiating event was the discovery in 1948 of radioactive particles up to 600 µm in size on the ground around the reactor stack. A reinforced concrete filter house capable of handling 140,000 cubic feet per minute (cfm) of air at a temperature of 215 degrees Fahrenheit and a negative pressure of 50 inches water gauge (in.wg) was constructed to prevent further emissions.[26] This was also one of the first installations to use prefilters to extend the life of absolute filters as a means of reducing air cleaning costs. The filtration system contained 1-inch-deep resin-bonded fiberglass prefilters that removed the coarsest dust fraction, followed by 24 inches × 24 inches × 11 1/2 inches Army Chemical Corps cellulose-asbestos (later designated AEC No. 1) units in plywood frames. Design efficiency was 99.9 percent for particles down to 0.1 µm. The high-efficiency filters were changed when airflow resistance increased from 1 in.wg to 5 in.wg over a period of about 2 1/2 years. It was found that the service life of the absolute filters could be extended to more than 2 years by changing the prefilters two to three times per year. Although there have been situations where a cost analysis has failed to show an advantage from using prefilters, most installations seem to benefit from using cheaper prefilters. Interest in the use of metal prefilters continues because, in addition to coarse particle filtration, they provide fire and blast protection by acting as baffles and fire screens.

1.1.8 HEPA Filter Quality Assurance

During the 1960s, major efforts in the United States were directed toward standardizing manufacturing and test criteria for paper and fabricated filters, with special emphasis on fire and water resistance. Manufacturer testing of each individual filter for collection efficiency and airflow resistance has always been a unique requirement for filters intended for use in nuclear service. The results of each test are noted on the filter frame to ensure the filter meets the requirements of applicable standards. Initially, the efficiency standard for 0.3-µm test aerosols was 99.95 percent, but it was raised to 99.97 percent after commercial filter manufacturers found ways of improving their materials and assembly techniques to a degree that enabled them to turn out filters exceeding the required particle retention efficiency by more than an order of magnitude. These new filters also featured improved resistance to corrosive chemicals, fire, and radiation.

Similar filter efficiency standards were developed in Great Britain (using a nebulized salt aerosol),[8] France (using a nebulized uranine aerosol),[27] and Germany (using a paraffin oil aerosol).[28] Because of differences in measuring filter efficiencies, considerable effort has been expended (with indifferent success) on laboratory studies to develop conversion factors that would translate the filter efficiency measurements made by one method to equivalent values derived using a different measurement method.[29] It would be convenient if everyone used the same filter test method, but this is unlikely in the foreseeable future.

The wide diversity of aerosols generated in the nuclear industry raises an important question regarding the relevance of the qualification test procedures utilized. For example, the aerosols predicted to be present inside the confinement vessel of a power reactor following a loss-of-coolant accident (LOCA) are certain to be very different from the test aerosols and efficiencies observed during the standardized qualification tests and are not necessarily the results that will be obtained in practice. They may be better or worse, depending on the characteristics of the aerosol challenge. However, passing a standardized qualification test gives reasonable assurance that the filters have been produced from high-quality components and carefully assembled to exacting standards. Therefore, the standard qualification test results should be viewed as an index of merit (an indication of quality) rather than a quantitative description of filter efficiency under unknown or ill-defined operating conditions.

Nevertheless, about 1990, the U.S. Department of Energy (DOE) undertook a program designed to define HEPA filter efficiency more precisely. This involved the use of an intercavity laser particle size spectrometer capable of counting and sizing aerosol particles down to approximately 0.08 µm under careful laboratory manipulation. The impetus for this program was the discovery that the monodisperse 0.3-µm test aerosol (when defined using methods developed during the 1940s) was neither monodisperse nor always 0.3 µm.[29] Filter efficiency studies conducted at Los Alamos National Laboratory produced the following results:

- The most penetrating particle size for all-glass-paper HEPA filters operated at the design airflow rate is close to 0.1 µm.
- A new HEPA filter acceptance standard was developed that used a polydisperse aerosol, but this method counted only 0.1-µm particles upstream and downstream of the filter to rate particle retention efficiency.[30]
- Programs were conducted at DOE filter test stations to improve the characteristics of the aerosol used for routine filter testing (e.g., making the test aerosol more uniform in size and closer to an average size of 0.3 µm).

To a significant degree, the establishment of AEC QA filter test stations in 1960 made it imperative for filter manufacturers to institute their own rigid quality control practices to avoid product rejection. For example, 49 percent of filters manufactured prior to 1960 were rejected, whereas only 5 percent were rejected during the following 8 years.[30] By 1978, the rejection rate had declined to a point where the NRC was willing to forego QA filter test station inspection of filters intended for use in engineered safety feature (ESF) systems in commercial nuclear power plants. The basis for this decision was that the marginal increase in the reliability of tested filters no longer justified the additional cost. It should be noted that commercial ESF system filters are usually in a standby mode, in a clean system, and assigned minimal removal efficiencies (relative to DOE facilities) in their safety basis. DOE continues to require the use of a filter test station because contaminated processes continuously challenge DOE filter systems.

Only one DOE QA filter test station, now called the Filter Test Facility (FTF), is currently operating. The rejection rate of filters tested there has been as high as 18.7 percent and as low as 1.6 percent in recent years. The rejection rate continues to fluctuate, indicating that the FTF is still necessary. The Secretary of Energy mandated continued use of the FTF in 2001.

Considering the large number of specifications, requirements, and standards that have been proposed and adopted for HEPA filters, it is clear they are among the most extensively and thoroughly documented devices in the entire air filtration spectrum.

1.1.9 HEPA Filter Application Assurance

In spite of the many improvements in absolute (HEPA) filters, it was discovered as early as the initial installation of HEPA filters at the ORNL graphite reactor that the full capabilities of improved filter performance were not always achieved due to damage during shipment or faulty installation. Consequently, it has become routine to conduct in-place testing of all filter installations using methods initiated and developed at ORNL prior to startup of new facilities and periodically thereafter. A great deal has been learned about the correct design of filter housings and filter installation methods from in-place testing. For example, considerable difficulty was experienced in conducting tests at old installations due to lack of easy access to the filter structures. It became clear that suitable facilities for in-place filter testing must be designed into all new systems as part of the construction specifications.

The value and effectiveness of correctly designed and installed nuclear-grade aerosol filtration systems are illustrated by the very different events that took place at the Three Mile Island-2 (TMI-2) and Chernobyl reactors. During the March 1979 LOCA at TMI-2, two 30,000 CFM filter systems prevented essentially all of the particulate material and the bulk of the radioiodine released to the Auxiliary Building from being released to the environment.[31] Consequently, release of radioactive particles to the environment was negligible. The outcome was very different, however, during the April 1986 fire at Chernobyl Unit 4, where engineered safeguards did not include complete confinement with air filtration systems. The widespread apprehension caused by that accident is likely to produce a demand for still higher collection efficiency and greater filter resistance to internal disruptive events (fires, explosions) and to external natural disasters (earthquakes, tornadoes). Germany[32] and the United States[32] have responded to this by developing filters composed of stainless steel fibers.

1.1.10 Increasing Airflow Capacity of HEPA Filters

Although British filter construction methods and materials closely paralleled American ones, manufacturers in other European countries developed a different HEPA filter design that is now produced by some U.S. manufacturers. Instead of filter paper pleats that extend the full depth of the filter frame, the paper is folded into mini-pleats about 20-millimeters (mm) deep with a pitch of 3 mm. Adjacent pleats are separated by ribbons or threads of glass, foam, or plastic. A full-size filter is assembled from several component panels of this construction and arranged around a series of V-shaped air passages. This design allows considerably more filter paper to be incorporated into a given volume, making it possible to replace a standard 24 inch $\times$ 24 inch $\times$ 11 1/2 inch U.S. filter unit with one of identical dimensions that: (1) can handle volumes up to 1,900 CFM instead of 1,000 CFM at a clean filter resistance of 1 in.wg, and (2) can meet the maximum test aerosol penetration standard of 0.03 percent at the higher volumetric flow rate.

A U.S. manufacturer has fabricated a different filter that does not use separators. The corrugations are made by vacuum-molding the wet filter paper onto narrow longitudinal ridges while it is still on the paper-making machine, then accordion-pleating the paper as it comes off the machine.[33] The preformed corrugations are impressed into the paper at a slight angle to the run of the sheet so that, when folded, the pleats in alternate layers resist nesting. A later development of this process is to impress dimples into the forming paper so that, when folded, the dimples prevent alternate paper layers from touching each other. This filter construction method is different from the one used for the older mini-pleat filters in that the filter pack is mounted into the filter frame in the usual way (i.e., perpendicular to the direction of airflow) rather than as a number of 20-mm-deep panels arranged inside the filter frame in a series of V-formations. A 6-inch-deep mini-pleat filter without separators contains the same area of filter paper as the 12-inch-deep separator type. This filter has been placed into service, but there is no experience to report concerning nuclear applications.

1.1.11 Disposal of Spent Filters

It costs more to dispose of a contaminated spent filter than its initial purchase price, which reflects the difficulties associated with handling contaminated wastes and the shrinking number of authorized disposal sites. During the early years of the nuclear age (when HEPA filters were constructed with wooden frames, corrugated separators, heavy Kraft paper, cellulose-containing filter paper, and conventional rubber cement), high-temperature incineration resulted in a 99 percent reduction in bulk. At the time, this was considered the best way to handle used filters, and a number of incinerators were constructed and used to reduce the bulk of all combustible contaminated wastes, including spent filters. However, the incinerators quickly became contaminated and proved difficult to safely operate and repair. To protect the environment, HEPA filters were installed as the final flue gas cleaning element, but they proved to have a short life in incinerator service. In addition, processing the spent flue gas filters through the same incinerator they were installed to serve greatly increased the burden on the incinerator, thereby reducing productive throughput and elevating costs.

During the 1960s, as a result of the introduction of noncombustible elements into the structure of HEPA filters intended for nuclear service and the introduction of heavy presses designed to crush HEPA filters into a small volume for ground burial at little cost, outmoded high-temperature volume reduction incinerators were shut down and dismantled. Where recovery of transuranic elements from spent filters remained a requirement, devices were developed to extract only the filter paper from the frame for chemical or high-temperature treatment. The remainder of the filter was disposed of by crushing and burial.

The rapidly escalating cost of land disposal for radioactive wastes, in addition to new requirements for corrosion- and leak-proof containers that substantially increase the bulk of the waste package, have combined to renew interest in volume reduction of wood frame filters by high-temperature incineration in spite of an obvious incompatibility between the need for noncombustible filters and the need to minimize disposal costs via high-temperature volume reduction. Exclusive use of HEPA filters without separators help reduce the residue from incineration. When using metal frames and corrugated aluminum separators, alternatives include punching out the filter pack in a high-pressure press for volume reduction and decontaminating the metal parts via chemical treatment. Incineration of contaminated HEPA filters continues to present formidable operating difficulties and high costs. Additional difficulties are experienced when the substances collected on filters are classified as both hazardous chemical and radioactive wastes.

1.2 Deep-Bed Sand and Glass Fiber Filters

Although HEPA filters came to dominate aerosol confinement for most nuclear applications, from the beginning there were other filter innovations of note. When a high-activity level was detected at the Hanford, Washington, site in 1948 and traced to radioactive particles emitted from the chemical processing ventilation stacks, the chemical engineering practice of using deep beds of graded granular coke to collect mists escaping from contact sulfuric acid plants was recalled, and a number of large sand filters were constructed during the late 1940s and early 1950s at both the Hanford and Savannah River Sites (SRS).[34] The sand filter construction closely followed the deep-bed (40- to 120-inch deep), graded-granule techniques for building granular filters that were widely accepted at sulfuric acid manufacturing plants and for the purification of municipal drinking water supplies. These filters had collection efficiencies for particles greater than 0.5 µm that compared favorably with the best fibrous filters then available. They operated at a superficial face velocity of 6 feet per minute, an initial pressure drop of 8 in.wg, and an activity reduction of 99.7 percent. Additional units were later built at SRS, and each has given many years of continuous service. Such deep-bed sand (DBS) filters offer several advantages. They offer a higher design airflow resistance and lower retention efficiency than may be obtained using absolute filters. They also are nonflammable and largely unaffected by condensed water and strong acids. In addition, they provide a substantial heat sink in the event of fire or explosion. Freedom from servicing and replacement over many years is another important advantage when the collected material is intensely radioactive. DBS filters are not completely maintenance-free, however. Collapsed laterals have led to replacement of tons of sand and increased surveillance. The disadvantages of DBS filters are that they are large, expensive to operate and build, and nondisposable.

Rapidly emerging glass fiber technology during the 1940s and 1950s shifted attention to the use of very deep beds (10 inches or more) of curly glass fibers in combination with HEPA-quality final filters as a satisfactory substitute for sand filters when treating gaseous effluents from chemical operations.[34] These proved to be more efficient and to have lower airflow resistance than the sand filters they replaced. Deep-bed glass fiber filters have been used at Hanford for several decades on the Purex process effluent stream, and a similar installation is in place at DOE's Idaho Chemical Plant. They also have withstood the buildup and mitigation of potentially explosive nitrates.

There has been interest in sand filters for emergency confinement venting for light water reactors. An installed Swedish confinement venting system known as FILTRA features large concrete silos filled with crushed rock. These silos were designed to condense and filter steam blown from the confinement and to retain at least 99.9 percent of the core inventory.[35] Later designs for confinement venting utilized wet systems to remove gaseous radioiodine.

1.3 Brief History of Gas Adsorption

[Note: The following discussion concerns adsorbers used to capture gaseous and volatile fission products and is included as history only. Adsorbers are commonly used for iodine removal in commercial nuclear power plants (see AG-1[11] for more information). Current DOE nuclear applications predominantly rely on HEPA filters rather than adsorbers. However, references to adsorbers will be found in nearly each chapter.]

1.3.1 Introduction

Iodine in its many chemical forms is probably among the most extensively studied fission products produced in the nuclear industry. The generation, release mechanism, properties, forms, trapping and retention behavior, and health effects of iodine-131 have been the subject of numerous studies, but a comprehensive understanding of the significance of its release to the environment and integration of the chemical technology into protection technology may remain incomplete in some aspects. The technology associated with the removal and retention of all iodine isotopes is similar to that for iodine-131, but interest in removal efficiency has shifted somewhat toward the importance of long-term retention with the increasing half-life of the iodine isotope.

A removal technology for the radioactive noble gases (krypton, xenon, and radon) using adsorbents also has been studied extensively. This removal technology has become a standard control method for boiling water reactor (BWR) offgas decontamination and has replaced pressurized tank retention for pressurized water reactor (PWR) offgas control. A similar technology can be used to hold up the relatively long-lived krypton-85 contained in reprocessing offgases.

Volatile metal compounds such as ruthenium and technetium can be removed from gas streams by adsorption, but a solid-surface-supported chemical reaction is often necessary for good retention. Removal technologies for carbon-14 and tritium also involve the use of adsorbents, either as collecting agents or as catalysts for conversion to other, more easily removed compounds.

Vapor recovery by adsorption was a well-established chemical engineering unit operation process prior to nuclear technology development for weapons and power production. Generally, vapor recovery systems utilized beds of activated carbon that were 24 inches deep or more and often consisted of two or more identical units in parallel, so that one could be onstream while a second was being desorbed by low-pressure steam and a possible third was undergoing cooling after steam desorption. These multi-bed arrangements enabled continuous operation of vapor production processes.

Adsorbents of various types, both impregnated and unimpregnated, became widely used during and following World War I (WWI) in military and civilian gas mask canisters and cassettes for removing a wide range of toxic substances from breathing air. Activated carbon derived from nut shells was used in the U.S. Army service gas mask during WWI. Later, the activated carbon used in the service gas mask was derived from coal and impregnated with metals that catalyze reactions with gas warfare agents. Activated carbon also was used to treat ventilation air in special applications such as removing sulfur dioxide and ozone from air supplied to libraries housing rare book collections to prevent paper embrittlement. Ventilation applications used shallow beds of activated carbon, generally 1 inch or less, because complete removal of outdoor contaminants was seldom a requirement and low airflow resistance was essential to prevent unacceptable fan noise levels. The theoretical basis for adsorption processes was greatly advanced by the need to develop gas mask applications during WWI, and Langmuir made an early theoretical analysis of physical adsorption. Thus, there was a considerable body of knowledge available on the application of adsorbents, especially for activated carbon, when the nuclear industry developed a need for this technology.

Control of iodine emissions from chemical processing of spent nuclear fuel was initially done by liquid scrubbing using caustic solutions, and sometimes with the addition of sulfate salts, but retention efficiency by scrubbing seldom exceeded 90 percent. To improve iodine retention efficiency for dissolver offgas cleaning, activated carbon beds were added to the caustic scrubber at DOE's Idaho Chemical Plant in 1958, where they were reported to provide additional decontamination factors of 10 to 30. Silver-plated Fiberfrax fibers also were investigated at the Idaho Test Station for use as a combined particulate filter and iodine retention device for hot calciner offgas cleaning. Other studies of this nature were conducted with silver-plated copper filaments, and an iodine decontamination factor of 10 was reported.

Iodine releases to the atmosphere in the event of a reactor accident became a major concern as the nuclear industry began its rapid expansion during the early 1960s, and attention focused on iodine removal during normal and abnormal conditions at ambient and elevated temperatures. An iodine decontamination factor of 10 was reported. At ORNL, studies were conducted on activated carbon beds for the holdup of radioactive fission gases generated during the operation of nuclear reactors and during nuclear fuel reprocessing. The principal area of interest was delaying release until short-half-life isotopes decayed to levels that were acceptable for release. This approach utilized conventional theoretical plate equations.

The application of adsorbents for noble gas retention was developed at ORNL. The concept involves self-regeneration of the adsorbent due to decay of the noble gases to solid daughter products as they pass through very deep adsorbent beds that require a long time for passage and results in the successive extinction of noble gas radioisotopes (i.e., those with the shortest half-lives disappear first). This technology is generally used to decontaminate all noble gas isotopes (except krypton-85 because of its relatively long half-life—nearly 11 years). The process is particularly well suited to treat BWR offgas streams and was applied first at the KRB site in Germany. The first BWR installation in the United States was the Interim Offgas System at the Vermont Yankee Plant. It was succeeded by the Advanced Offgas System at the same site. Earlier technology involved ambient temperature systems. Cooled or refrigerated systems were later designed by the General Electric Company.

Storage tanks were used for PWR degasifier gas processing at first, but a continuous-flow adsorption system was installed at the Seabrook nuclear power plant, the first for a U.S. PWR. Design parameters for noble gas adsorption systems were established on a more systematic basis than was the case for control of radioiodine, and the few problems that have occurred with these plants were related to improper humidity control or accidental wetting of the carbon prior to operation. Two temperature excursions have been reported in these systems—one at ORNL, where an oxygen stream was being decontaminated, and one at the Brown's Ferry nuclear power plant, where a hydrogen recombiner malfunctioned.

Testing of Iodine Adsorbents

The current test protocol is ASTM D3803-89,[36] which superseded RDT M-16.[37] Both standards have numerous typographical and editorial mistakes, such as inaccurate decay constants for iodine-131 and inconsistencies in time duration between the text and tables. In addition, both are merely guides as far as equipment setup is concerned, but the critical parameters listed in both Table No. 1 and Section 13 of ASTM D3803-89[36] specify reporting requirements.

Testing of Noble Gas Adsorbents

The results of noble gas delay cannot be correlated because important test parameters either were not reported or were not standardized. Omissions include the unspecified moisture content of the adsorbent, relative humidity of the gas, and duration of pre-equilibration for the experiment. In some cases, tests involved only a few grains of carbon, and the results have been extrapolated to full-size systems with bad results.

Operating Experience with Iodine Adsorption

Several important lessons concerning iodine control were learned from the TMI-2 accident. The first is that conventional iodine release and transport theories were incorrect. Most of the iodine stayed in the liquid phase or plated out in the confinement vessel. The total amount of iodine that reached the operating filter adsorber trains can be conservatively estimated at 150 curies (Ci), of which approximately 15 to 32 Ci were released to the environment. This value, when compared with approximately 13×10^6 Ci of xenon-133 released (the approximately hundreds of millions of iodine curries released into the containment), is a good indication of a lack of the predicted partitioning of iodine species into the airstream. One indication of the iodine species distribution showed a predominance of methyl iodide, followed by elemental iodine. The system available for controlling iodine releases was comprised of two trains in the Unit 2 Auxiliary Building, identified as trains A and B, and two trains in the Fuel Handling Building, identified as trains A and B. The Auxiliary Building trains were not classified as ESFs. They captured approximately 12 to 14.6 Ci of iodine and released approximately 1.2 to 1.8 Ci. The Fuel Handling Building filters captured approximately 36 to 48 Ci of iodine and released approximately 5 to 15 Ci.

1.3.2 Radiochemical Processing

The quantity of radioiodine used in radioactive tracer studies is small compared to the concentrations present in power reactors, but the variety of radioiodine-containing organic compounds is greater. Based on available theoretical and experimental data, the removal efficiency of impregnated nuclear carbons for many organic compounds is lower than for methyl iodide. Furthermore, most radioiodine decontamination systems found in connection with laboratory fume hoods are inadequate even for methyl iodide, as they usually only contain a depth of 1 inch of some unimpregnated carbon that has not been specifically qualified for this intended use. For laboratory hood service, carbon depth should provide at least a 0.25- to 0.50-seconds residence time and should permit removal of representative samples for periodic laboratory testing to determine remaining service life. Representative samples should be removed at least every 720 hours of continuous use and should be tested under conditions corresponding to the hood effluent conditions with respect to relative humidity, temperature, and the presence of compounds that compete with the radioiodine species for adsorption sites. For example, when relative humidity is variable, the adsorbent should be tested at the maximum relative humidity conditions likely to be present to obtain conservative values.

1.3.3 Fuel Reprocessing Plants

The isotope of importance in the effluent gases from fuel reprocessing systems is iodine-129, which has a half-life of 1.7×10^7 years. Generation of gaseous iodine-129 occurs in the presence of oxidizing acid gases such as nitrogen oxide under very-high-humidity conditions, and often when there are high concentrations of competing organic compounds. This is a highly demanding environment for adsorption media. At the beginning, reprocessing effluent treatment in the United States usually involved liquid scrubbing with alkaline solutions. However, there are anecdotal reports of a packed bed scrubber at Hanford that utilized silver dollars for the packing to make the captured iodine more insoluble as silver iodide. Although alkali, mercuric nitrate, and hyperazeotropic nitric acid absorption systems are still used for this purpose, direct removal of iodine using solid adsorbents has been gaining favor in treating the gaseous effluent at newer fuel reprocessing plants. The use of solid adsorbents for this service was first evaluated at the SRS with activated carbon, but it proved to be unstable in the dissolver offgas environment. In 1968, a switch was made to a silver-impregnated inorganic adsorbent. The solid adsorbents under consideration included primary silver-containing materials such as silver-exchange zeolites and silver-impregnated adsorbents, where the adsorbent acts as a carrier for the silver-iodine chemical reaction. Due to the relatively high cost of silver, it is important that as much silver as possible is utilized before exhaustion of the adsorbent system. Numerous studies have been conducted to evaluate these materials for full reprocessing service.

The most commonly used adsorbents for dissolver offgas treatment include AC6 120, a silver-nitrate-impregnated, high-silica-base adsorbent; a silver-and-lead-nitrate-impregnated, high-temperature base adsorbent; and silver-exchange zeolites and mordenites. Several reaction mechanisms lead to various silver-iodine compounds. The most common compound for both elemental and organic iodine is silver iodide, which is very stable except in a high-temperature hydrogen environment where reduction to elemental forms occurs.

1.3.4 Power Reactors

The first major U.S. effort related to control of radioiodine from reactors consisted of design studies of confinement systems for the nuclear-powered commercial ship N. S. Savannah and the Hanford N Reactor.[36, 37, 38] At that time, control of elemental iodine was of primary interest, mainly because data from various prior accidents failed to differentiate iodine forms. A process-engineering solution to iodine retention was proposed that recommended 12-inch-deep carbon beds operated at high velocity with a 0.5-sec residence time. In the United States, however, the heating, ventilating, and air-conditioning (HVAC) shallow-bed model was adopted by the nuclear industry, and shallow beds of carbon became the predominant method for iodine capture.

The U.S. activated carbon adsorber design was based on a series of relatively short-term laboratory experiments using fresh carbon, clean carrier gas, and nonsystematic iodine inlet concentrations. Results indicated an iodine removal efficiency for 0.8- to 1.0-inch-deep carbon beds that could not be obtained in practice. Typically, the early installations were constructed in pleated form and contained 44 to 55 pounds of carbon for every 10,000 CFM of airflow. This design became known as a Type I Adsorber Unit. It was later found that, under high-humidity conditions (greater than 70 percent relative humidity), shallow carbon beds were incapable of high-efficiency removal of organic iodides, particularly methyl iodide. In addition, it was accidentally discovered that: (1) isotope exchange would take place on carbon surfaces, and (2) gas mask carbons impregnated with tertiary amines to control low-molecular-weight chemical warfare agents containing organic halides would also react with radioactive organic halides. This discovery led to the use of carbons impregnated with stable iodine or iodide salts to control methyl iodide by isotope exchange, as well as the use of amine-impregnated carbons to control methyl iodide by complex formation.

Although laboratory experiments with unimpregnated carbons indicated that a 1-inch bed performed acceptably for elemental iodine removal when the exposure was a short duration and the carbon was fresh, a minimum acceptable bed depth of 2 inches was needed under ideal conditions for the impregnated carbons used for methyl iodide removal. This led to development of a tray-type design for nuclear adsorber units consisting of two 2-inch-deep military-type adsorber trays that were attached to a 24-inch × 24-inch face plate for mounting in ladder frames. This adsorber design became known as a Type II Adsorber Unit. It provided a 0.25-second gas residence time in the carbon and operated at a gas velocity of 40 feet per minute (fpm).

Standardization of the external dimensions of the tray-type units did not occur for many years, and there are currently approximately 10 different adsorber sizes in service in the United States. This creates logistical difficulties for warehousing spares and obtaining fast replacements in case of an accident. For example, between the two reactors on the TMI site at the time of the TMI-2 accident, there were four different adsorber shapes and sizes—three of them supplied by the same vendor.

In the beginning, criteria for the selection of adsorbent media were not well standardized in the United States. Based on short-term tests, carbon impregnated with potassium iodide and iodine performed better than unimpregnated carbon, and its use dominated early iodine control technology. A water extract from finished impregnated carbons varied in pH from neutral to acidic depending on the method of preparation. As the pH of the water extract of the base carbon also influences the pH of the impregnated carbon, the choice of vegetable-base (coconut shell) carbons for impregnation was helpful because, in addition to being hard, such carbons contain approximately 1 percent potassium hydroxide or sodium hydroxide that reacts with free elemental iodine to produce iodide forms that migrate through the carbon less easily than elemental iodine.

In the late 1960s and early 1970s, researchers realized that design data derived from short-term experiments with fresh carbons provided inadequate adsorber designs for the long-term protection needed from carbon beds. Carbons deteriorate from long exposure to air pollutants (weathering), as well as inadvertent adsorption of widely used organic-compound-containing materials (poisoning; e.g., paint or solvent vapors). Both situations result in a loss of capacity for iodine species. Such observations led to development of deep-bed adsorbers constructed with 4- to 20-inch-deep beds of impregnated carbon that could be filled by pouring the granules into large panels, thereby eliminating the many leak paths associated with tray-type units. This adsorber design was designated a Type III Adsorber. [Note: As of this writing, an addition to the AG-1 Code[11] is being developed that will address Type IV Adsorbers, which are similar to Type I Adsorbers.]

The nuclear reactor post-accident iodine release concepts that became established and codified during the late 1960s were based on the assumption that a large quantity of elemental iodine would be released and would have to be adsorbed. The design criteria were based on the release of 50 percent of core iodine with half of the released iodine captured by plate-out on surfaces. Of the remaining airborne iodine, 85 percent would be elemental, 10 percent would be organic, and 5 percent would be particulate. Contemporary transport concepts contemplated a need to treat large air volumes at locations several steps away from the point of release of the iodine fission products. It was anticipated that iodine capture would be made more difficult by dilution in a large volume of air, as well as by the presence of a large quantity of other chemicals in the air that would compete with iodine for adsorption sites or react more rapidly with the impregnants.

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CHAPTER 2

SYSTEM CONSIDERATIONS

2.1 Introduction

A nuclear air cleaning system is an assembly of interrelated, interactive parts that include the air cleaning system components, the contained space served by the air cleaning system (e.g., the glovebox, hot cell, room, or building), and the processes served by that system.

This chapter discusses the design, operational, and codes- and standards-related requirements for nuclear facility air cleaning systems. Topics will include system, subsystem, and component design considerations, as well as general descriptions of various systems used in production and fabrication facilities, fuel processing and reprocessing plants, research facilities, storage facilities, and other applications. This chapter will also consider operating costs and how the design of an air cleaning system directly affects the ventilation system performance and costs. Examples of some lessons learned from the operation and maintenance of nuclear air cleaning systems will be provided.

2.2 Environmental Considerations

The complexity of the air cleaning system needed to provide satisfactory working conditions for personnel and to prevent the release of radioactive or toxic substances to the atmosphere depends on the following factors:

- Nature of the contaminants to be removed (e.g., radioactivity, toxicity, corrosivity, particle size and size distribution, particle shape, and viscidity);
- Heat (e.g., process heat, fire);
- Moisture (e.g., sensible humidity process vapors, water introduced from testing);
- Radiation (e.g., personnel exposure and material suitability considerations);
- Other environmental conditions to be controlled; and
- Upset or accident or accident hazard considerations.

In designing an air cleaning system, development of the environmental operating conditions must be the first step. Before appropriate individual system components can be environmentally qualified, the designer must consider all environmental parameters on an integrated basis. This may require additional qualifications.

The facility owner normally identifies the design and environmental parameters that are compatible with the overall facility design. These parameters must be identified prior to system design because they must be the basis for the equipment design. If the environmental parameters are carefully considered, a detailed analysis of cost versus long-term operation will provide an environmental maintenance schedule for replacing components and parts throughout the intended operational life of the system. This will ensure that the system will perform its intended function properly, efficiently, and cost-effectively. **Table 2.1** lists some common system environmental parameters that should be considered for system design.

Table 2.1 – Environmental Parameters for System Design

Parameters	***Examples***
Types of gases treated	Air, hydrogen, oxygen, nitrogen, argon, etc.
Flow rate(s)	The maximum and minimum operating flow rates for normal and accident conditions.
Pressure and pressure drop	The external pressure and/or vacuum pressure at the inlet and/or outlet of the system; the maximum system pressure, usually accident or upset mode; the maximum allowable pressure drop across the air cleaning system components.
Temperatures	The maximum and minimum operating temperatures of the airstream and equipment.
Radiation	The maximum expected alpha, beta, and gamma radiation dose rates (rads/hour) and cumulative levels (rads).
Relative humidity, condensation, and direct introduction of liquids	The maximum and minimum relative humidity of the gas entering the air cleaning system, condensation with potential for wicking, and direct introduction of water sprays for fire protection.
Contaminants that may be removed (or not) from the gas stream	Removal efficiencies for particulate, gaseous, entrained water, chemical, radiological, volatile organic chemicals, and other materials, as well as considerations of other materials' capabilities for air contaminants.
Seismic requirements	Seismic response curves for the expected equipment location.
Pressure-time transients	Deflagration (internal), tornado (external)
Design life and operating life	Projected facility and equipment operating life [e.g., high-efficiency particulate air (HEPA) filter service life].

2.2.1 Airborne Particulates and Gases

To properly design an air cleaning system and optimize its performance, the types of contaminants in the gas stream must be identified. All of the contaminants, both particulate and gaseous, including concentration levels and particle sizes, must be evaluated to properly design and size the system. The presence of other particulates, gases, and chemicals must be clearly determined. The presence of volatile organic chemicals (VOCs), entrained water, and acids will affect the performance of various system components and must be addressed, if they are present, in the design of the system and its components.

Intake air cleaning systems or supply systems filter the atmospheric dust brought into the facility. Recirculating systems, if used, clean the air in a building or location and return the air to that location. Other sources of particulate and gaseous contamination are infiltration and "people-generated" particulates (e.g., lint, skin, hair) and offgassing of materials such as paint, solvents, carpets, and furniture. All of these factors must be considered in determining the parameters for proper system design. These contaminants contribute to degradation and sometimes become radioactive when exposed to certain environments (e.g., by adsorption of radioactive vapors or gases or by agglomeration with already radioactive particles). Because particles in the size range of 0.05 to 5 micrometers (µm) tend to be retained by the lungs when inhaled, they are of primary concern in operations that involve radioactive material.[1] They are also recognized as among the health hazards of nonradioactive air pollution. As shown in **Table 2.2**, over 99 percent, by count, of typical urban air samples have a mean particle size of 0.05 µm.

Table 2.2 – Distribution of Particles in Typical Urban Air Sample

Mean Particle Size (µm)	***Particle Size Range (µm)***	***Approximate Particles Count per Cubic Foot of Air***	***Percent by Weight***	***Percent by Count***
20.0	50-10	12.5×10^{3}	28	1×10^{-10}
7.5	10-5	10×10^{4}	63	8×10^{-10}
2.5	5-1	12.5×10^{6}	6	1×10^{7}
0.75	1-0.5	10×10^{7}	2	8×10^{7}
0.25	0.5-0.1	12.5×10^{9}	1	1×10^{4}
0.05	0.1-0.001	12.5×10^{15}	<1	99.9999

Reports of dust concentrations in air are generally based on the masses of the particulate matter present. As shown in Table 2.2, mass accounts for only a negligible portion of the total number of particles in the air. This is important in filter selection because it indicates that some filters with a high efficiency based on weight may be inefficient on a true count basis. That is, the filters are efficient for large particles, but inefficient for small (less than 0.75 µm) particles. This is true of most common air filters used as prefilters. On the other hand, the HEPA filter is highly efficient for all particle sizes down to and including the smallest shown in Table 2.2. The 99.97 percent minimum efficiency claimed for these filters is actually for the most penetrating size particles, i.e., those ranging in size from 0.07 to 0.3 µm. Dust concentrations vary widely from place to place and, for the same location, from season to season and from time to time during the same day. Concentrations in the atmosphere may vary from as low as 20 micrograms per cubic meters ($\mu g/m^{3}$) in rural areas to more than 20 mg/m^3 in heavily industrialized areas. Dust-producing operations may generate concentrations as great as several thousand g/m^3 at the workplace. Because the weight percent determinations on which these concentrations are based account for only a small fraction of the number of particles present, the true count of particles smaller than 5 µm may number in the billions per 1000 cubic feet (ft^3). Atmospheric dust concentrations can vary significantly through the year.[2]

Filter selection, particularly prefilter and building supply filter selection, must consider the atmospheric dust concentrations that can be encountered at a particular site at any time of the year.

Figure 2.1, *Distribution of Particles*, shows the distribution of particles (by weight percent) in atmospheric air as a function of particle shape. Variations in particle shape, mean particle size, particle size range, and concentration affect filter life, maintenance costs, and operational effectiveness. The size range of various types of particles, the technical nomenclature of various types of aerosols, and the applicability of various types of air cleaning devices as a function of particle size are shown in **Figure 2.2**. A major source of the lint often found on filters is derived from the abrasion of clothing as people move about. In addition, a person at rest gives off more than 2.5 million particles (skin, hair, etc.) and moisture droplets/minute in the size range of 0.3 to 1 µm.[3] Process-generated aerosols fall into two general size ranges. Those produced by machining, grinding, polishing, and other mechanical operations are generally large, (from 1 to several hundred µm), according to the nature of the process, and can be removed effectively by common air filters or other conventional air cleaning techniques. The other size range includes those produced by evaporation/condensation and other chemical operations, which generate droplets and solid

Description	Appearance	Kinds	Percent Present by Weight	
			Range	Average
Spherical		Smokes Pollens Fly Ash	0-20	10
Irregular Cubic		Minerals Cinder	10-90	40
Flakes		Minerals Epidermis	0-10	5
Fibrous		Lint Plant Fibers	3-35	10
Condensation Flocs		Carbon Smokes Fumes	0-40	15

Figure 2.1 – Distribution of Particles

particles that are often submicrometer-sized. These aerosols are more difficult to separate from air or gases, requiring collectors such as HEPA filters. Ultra Low Penetration Air (ULPA) filters provide a higher cleaning efficiency (up to 99.9999 percent for submicrometer particles). [Note: A need for this level of efficiency is rare for nuclear applications. The media used in ULPA filters is weaker than that used in nuclear-grade HEPA filters, a factor that must be considered for any application of ULPA filters to a nuclear air cleaning system or other applications where durability and reliability are concerns.]

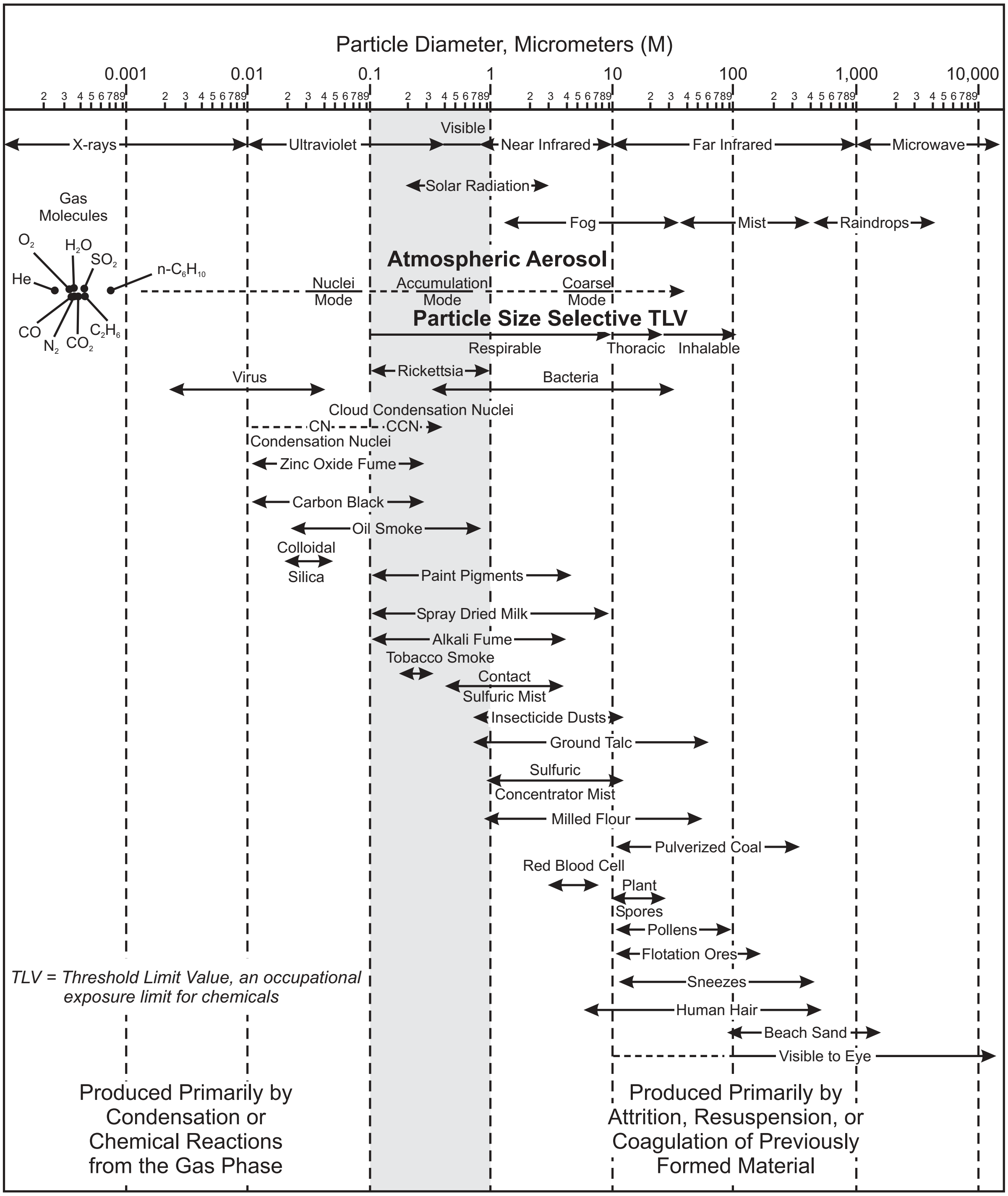

Figure 2.2 – Characteristics of Atmospheric and Process-Generated Particulates, Fumes, and Mists and Effective Range of Air Cleaning Equipment

For reactor operations, process-generated contaminants include radioactive noble gases and halogens. Because of their chemical inertness, limited reactivity with available sorbents, and the great difficulty of separating them, the noble gases (xenon and krypton) have been treated in the past by simple holdup to allow time for radioactive decay of the shorter half-life elements, as well as dilution before discharge to the atmosphere. They can also be separated by cryogenic fractionation, charcoal adsorption, or fluorocarbon adsorption and stored until a significant degree of radioactive decay takes place. The halogen gases, essentially elemental iodine and certain volatile organic iodides, are captured by adsorption either on activated carbon or certain synthetic zeolites.

2.2.2 Pressure

Pressure is one of a number of variables that needs to be evaluated in the course of designing the air cleaning system because it can significantly affect the fan power requirements and the airflow rate. The pressure of the airstream can be impacted significantly by the change from the normal operating pressure to the accident or upset air pressure (e.g., fire may cause pressure increases). See Chapter 5, Section 5.4, entitled "Fans and Motors," for fan requirements.

2.2.3 Moisture

Moisture is an important consideration in air cleaning system design. Moisture in the air may affect the performance of the air cleaning system by binding the particulate filters and/or blocking pores and fissures in the activated charcoal. Where water mist or steam can be expected under either normal or upset conditions, moisture separators and heaters, if appropriate, must be provided upstream of the filters to prevent plugging, deterioration, and reduced performance. Condensation from saturated air and gas streams or carryover from air washers and scrubbers are common sources of moisture. When fire-protection sprinklers are provided in operating areas, ducts, or plenums, moisture can be drawn into the filters if they are activated. In nuclear reactors, large volumes of steam and moisture should be expected in the highly unlikely event of a major loss-of-coolant accident (LOCA) or heat exchanger failure. Moisture on the face of a filter will blind or plug the filter, creating the potential for filter failure. [Note: HEPA filters exposed to carryover from intentional or inadvertent fire sprinkler actuation must be replaced.]

Condensation is particularly troublesome when filters are installed in underground pits, in outdoor housings, or in unheated spaces within buildings. Even when the air entering through the ducts is above the dew point, duct walls, dampers, or filters may be cold enough to cause condensation on their surfaces. Condensation can also take place in standby systems. Inspection of standby filters on a monthly or even weekly basis is recommended to prevent the detrimental effects of condensation.

2.2.4 Temperature

Although some air cleaning system components are prequalified to operate in a given temperature range, the air cleaning system designer must verify all components of the system will function at the maximum and minimum temperature conditions for the specified application. If the temperature range of the specific application exceeds the components' design qualification temperature, requalification is necessary to meet the operational and design life requirements of the system.

In general, continuous operation at high temperature (greater than 250 degrees Fahrenheit) is detrimental to both HEPA filters and activated carbon-filled adsorbers.[4] At high temperatures, the shear strength of adhesives and binders used in the manufacture of HEPA filters and filter media may diminish, thereby limiting the safe pressure drop to which they can be subjected. The limiting temperature varies with the specific adhesive and binders used. Filter manufacturers have designed HEPA filters for temperatures above 250 degrees Fahrenheit (a 500-degree Fahrenheit filter is also available). The filter manufacturer should provide objective evidence that the filters are qualified for the higher-temperature environments of the specific application.

For high-temperature applications, particulate filtration can be accomplished with the use of metal filters constructed of sintered metal or metal mesh. The construction and performance requirements for metal filters will be found in American Society of Mechanical Engineers (ASME) Code AG-1, *Code on Nuclear Air and Gas Treatment*.[4] Metal filters are manufactured for medium efficiency and HEPA efficiency ranges. Due to their relatively high cost, metal filters should be considered only for those applications where standard glass fiber filters would not meet the environmental or design conditions.

The limiting temperature of adsorbents for capturing radioactive iodine and iodine compounds is related to the desorption temperature of the adsorbed compound and the chemicals with which it has been impregnated to enhance its adsorption of organic radioiodides. For example, the limiting temperature of adsorbents impregnated with chemicals (e.g., triethylene-diamine- and iodine-impregnated activated carbon) is 280 degrees Fahrenheit.

When temperatures higher than the operating limits of air cleaning system components must be accommodated, chilled water coils, heat sinks, dilution with cooler air, or some other means of cooling must be provided to reduce temperatures to levels that the components can tolerate. Environmental qualification of an air cleaning system must address thermal expansion and the heat resistance of ducts, dampers, filter housings, component mounting frames and clamping devices, and fans. Electrical and electronic components are specifically susceptible to high and low temperatures and must be designed and qualified for Safety Class and Safety Significant systems in accordance with the ASME AG-1 Code[5] and Institute of Electrical and Electronics Engineers (IEEE) 323, *Standard for Qualifying Class 1E Electrical Equipment for Nuclear Generating Stations*[5] and IEEE 344, *Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Generating Stations*.[6] Operational consideration also must be given to the flammability of dust collected in the ducts and on the filters. All Safety Class and Safety Significant systems must be built to ASME AG-1.

2.2.5 Corrosion

Many radiochemical operations generate acid or caustic fumes that can damage or destroy filters, system components, and construction materials. Some products of radiochemical operations can produce shock-sensitive salts (e.g., perchloric acid salts and ammonium nitrate) that must be specifically considered in the design and operation. The air cleaning system designer must select components and materials of construction suitable for the corrosive environment to ensure high levels of system performance and reliability.

Acid-resistant prefilters and HEPA filters are available. These filters utilize media constructed with Nomex® or Kevlar® fibers mixed with glass fibers during manufacturing, epoxy-coated separators to extend the life of the aluminum separators, and stainless steel frames.

Metal filters with a demonstrated suitability for a corrosive atmosphere, in accordance with the ASME AG-1 Code[4], are recommended for hydrogen fluoride or other highly acidic applications. Hydrogen fluoride is a concern because it will attack the glass media. Wood-case filters are vulnerable to attack by nitric acid that will form nitrocellulose.

Stainless steel is recommended for ductwork and housings when corrosion can be expected. Even this material may be insufficient in some cases, and coated (e.g., vinyl, epoxy) stainless steel or fiber-reinforced plastics may be necessary (corrosion-resistant coatings are covered by American Society for Testing and Materials (ASTM) D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*.[7] The system designer can either: (1) use existing databases containing information about the performance of materials (including the filter media) exposed to various concentrations of corrosive contaminants, or (2) perform actual testing to validate the air cleaning system design.

Scrubbers or air washers may be employed to pretreat the air or gas before it enters the air cleaning system or to scrub the airstream of perchloric and ammonium nitrate salts, but consideration must also be given to moisture carryover if the scrubbers or air washers are not designed and operated properly. Stainless steel moisture separators are recommended ahead of the filters. Corrosion is always a danger, but is not always obvious. In activated carbon-filled adsorbers, for example, even trace amounts of nitrous oxide or sulfur dioxide will concentrate in the adsorbent over time. In the presence of moisture, these compounds can form nitric or sulfuric acids that are capable of corroding the stainless steel parts of the adsorber, i.e., the perforated metal screens. Aluminum and carbon steel are subject to corrosion when in contact with moisture-laden carbon. For this reason, stainless steel is always specified for adsorber cells and for adsorber-cell mounting frames.

Electrical and electronic components are particularly susceptible to corrosive atmospheres. Plastics become brittle over time, contacts corrode, etc. For this reason, all electronic components must be environmentally qualified for the intended application.

Care must be exercised in selecting and using gaskets, as some gasket material reacts with the moisture in the airstream and releases chlorides that can corrode steels (including stainless steel). Gasket material selection should also include consideration of the effects of the material's use in acidic, radioactive, or other harsh environments. In addition, care must be exercised for gasket stability when dealing with radiation. Radiation may also lead to undesirable reactions such as decomposition of Teflon™ into hydrofluoric acid.

2.2.6 Vibration

Vibration and pulsation can be produced in an air or gas cleaning installation by turbulence generated in poorly designed ducts, transitions, dampers, and fan inlets and by improperly installed or balanced fans and motors. Excessive vibration or pulsation can result in eventual mechanical damage to system components when accelerative forces (e.g., from an earthquake or tornado) coincide with the resonant frequencies of those components. Weld cracks in ducts, housings, and component mounting frames can be produced by even low-level local vibration if sustained, and vibrations or pulsations that produce no apparent short-term effects may cause serious damage over longer periods.

Vibration produces noise that can range from the unpleasant to the intolerable. Important factors in the prevention of excessive vibration and noise include planning at the initial building layout stage and space allocation to ensure that adequate space is provided for good aerodynamic design of ductwork and fan connections. Spatial conflicts with the process and with piping, electrical, and architectural requirements should be resolved during early design to avoid the compromises so often made during construction that frequently lead to poor duct layout and resulting noise and vibration. Ducts should be sized to avoid excessive velocities, while maintaining the transport velocities necessary to prevent the settling out of particulate matter during operation. Fan vibration can be minimized through the use of vibration isolators and inertial mountings. Some designers require hard mounting of fans where seismic requirements and continued operation during and after an earthquake must be considered. Flexible connections between the fan and ductwork are often employed, but must be designed to resist seismic loads and high static pressures, particularly in parts of the system that are under negative pressure to minimize air-in leakage. Finally, the ductwork system must be balanced after installation, not only to ensure the desired airflows and resistances, but also to "tune out" any objectionable noise or vibration that may have been inadvertently introduced during construction.

2.2.7 Electrical

Emergency electrical power is required when specified by facility safety documentation. Emergency power has specific requirements and may not be required for all systems. Standby electrical power is used for many safety air cleaning systems not classified as Safety Class. Standby power is required for safety-significant air cleaning systems.[8, 9, 10] The amount of emergency power required for fans, dampers, valves, controls, and electrical heaters to control the relative humidity of the effluent airstream (as dictated by the facility design requirements) must be accounted for during accident or upset conditions. Close coordination between the system designers of both the air cleaning and electrical systems is required to ensure this is done, as there is a set amount of emergency power available.

2.2.8 Radiological Considerations

Radiation may affect the air cleaning system in at least three different ways:

- The buildup of radioactive material in and around the air cleaning system may limit personal access during operations and maintenance, and must be specifically factored into the design.
- The buildup of radioactive material in and around the air cleaning system may lead to special considerations for construction materials used for the system—particularly those containing Teflon® or Kel-F®. This buildup can also limit component life.
- The amount of radioactive material that may be released limits the acceptable selection and operating ranges for the air cleaning system components (e.g., the HEPA and adsorption units).

The design of workroom ventilation systems should be consistent with the requirements of 10 CFR 835, *Occupational Radiation Protection,* Subpart K, "Design and Control," which establishes the U.S. Department of Energy's (DOE) design objectives for workplace radiological control.[11] Two key components of these requirements are that: (1) for controlling airborne radioactive material, under normal conditions, the design objective will be to avoid releases to the workplace atmosphere, and (2) confinement and ventilation will normally be used to accomplish this objective (i.e., engineered controls should be applied rather than relying on administrative controls). Furthermore, effluent releases from ventilation systems must be in accordance with DOE directives and relevant regulatory requirements (e.g., DOE Order 5400.5, *Radiation Protection of the Public and the Environment*,[12] and 40 CFR Part 61, subpart H, *National Emission Standards for Air Pollution*.[13]

All work conducted within areas serviced by these ventilation systems, or work on the systems themselves, should be performed in accordance with site policies and procedures. The requirements for control of radiation and radioactive material in the workplace are contained in 10 CFR 835.[11] This rule also establishes the requirements for monitoring of workplaces within and surrounding these areas, and that these activities should be conducted in accordance with site policies and procedures.

Some systems have actually experienced radiological degradation from excessive radiation exposure (e.g., the A and B underground filters at the Hanford B-Plant). Radiological degradation, overloading, and faulty installation and change-out of HEPA filters led to contamination of several parking lots and grounds around ORNL's Building 3098.

2.2.9 Confinement Selection Methodology

Workroom ventilation rates are based primarily on cooling requirements, the potential combustion hazard, and the potential inhalation hazard of substances that are present in or could be released to the workroom. Concentrations of radioactive gases and aerosols in the air of occupied and occasionally occupied areas should not exceed the derived air concentrations (DAC) established for occupationally exposed persons under normal or abnormal operating conditions, and releases to the atmosphere must not exceed permissible limits for nonoccupationally exposed persons.[11] Because radioactive gases and aerosols might be released accidentally in the event of an equipment failure, a spill, or a system upset, the ventilation and air cleaning facilities must be designed to maintain airborne radioactive material within prescribed limits during normal operations.[12, 13] In addition, the ventilation and air cleaning facilities must perform in accordance with expectations established during the evaluation of potential accident conditions.[8, 10]

The current DACs for radioactive substances in air are specified in 10 CFR 835, Appendix A.[11] These DACs should be applied to the design of a ventilation system using a hazard categorization process where the level of ventilation control is commensurate with the radiological risk present in the proposed operation. [Note: In a similar manner, the same conceptual process can also be applied to nonradiological airborne hazards.] There are no current DOE directives or technical standards that establish such an approach, but guidance is contained in the archived DOE Order 6430.1A, *General Design Criteria*,[14] and further expanded in the *Heating, Ventilating, and Air Conditioning Design Guide for the Department of Energy Nuclear Facilities*,[15] published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., (ASHRAE).

Based on the guidance cited above, one approach would be to group the material in use into the hazard classes shown in **Table 2.3**, and then to zone the facility ventilation systems based on the criteria shown in **Table 2.4**. [Note: The limits given in the tables are guides and should not be considered absolute.] An alternative approach would be to classify the risk based on the anticipated airborne and surface contamination levels, as shown in **Table 2.5**. The user must note that these criteria are based on the potential for the activity to generate airborne radioactive materials; they do not consider the direct radiation from the material, which would require separate shielding considerations. By introducing such indexes of potential hazards and limitations on the quantities of materials that can be handled, it is possible to establish a basis for ventilation and air cleaning requirements in various parts of a building or plant. **Figure 2.3** illustrates a typical zoning plan for a nuclear facility. Not all of the confinement zones listed in Table 2.4 would be required in all buildings, and an entire building could possibly be designated a single zone. Confinement zones are defined with respect to function and permitted occupancy in the following paragraphs.

Confinement Zones

As shown in Figure 2.3, the general approach is to establish ventilation zones in a three-tiered manner. Multizoned buildings are usually ventilated so that air flows from the less contaminated zone to the more contaminated zone. Areas from which air is not recirculated include areas that produce or emit dust particles, heat, odors, fumes, spray, gases, smoke, or other contaminants that cannot be sufficiently treated and could be potentially injurious to health and safety of personnel or are potentially damaging to equipment. These areas are 100 percent exhausted. Recirculation within a zone (circulating the air through a high-efficiency air cleaning system before discharge back to the zone) is permitted, but recirculation from a zone of higher contamination back to a zone of lesser contamination is prohibited. The interiors of exhaust and recirculating ductwork are considered to be of the same hazard classification as the zone they serve. Airflow must be sufficient to provide the necessary degree of contaminant dilution and cooling and to maintain sufficient pressure differentials between zones where there can be no backflow of air spaces of lower contamination, even under upset conditions. The pressure differentials should be determined during the facility's design, and should be in accordance with the applicable standards. [Note: Substantially higher differentials are often specified between Primary and Secondary Confinement Zones (see below) than for other boundaries.]

Table 2.3 – Hazard Classification of Radioisotopes

Hazard Class	Relative Hazard	DAC, Air (μCi/ml)
1	Very High	$<10^{-10}$
2	High	10^{-10} to 10^{-8}
3	Moderate	10^{-8} to 10^{-6}
4	Negligible	10^{-6}

Table 2.4 – Zoning of Facilities Based on Radiotoxicity of Materials Handled

Quantity of Material Permitted in Zone at any One Time [a, b]			
Radiotoxicity of Isotopes	Primary Confinement	Secondary Confinement	Tertiary Confinement
Very High	> 10 mCi	0.1 μCi-10mCi	0-0.1 μCi
High	> 100 mCi	1.0 μCi-100mCi	0-1.0 μCi
Moderate	>1 Ci	10 μCi-1 Ci	0-10 μCi
Negligible	>10 Ci	100 μCi-10 Ci	0-100 μCi

a There are practical upper limits to the quantities of materials in any particular zone, based on the type of material and design of the confinement systems. For example, criticality safety concerns may restrict the amount of fissile material that can be handled at one time, fire protection concerns may limit the amount of pyrophoric materials, and shielding considerations may limit the amount of materials when penetrating radiation is emitted. An activity-specific hazards analysis should always be conducted to determine the actual limits to be applied in practice.

b These criteria are based on the potential for the activity to generate airborne radioactive materials.

Table 2.5 – Zoning of Facilities Based on Contamination Levels

Anticipated Contamination Levels			
Type of Contamination	Primary Confinement	Secondary Confinement	Tertiary Confinement
Airborne[a]	$>100 \times$ DAC	$1 \times$ DAC to $100 \times$ DAC	$< 1 \times$ DAC
Removable Surface[b]	>>RSCV[c]	>RSCV[c]	<RSCV

a For airborne contamination, the DAC is the derived airborne concentration value listed in 10 CFR 835,[11] Appendix A, for the type and chemical form of the material being handled.

b For removable contamination, the RSCV is the removable surface contamination value listed in 10 CFR 835,[11] Appendix D, for the type of the material being handled.

c Removable surface contamination levels do not always directly lead to an increasing level of airborne contamination. The level of airborne contamination strongly depends on the potential for the particular activity to resuspend the deposited particles into the atmosphere. For this reason, it is difficult to establish a generic correlation. If the RSCV is the main consideration for differentiating between a secondary and primary confinement specification, then the approach established in Tables 2.3 and 2.4 should be applied.

The methodology used above is based on the DACs for radioactive substances in air, as specified in 10 CFR 835.[11] For toxics and noxious substances, the DACs must be replaced with Permissible Exposure Limits (PEL), including irritant and nuisance substances, as specified in 29 CFR 1910.[16] However, because the Federal PELs are obsolete in some cases, the Threshold Limit Values (TLVs) published annually by the American Conference of Governmental Industrial Hygienists (ACGIH)[17] should be consulted. In the case of a difference between the PEL and TLVs, it is generally recognized and accepted practice among industrial hygienists to use the more stringent of the two limits. A more convenient (and generally more current) tabulation of occupational exposure limits is published by the ACGIH in the annual issue of *Threshold Limit Values*. The latter reference includes a procedure for determining TLVs for mixed toxicants, as well as limit values for heat stress, nonionizing radiation, and noise. DOE Order 440.1A, *Worker Protection Management for DOE Federal and Contractor Employees*,[18] specifies how to select PELs and TLVs.

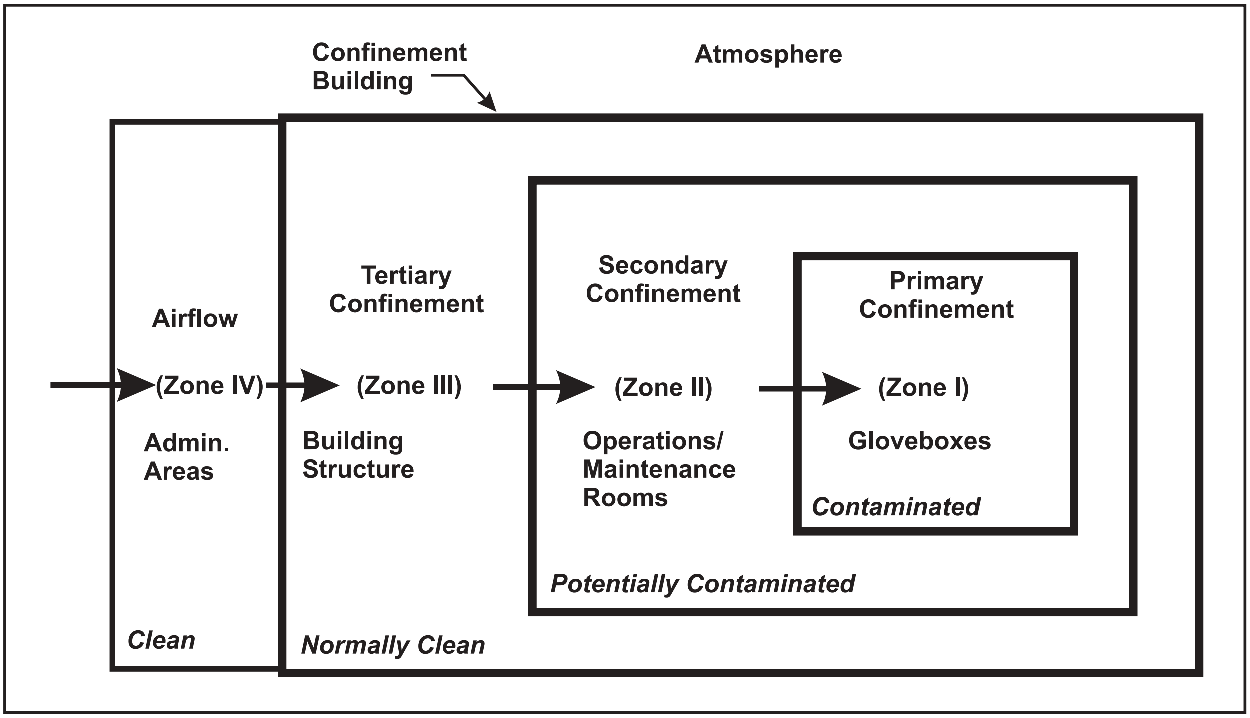

Figure 2.3 – Typical Process Facility Confinement Zones

Primary Confinement Zone

The primary confinement zone comprises those areas where high levels of airborne contamination are anticipated during normal operations. Facility personnel do not normally enter primary confinement zones. When entry is necessary, it is done under tightly controlled conditions. This zone includes the interior of a hot cell, glovebox, piping, vessels, tanks, exhaust ductwork, primary confinement HEPA filter plenums, or other confinement for handling highly radiotoxic material.[16] Confinement features must prevent the spread of radioactive material within the building under both normal operating and upset conditions up to and including the design basis accident (DBA) for the facility. Complete isolation (physical separation) from neighboring facilities, laboratories, shop areas, and operating areas is necessary. Unavoidable breaches in the primary confinement barrier must be compensated for by an adequate inflow of air or safe collection of the spilled material. The exhaust system must be sized to ensure an adequate inflow of air in the event of a credible confinement breach. An air exhaust system that is independent of those serving surrounding areas is required. High-efficiency filters, preferably HEPA type, are typically required in air inlets, and two independently testable stages of HEPA filters are required in the exhaust. The exact number of testable stages is determined by safety analysis.[8, 10]

Secondary Confinement Zone

The secondary confinement zone comprises those areas where airborne contamination could be generated during normal operations or as a result of a breach of a primary confinement barrier. This zone consists of the walls, floors, ceilings and associated ventilation systems that confine any potential release of hazardous materials from primary confinement. Related areas include glovebox operating areas, hot cell service or maintenance areas, and the ventilation system servicing the operating areas.[15] Pressure differentials must be available to produce inward airflow into the primary confinement should a breach occur. Penetrations of the secondary confinement barrier typically require positive seals to prevent migration of contamination out of the secondary confinement zone. Air locks or a personnel clothing-change facility are recommended at the entrance to the zone. Restricted access areas are generally included in the secondary confinement zone.

Tertiary Confinement Zone

The tertiary confinement zone comprises those areas where airborne contamination is not expected during normal facility operations. This zone consists of the walls, floors, ceilings, and associated exhaust system of the process facility.[15] It is the final barrier against release of hazardous material to the environment. This level of confinement should never become contaminated under normal operating conditions. The secondary and tertiary boundaries may exist in common, as in a single-structure envelope.

Example Airflow Criteria

As an example of the zoning approach discussed in this section, the criteria listed in **Tables 2.6**, **2.7**, **2.8**, **2.9**, and **2.10** are specified at one of DOE's national laboratories for the design and operation of radiochemical and laboratory facilities and for the buildings that contain them.[19] [Note: Numerical values can be reduced or increased depending on the requirements for operating conditions and the DBA for that facility.] **Table 2.11** contains recommendations for the pressure differentials between zones in multizoned buildings.

Table 2.6 – Airflow Criteria for Design and Operation of Hot Cells, Caves, and Canyons (Primary Confinement)

1. A vacuum equal to or greater than 1 (inches water gauge) in.wg relative to surrounding spaces must be maintained at all times to ensure a positive flow of air into the confinement.
2. Confinement exhaust must be at least 10 percent of cell volume/min to minimize possible explosion hazards due to the presence of volatile solvents and to ensure that, in the event of cell pressurization due to an explosion, the confinement will be returned to normal operating pressure (1 in.wg) in a minimum of time.
3. The maximum permissible leak rate must not exceed 1 percent of cell volume/minute for unlined cells and 0.1 percent of cell volume/minute for lined and sealed cells at a Δp of 2 in.wg to ensure minimal escape of radioactive material in the event of cell pressurization; the maximum permissible leak rate for ductwork is 0.1 percent of duct volume/minute at Δp equal to 1.5 times the static pressure of ductwork. Hot cells, caves, and canyons must not be hermetically sealed.
4. Seals and doors must withstand a Δp of at least 10 in.wg to ensure the integrity of closures and penetrations under all operating and design basis upset conditions.
5. The confinement structure must withstand the DBA for that facility without structural damage or loss of function.
6. Operating procedures must be designed to limit quantities of flammable and smoke-producing materials and solvents within limits that can be accommodated by the ventilation system without endangering the functionability of the air cleaning facility.

Table 2.7 – Airflow Criteria for Gloveboxes (Primary Confinement)

1. The vacuum must be at least 0.3 in.wg between the glovebox and the surrounding room. Consult the latest edition of the American Glovebox Society's *Guidelines for Gloveboxes*, AGS-G001,[20] and the ACGIH's *Industrial Ventilation – A Manual of Recommended Practice*[21] for guidance concerning ventilation of gloveboxes.
2. The exhaust rate is not specified, but must be adequate for the heat load and dilution requirements of operations conducted in the glovebox. For example, operations with flammable materials must maintain concentrations below those specified.
3. Airflow must be sufficient to provide an adequate face velocity at the passthrough port to the glovebox [50 linear feet per minute (fpm)] and to maintain an inward velocity of at least 125 linear fpm (with higher velocities mandated by some operators for gaseous effluents) through one open gloveport in every five gloveboxes in the system. This will ensure adequate inflow to prevent the escape of contamination in the event of glove failure.
4. Individual gloveboxes must be isolated or isolatable (under upset conditions) to prevent fire spreading from one box to another.

Table 2.8 – Airflow Criteria for Chemical Fume Hood (Primary Confinement)

1. A vacuum must be at least 0.1 in.wg between the laboratory in which the fume hood is installed and the corridor from which the laboratory is entered.
2. The exhaust rate of the fume hood must be sufficient to maintain sufficient airflow face velocity into the hood to prevent the release of fumes from the hood to the room, even when the operator walks rapidly back and forth in front of and close to the hood face. A face velocity of 80 to 100 linear fpm is recommended for operations with highly hazardous (including radioactive) materials. Higher velocities were once recommended, but are not now due to the generation of vortices by faster airflows which cause air inside the hood to migrate to the outside. Consult the latest edition of the American Industrial Hygiene Association's *American National Standard for Laboratory Ventilation*, Z9.5,[22] for guidance.
3. Each hood in the laboratory should be isolatable by means of dampers to prevent backflow through a hood when it is not in service.
4. Each hood used for handling radioactive materials should have a testable HEPA filter in its exhaust duct, located close to the duct entrance. All hoods should, where practicable, exhaust to a common stack.

Table 2.9 – Airflow Criteria for Secondary Confinement Structures or Buildings

1. The building (structure) must be designed to prevent the dispersal of airborne contamination to the environment in the event of an accident in a hot cell, glovebox, fume hood, or building space.
2. Under emergency conditions, the building must be capable of being maintained at a vacuum of 0.1 to 0.3 in.wg relative to the atmosphere. For increased reliability and simplicity, some buildings are held at this pressure under normal operating conditions. However, if this is not practicable, the ventilation system must be capable of reducing building static pressure to 0.2 in.wg in 20 seconds or less. All building air must be exhausted through at least one stage of HEPA filters. During an emergency, the differential pressure between primary confinement spaces (gloveboxes, hot cells) and other building spaces must also be maintained.
3. Airflow within the building must be from areas of less contamination to areas of higher (or potentially higher) contamination.
4. Recirculation of air within the same zone or room is permitted, but recirculation from primary and secondary confinement zone exhausts to other building volumes is prohibited.

Table 2.10 – Airflow Criteria for Air Handling Systems

1. It is recommended that ventilation (recirculating, supply, or exhaust) and offgas systems must be backed up by redundant air cleaning systems (including filters and fans) to maintain confinement in the event of fan breakdown, filter failure, power outage, or other operational upset. Airflow must always be from the less hazardous to the more hazardous area under both normal and upset conditions.
2. Air exhausted from occupied or occasionally occupied areas must be passed through prefilters and at least one stage of HEPA filters. Contaminated and potentially contaminated air exhausted from a hot cell, cave, canyon, glovebox, or other primary confinement structure or vessel should pass through at least two individually testable stages of HEPA filters in series, as well as prefilters, adsorbers, scrubbers, or other air cleaning components that are required for the particular application. Exact HEPA filter stages are determined by safety analysis.[8, 10] Only one stage of HEPA filters is required for the exhaust of: (1) air that is normally clean, but has the potential of becoming contaminated in the event of an operational upset (e.g., exhaust from a Secondary Confinement operating area) or during service operations when the zone is opened to a zone of higher contamination (e.g., a hot cell service area), and (2) air from a potentially mildly contaminated space (e.g., a Secondary Confinement area).
3. Moisture or corrosives in the exhaust that are capable of damaging or unduly loading the HEPA filters (or other components such as adsorbers) must be removed or neutralized before they can reach components that could be affected.
4. HEPA filters and adsorbers (where required) must be tested in place at a prescribed frequency in accordance with ASME Code AG-1, Section TA[4] and ASME N510.[23] HEPA filter stages should exhibit a stage leak rate better than 0.05 percent, as long as the leak rate is supported by documented safety analysis and provides an adequate safety margin, as determined by an in-place test performed in accordance with ASME Code AG-1.[4]

Table 2.11 – Recommended Confinement System Differential Pressure (in.wg)[15]

Type of Facility	Primary/Secondary	Secondary/Tertiary	Tertiary/Atmosphere
New	-0.7 to -1.0[b,c]	-0.1 to -0.15	-0.1 to -0.15
Existing[a]	-0.3 to -1.0[c,d]	-0.03 to -0.15	-0.01 to -0.15

[a] These guidelines should be used if the existing area/facility differential pressure design basis is unknown or if there are no site-specific standards.
[b] Canyons, cells: -1.0 in.wg (minimum).
[c] Gloveboxes (air) typically operate at -0.3 to -1.0 in.wg with respect to the surrounding room. Gloveboxes (air) typically have alarms set at -0.5 in.wg. Gloveboxes (inert gas): -0.3 to -1.25 in.wg with respect to surrounding room. For the purposes of enabling the operator to work at the glovebox (ergonomic considerations), the operating differential pressure should be closer to -0.3 in.wg
[d] Canyons, cells: approximately -1.0 in.wg.

NOTES:
1. It may be necessary in some cases to split a single zone into two areas, "a" and "b," where one area contains a greater hazard than the other. If area "a" were the more hazardous area, it would be at a negative pressure compared with area "b." Usually, no differential pressure guidelines exist for areas within the same zone. Therefore, maintaining proper airflow directions is typically the primary requirement.
2. Pressure cascades may need to be established within the secondary confinement. A 0.05–in.wg pressure differential between cascade stages is generally adequate.
3. If glovebox relief valves are included, they are typically set at -0.4 in.wg. Relief valves are designed for breach of the glove port.

2.3 Operational Considerations

This section addresses safety and design requirements, safety classification, regulatory requirements, codes and standards requirements, redundancy and separation, and material restrictions.

2.3.1 Operating Mode

According to operational requirements, an air cleaning system may be operated full-time, part-time, or simply held in standby for emergency service. If processes in the building are operated only one or two shifts a day, the designer may have a choice between continuous operation and operation only during those shifts. The designer must evaluate and compare the effects of daily starts and stops on the performance and life of filters and other components to the higher power and maintenance costs that may be incurred by continuous operation. All factors considered, experience has shown that continuous operation of air cleaning facilities, perhaps at reduced flow during weekends and holidays, is generally the most satisfactory mode of operation for buildings in which radioactive operations are conducted. Unless ducts, filter housings, damper frames, and fan housings (i.e., the pressure boundary) are extremely leaktight, outleakage of contaminated dust into occupied spaces of the building may occur during shutdown periods.

Many facilities require standby exhaust or air cleanup systems that are operated only in the event of an emergency or redundant air cleaning facilities that are brought into operation when a parallel online facility is shut down because of failure or for maintenance. When designing standby systems, the engineer must keep in mind the possibility of component, filter, and adsorber deterioration from environmental conditions (e.g., condensation, temperature) even when the system is not in use.

2.3.2 Particulate Filter Change Frequency

The principal costs of operating a high-efficiency air cleaning system are power (e.g., for fans), replacement filters and adsorbers, labor, and waste disposal costs for radioactive contaminated wastes. The principal factor that affects these costs is the frequency of filter changes. Replacement filters and adsorbers and the labor costs to install and test the filter system in-place after installation of replacement filters may make up as much as 70 percent of the total cost of owning a system (including capital costs) over a 20-year period.

Power accounted for only 15 percent of total owning costs in a study made by the Harvard Air Cleaning Laboratory.[24] Measures such as use of high-efficiency building supply-air filters, use of prefilters ahead of HEPA filters, operation of the system below its rated airflow capacity, and operation of HEPA filters until they have reached high airflow resistance before replacement all tend to decrease filter change frequency and thereby reduce costs. Caution should be exercised when establishing filter change frequency. Filters can become loaded with radioactive particles or reach an age when replacement is warranted even though they may not be dust/dirt-loaded to a point that indicates change-out is necessary due to pressure drop. These same filters may also have an acceptance in-place field test result.

For systems governed by commercial nuclear power plant technical specifications, strict requirements for operating filters at maximum pressure drops are specified. Therefore, filters should not be operated at maximum pressure drop; they must always be ready with enough remaining capacity and strength to handle the loading that can be expected from a design basis event.

Lawrence Livermore National Laboratory recently developed the requirement that HEPA filters be replaced 10 years after the date of manufacture. Exceptions to this requirement include:

- Any filter that becomes wet (e.g., as a result of an in-duct water sprinkler's activation or water spraying directly on the filter) must be replaced promptly.

- Any filter that potentially could become wet (e.g., via an in-duct water sprinkler's activation) must be replaced within 5 years of the date of manufacture.[25]

The underlying rationale for this set of requirements is found in Bergman's *Maximum HEPA-Filter Life*.[25] Part of the author's rationale is based on remaining acceptable tensile strength, which cannot be determined by nondestructive field tests.

2.3.3 Building Supply-Air Filters

Atmospheric dust brought into the building with ventilation air constitutes a substantial fraction of the dirt load in the building and the dust load in the exhaust air cleaning system. Removing this dust before it gets inside the building provides the double advantage of protecting the exhaust filters from premature dust loading and reducing janitorial and building maintenance costs. When operations within a building do not generate heavy concentrations of smoke, dust, or lint, it may be possible to substantially reduce the dust loading in the exhaust system by providing medium-efficiency [50 to 65 percent ASHRAE Efficiency/Minimum Efficiency Reporting Value (MERV) 10-11][26] building supply-air filters, thereby shifting much of the burden of what would otherwise be a change of "hot" (radioactive) prefilters in the exhaust system to a more economical change of "cold" supply-air filters. The labor costs involved in replacing "cold" filters is a small fraction of those for replacing "hot" filters. Noticeable reductions in janitorial costs have been observed in several DOE installations after changing to higher-efficiency building supply-air filters.

Louvers and/or moisture separators must be provided at the air inlet to protect the supply filters from the weather. Rain, sleet, snow, and ice can damage or plug building supply-air filters, resulting not only in increased operating costs, but also upset of pressure conditions within the building and possible impairment of the more critical exhaust air cleaning system. Heaters are desirable in the building supply system even in warm climates. Icing has caused severe damage to building supply-air filters at a number of DOE installations, even in the South. Screens should be provided over supply-air inlets located at ground- or roof-level to protect inlet filters and demisters from grass clippings, leaves, dirt, and windblown trash. If possible, inlets should be located well above grade or adjacent roofs so they are not exposed to such materials.

2.3.4 Prefilters

Prefilters are intended to remove large particles upstream of HEPA filters. HEPA filters are intended primarily for removal of submicrometer particles and should not be used as coarse dust collectors. They have relatively low dust-holding capacity, particularly for large particles and lint, and may plug rapidly when exposed to high concentrations of such material or smoke. Lint may tend to bridge the pleats of the filter, further reducing its capacity. The HEPA filter is also the most critical particulate-removal element in the air cleaning system from the standpoint of preserving confinement, and its failure will result in failure of system function.

Prefilters, installed either locally at the entrances to intake ducts, in the central exhaust filter house, or both, extend the life of HEPA filters and provide at least a measure of protection against damage. Local duct-entrance filters also minimize dust accumulation in ducts and reduce an otherwise potential fire hazard. A typical increase in HEPA filter life through the use of prefilters is depicted in **Figure 2.4**. The increase for a specific application depends, of course, on the quality of the prefilter selected and the nature and concentration of dusts and particulate matter in the system.

Generally, prefilters should be provided when the potential dust concentration in the air leading to the air cleaning system exceeds 20 mg/m^3 and should be considered if the dust concentration exceeds 1 grain per 1000 cubic feet (ft^3). The use of prefilters is recommended in engineered safety feature (ESF) systems for nuclear reactors.[27] The decision to install prefilters should be based on providing the best operational balance between HEPA filter change frequency, and procurement and maintenance costs for the prefilters.

Duct-entrance prefilters can be changed without entering or interrupting the central air cleaning facility, can minimize dust buildup in the ducts, and can provide a measure of protection against duct corrosion, accidental high-moisture loadings, and flaming trash or sparks that may be produced by a fire in the working space. On the other hand, a system that has a number of local prefilter installations may cost from two to three times as much as one in which the same prefilter capacity is installed in a central housing.[24]

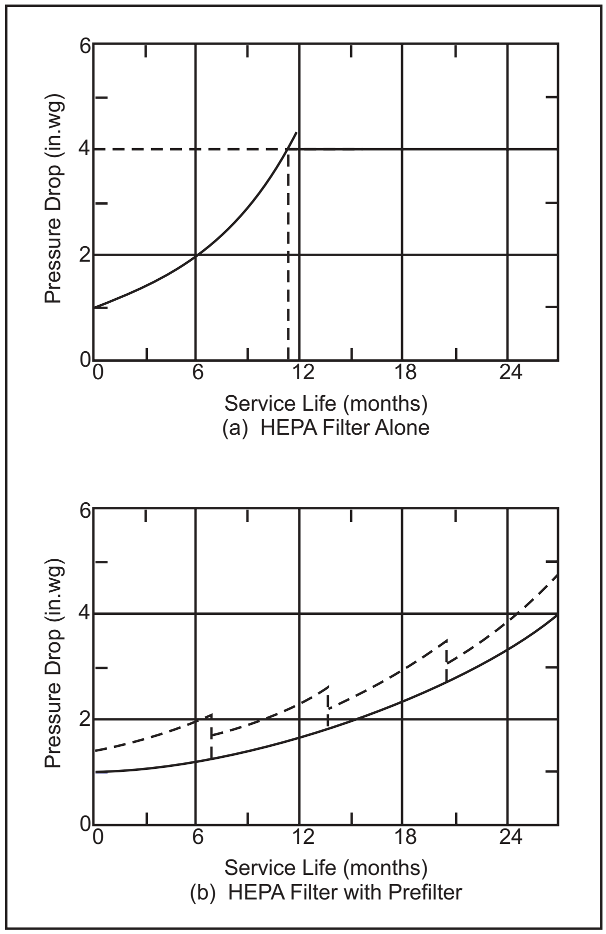

Figure 2.4 – Comparison of HEPA Filter Life With and Without Prefilter

Prefilters in a central air cleaning system should not be attached directly to or installed back-to-back to HEPA filters; they should be installed on a separate mounting frame located at least 4 to 5 feet upstream of the HEPA filters. This installation requires more building space and higher investment costs (particularly when building space is at a premium), but it is justified by increased safety and greater system reliability. Adequate space between prefilters and HEPA filters is needed for access and maintenance and to minimize the propagation of fire by sparks or direct flame impingement. If the possibility of fire is a serious consideration, a removable screen, fine enough to stop sparks (10 to 20 mesh), may be installed on the downstream side of the prefilters.

2.3.5 Operation to High Pressure Drop

Most HEPA filter manufacturers' literature suggests replacement of HEPA filters when the resistance due to dust loading has reached 2 in.wg. HEPA filters are qualified according to the requirements of ASME AG-1, Section FC,[4] to be capable of withstanding a pressure drop, when new, of 10 in.wg without structural damage or reduction of efficiency. [Note: This value is for qualification purposes only, and must not be used for operation.] When other factors such as radioactivity and fan capacity do not have to be considered, replacement at a pressure drop of only 2 in.wg is considered under-utilization of the filter. At many DOE facilities, HEPA filters are operated routinely to pressure drops as high as 4 in.wg. **Figure 2.5** shows the effect of such operation on filter life and maintenance costs.

The advantages of operating to high-pressure drop must be weighed against initial costs (higher-static-pressure fans, larger motors, heavier ductwork), higher power costs, and less efficient fan operation. The installed fan and motor must have sufficient capacity to deliver the design airflow at the maximum differential pressure under which the system will operate, with the filters at maximum dirty-filter pressure drop prior to change. Therefore, consideration must not only be given to the increased installed capacity required to operate to the higher pressure drop, but also to the fact that the fan operates at a penalty much of the time to provide the required airflow over the wide span of pressure drop between installation and replacement of filters.

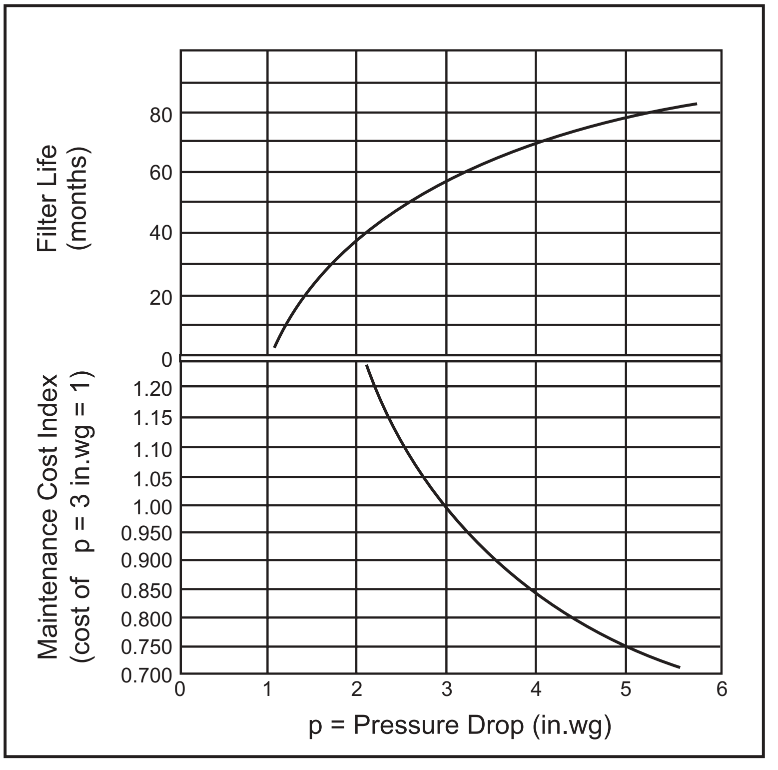

Figure 2.5 – Effect of Operating HEPA Filters to High-Pressure Drop on Filter Life and Maintenance Cost (including replacement filters and labor)

The cost of ductwork, on the other hand, may not be significantly affected by operation to a high pressure drop because there is a minimum sheet-metal thickness for effective welding, regardless of pressure. The cost of fans and motors is a function of the maximum total pressure that must be developed. Fan horsepower can be estimated from the following equations.[28]

$$hp_f = \frac{Q\Delta\rho}{6356E_f} \qquad (2.1)$$

where:

hp_f = fan hp
Q = system airflow, cfm
$\Delta\rho$ = maximum pressure drop across air cleaning system, in. wg., at time of filter replacement
E_f = fractional efficiency of fan (0.60 usually assumed for estimating).

Motor horsepower can be estimated from the equation:

$$hp_m = \frac{hp_f}{E_m} \qquad (2.2)$$

where:

hp_m = motor horsepower
hp_f = fan horsepower
E_m = fractional motor efficiency (0.90 usually assumed for estimating for 20 hp motors and larger).

Annual power costs can be estimated from the following equation:[28]

$$C = \frac{Q\Delta phr}{8520E'_f E'_m} \qquad (2.3)$$

where:

C = annual power cost, dollars,
h = hours of operation per year,
r = cost of power, cents / k / Whr,
E'_f and E'_m = efficiency of fan and motor, respectively, over the period of operation from filter installation to replacement; these will be less than the design efficiencies.

Although investment and power costs will be lower for systems operated to 2-in.wg pressure drop, the total annual cost of owning a system, including materials and labor costs for filter replacement, may be less for a system in which HEPA filters are replaced at pressure drops on the order of 4 in.wg. Total savings for the facility as a whole may be even greater when the reduced interruption of building operations due to the reduced frequency of filter change is taken into consideration.

Some prefilters can be operated to higher pressure drops than recommended by their manufacturers (but such overuse must be supported by operating experience). This results in less frequent prefilter changes than when prefilters are changed at a pressure drop of only two or three times the clean-filter pressure drop, as recommended by most manufacturers. Care must be taken in selecting prefilters. Because of the many types, efficiencies, configurations, and constructions available, the designer must specifically investigate the safe overpressure allowance for the particular model under consideration. **Figure 2.6** clearly shows the results of overpressuring prefilters. In the case shown, the problem of filter blowout was overcome by working with the manufacturer to reinforce the filter itself. Some benefit could also have been obtained by installing a screen or expanded metal grille on the downstream face of the prefilters against which the filter cores could bear; in any event, screens or grilles would have prevented damage to the HEPA filters when pieces of prefilter struck them.

2.3.6 Sizing and Rating

Underrating. The service of all internal components (except moisture separators) can be extended, and system pressure drop for a given level of dust loading can be reduced by underrating, i.e., by oversizing the system and installing more filter and adsorber capacity to meet system design airflow needs (based on the nominal airflow rating of the components). **Figure 2.7** shows that the increase in filter life obtainable by underrating is roughly proportional to the square root of the degree of underrating. A study by the Harvard Air Cleaning Laboratory suggests that the economic limit of underrating is about 20 percent (i.e., system design airflow capacity).[24]

Overrating. Operation of a system at airflows greater than the installed airflow capacity of the system must be avoided, particularly in systems with radioiodine adsorbers whose performance depends on the residence time of air within the adsorbent bed. When airflow rates exceed the rated airflow capacity of HEPA filters, efficiency is reduced and filter life decreases more rapidly than the equivalent increase in flow rate, as can be seen from the 120 percent curve in Figure 2.7. As noted above, the residence time of contaminant-laden air in adsorber units is inversely related to airflow rate. Overrating of these units decreases their ability to trap gaseous contaminants, thereby degrading their function.

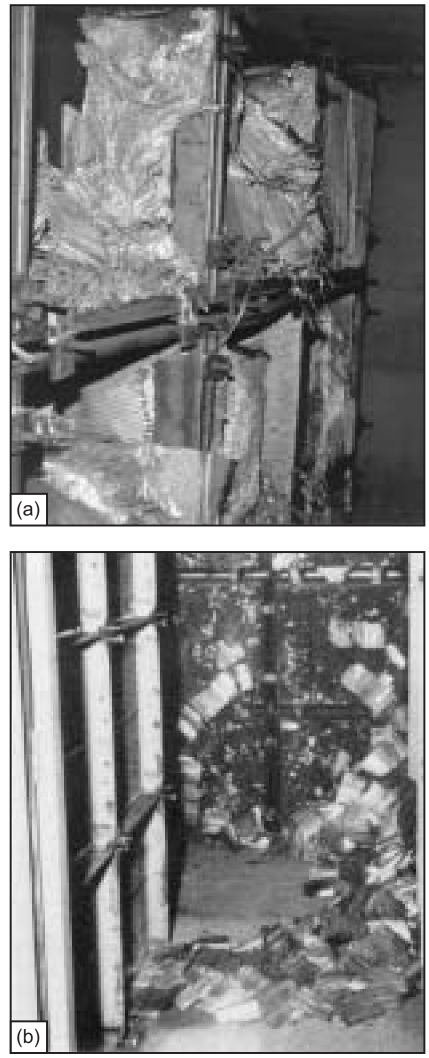

Figure 2.6 – Result of Overpressuring Prefilters

2.3.7 Uniform Airflow Design

In large air cleaning systems, because of the stratification of airflow due to poor transitions between ducts and housings or between housings and fans, or because of poorly designed housings, filters or adsorbers at the center of a bank may receive higher airflow than those on the periphery of the bank. This not only results in non-uniform dirt loading of filters but may also result in excessive penetration of those HEPA filters closer to the air intake if the degree of airflow non-uniformity is great. **Figures 2.8(a) and 2.8(b)** show that penetration of HEPA filters by very small particles is directly velocity-dependent and increases significantly at very high airflow rates. Conversely, penetration of HEPA filters by particles larger than 1 µm may increase at very low flow rates due to the reduction in effectiveness of the impaction mechanism on which trapping of those particles depends. If some filters are operating at very high airflow and some at very low airflow, as could happen in a poorly designed housing and filter bank, it is possible that significant penetration

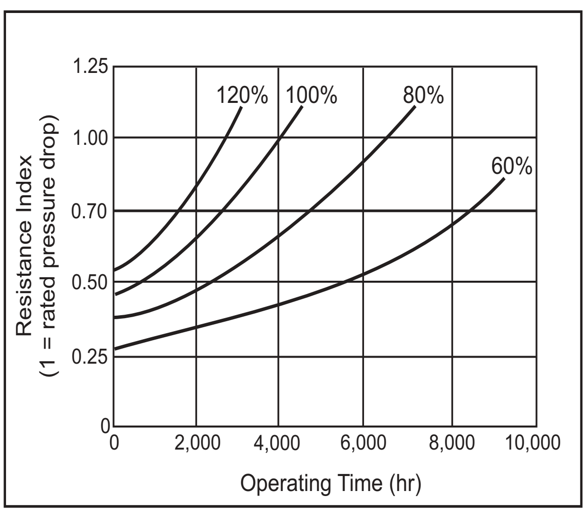

Figure 2.7 – Effect of Underrating on Service Life of Extended-Medium Filters, Based on Percentage of Manufacturer's Rated Filter Airflow Capacity

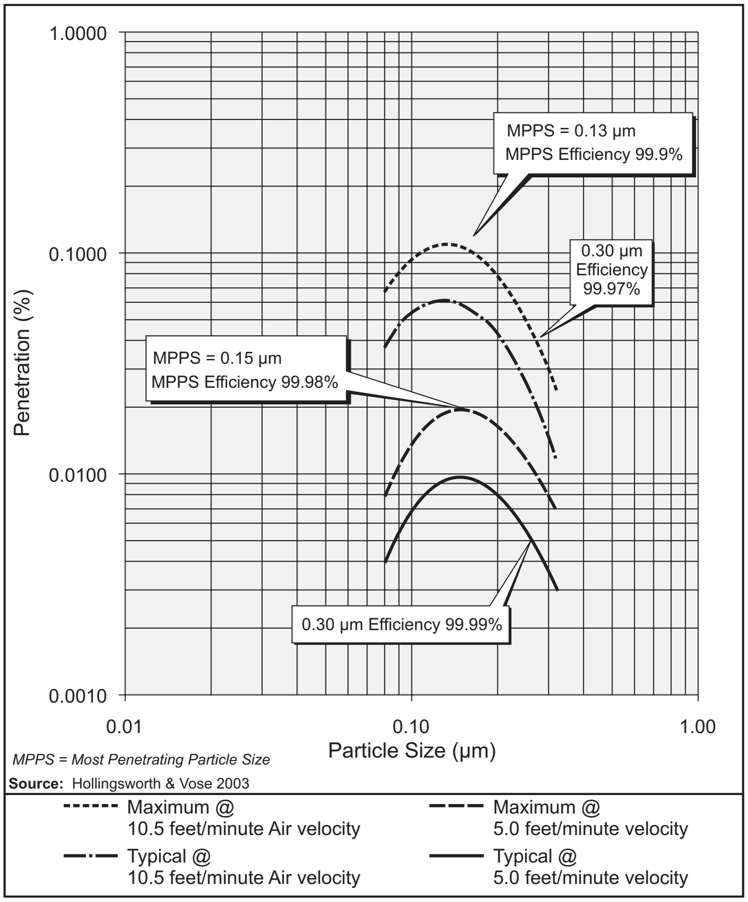

Figure 2.8(a) – HEPA Media Penetration[34]

could occur even though the filters are in good condition. Low flow rates improve the efficiency of radioiodine adsorbers, but high flow rates decrease efficiency. Therefore, significant non-uniformity of airflow through a bank of adsorber cells can reduce the overall efficiency for trapping radioactive gases of interest. A well-designed duct-to-housing transition will produce satisfactory airflow distribution through the banks of filters and adsorbers.[25]

Filter housings can be obtained with built-in devices to assist in generating uniform up- and downstream flow distribution using Stairmand disks and similar devices. These make testing faster and more accurate, and minimize those occasions when personnel must enter the filter housing (a confined space) for any reason.

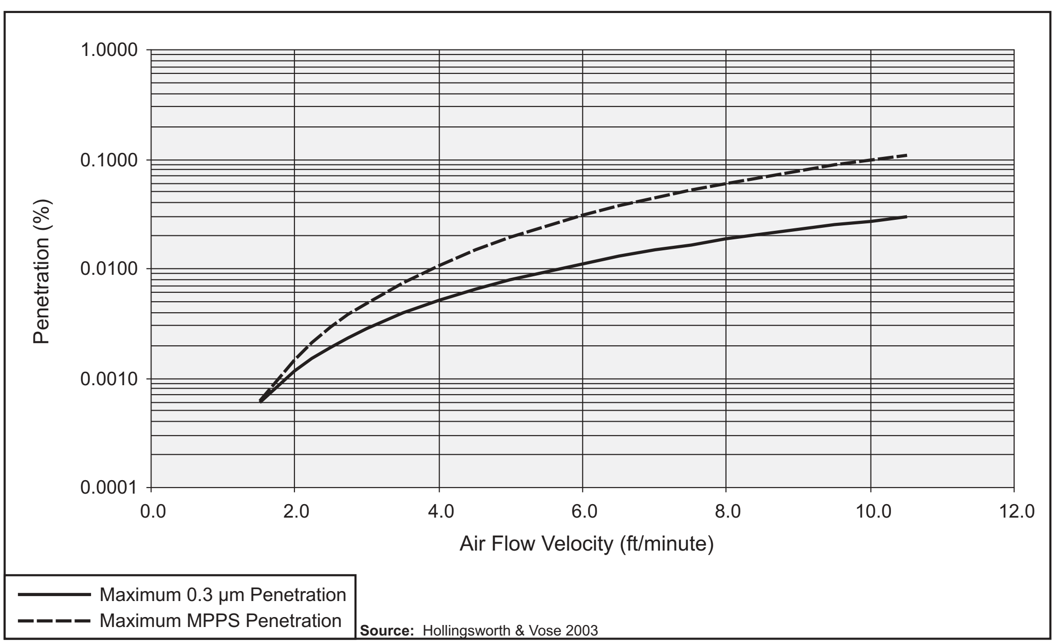

Figure 2.8(b) – Maximum Penetration Versus Airflow Velocity

2.3.8 Maintainability and Testability

Air cleaning systems designed in accordance with ASME AG-1[4] should result in optimum systems for maintainability and testability. There are many previously installed systems that were designed to ASME N509,[29] the predecessor to ASME AG-1.[4] Systems designed to ASME AG-1 requirements should be tested in accordance with ASME AG-1, Section TA. Those systems designed to ASME N509 or still covered by its 2002 maintenance revision, should be tested in accordance with the provisions of ASME N510.[23] Other older systems not designed to either ASME AG-1 or N509 are generally tested by following the guidance in ASME N510.

Maintenance and testing are two operational factors whose cost can be minimized by good initial design and layout of ventilation and air cleaning systems. Inadequate attention to maintenance and testing requirements at the initial phase of the project can result in much higher operating costs. New system specifications should be designed and tested in accordance with ASME AG-1.[4] Some existing systems may have been designed to ASME N509.[33] These and other non-ASME AG-1-designed systems may be tested in accordance with the guidelines provided in ASME N510.[23]

Design of air cleaning systems in accordance with ASME AG-15 will result in optimum maintainability and testability. Two elements that largely influence the costs of these functions are the accessibility of components requiring periodic test and service and the frequency of filter and adsorber replacement. In systems that involve handling of radioactively contaminated filters and adsorbers, the frequency of changing these components and the time required to accomplish the change can be especially critical, because the total integrated radiation dose a workman can be permitted to receive in each calendar period is limited. When all personnel have received their maximum permissible dose for the year, the supervisor faces the prospect of having no one available to carry out a needed filter change or a scheduled test. Maintenance and testing of radioactively contaminated and other highly toxic systems are much more costly than the same operations in nonradioactive systems because of the time required for personnel to change into and out of protective clothing; to decontaminate and cleanup the area, tools, and equipment after the operation; to dispose of contaminated filters (a significant cost itself); and to bathe and be monitored by health physicists.

In addition, extra attention must be given to filter or adsorber cell installation (compared with common air filters, for example). If the system does not meet the test requirements of ASME AG-1, Section TA,[4] after the change, then rework must be performed until the problems are found and corrected. There is also a need for health physics monitoring before, during, and after all maintenance operations. The fact that personnel have to work in protective clothing and respirators also adds to the time required. Regardless of these inherently high time and money costs, proper maintenance and testing are primary factors in ensuring the reliability of the air cleaning system, and they cannot be done properly unless the facilities have been properly designed and built.

Frequency of Maintenance and Testing

Measures that reduce the frequency of filter (HEPA and prefilter) and adsorber replacement also reduce system costs and downtime. Several of the factors discussed earlier—the use of good building supply-air filters and prefilters and underrating—serve to extend component life and reduce the frequency and cost of service. Exhaust system HEPA filter and adsorber installations must be tested to the requirements of ASME AG-1, Section TA,[4] after each component change so that any extension of service life also directly reduces testing costs. [Note, however, that regulatory bodies often dictate frequency of testing.]

Accessibility

When laying out ventilation and air cleaning facilities, the designer must consider the location of fans, dampers, instruments, and filter housings, as well as the working space adjacent to them; working space and spacing of banks within man-entry housings; height and array of filter and adsorber banks; and routes to be used for moving new and used filters and adsorbers between storage, installation, and disposal areas. Where it is permissible to fill and drain adsorbers in place, it is imperative to provide space and routing (from the storage location to the air cleaning unit) for the charging cart and the adsorbent drums. This apparatus is a large piece of movable equipment. In addition, space for drums of adsorbent must be provided because they are used in conjunction with operation of the charging cart. Failure to provide adequate space in and around housings and mechanical equipment (fans, dampers, etc.) results in high maintenance and testing costs, inhibits proper care and attention, creates hazards, and increases the chance for accidental spread of contamination during service or testing operations. Recommendations for arrangement and space requirements for air cleaning components should be in accordance with ASME AG-1[4] and ASME N509[29] (for those system components that have not been incorporated into ASME AG-1). Even greater space requirements are needed for remotely maintainable systems. For systems not designed to meet ASME AG-1 requirements, guidance can be found in ASME N510.[23]

Ease of Maintenance and Testing

Simplicity of maintenance and testing is a primary factor in minimizing the time personnel must remain inside a contaminated housing and restricted areas of a building during a filter or adsorber change or test. Therefore, it is an important factor in reducing both personnel exposures and costs. The following strategies will help ensure simplicity of maintenance and testing:

- Filter housings should be laid out and designed in accordance with ASME AG-1[4] and ASME N509[29] to ensure quantitative tests can be performed and to minimize reaching, stooping, and the use of ladders or temporary scaffolding for gaining access to filter or adsorber cells. Some reaching and stooping is unavoidable in man-entry housings, but it should not be necessary for personnel to perform physical contortions or climb ladders to remove and replace filters in single-filter installations. Similarly, in bank systems, it should not be necessary for workmen to climb ladders or temporary scaffolding to gain access to the upper tiers of filters or adsorbers. If this is unavoidable, then permanent ladders and platforms need to be built into the air cleaning housing. Personnel entries into housings should be minimized. These are, at best, confined spaces that require permits for access and have contaminated surfaces that require additional, potentially costly and difficult, precautions.

- Racks (frames) should be designed to the requirements of ASME AG-1, Section FG,[4] and ASME N509[29] to ensure proper spacing between components for maintainability and testability.

- Electrical, water, and compressed air connections should be available nearby, but in no case should they be located inside the filter house.

- Materials-handling equipment should be employed, including dollies for moving new and used filters and adsorbers, hoists or other means of handling the heavy adsorber cells in systems containing these components, and elevators or ramps for moving loaded dollies up and down within the building.

- Filter housings should be located inside the building. It is undesirable for personnel to: (1) conduct a filter change or test out of doors where wind or rain may cause a spread of contamination, (2) cross a roof to gain access to a filter housing, or (3) wait for good weather to carry out a scheduled filter or adsorber change or test. Weather damage and corrosion are always possible, especially with wood-framed filters.

- Decontamination and clothing-change facilities (including showers) should be located nearby.

- Maintenance and testing (per ASME AG-1, Section TA,[4] and plant maintenance procedures) should be well planned and rehearsed. This is particularly important to keep radiation exposure for workers at as low as reasonably achievable (ALARA) levels.

- Adequate finger space (1 inch minimum is desirable) should be available between filter elements, and handles should be provided on heavy components such as adsorber cells.

- Cradles or benches should be built into the component mounting frame for aligning and supporting filters (adsorbers) prior to clamping to face-sealed mounting framers (see Chapter 4, Section 4.4.4).

- For simple filter and adsorber clamping devices, a properly designed bolt-and-nut clamping system has proven most satisfactory in the past, although numerous methods of minimizing or eliminating loose parts are currently being investigated. Toggle clamps, over-center latches, and other devices are easily manipulated and require no tools; however, they often tend to jam, become difficult to operate, or lose their ability to properly clamp the filter or adsorber cell after extended exposure to the hostile environment of a contaminated air cleaning system. Such devices should be used only after due consideration of the difficulties that would be involved in replacing them in a contaminated system (see Chapter 4, Section 4.4.6).

- Ledges and sharp corners that a worker might stumble over or might snag or tear their protective clothing on should be eliminated.

- Adequate lighting should be provided in, and adjacent to, the filter house and to other items that require periodic service, inspection, or testing.

- Means of communication between personnel inside and outside the filter house should be provided.

- Floor drains in housing and adjacent workspaces should be provided to facilitate easy removal of water spilled or applied during decontamination of the area after a filter or adsorber change. Drains must be designed so that no air can bypass filters or adsorbers.

- Rigid, double-pin-hinged doors should be available on personnel entry housings and should be large enough for personnel to pass through without excessive stooping or twisting. It should not be necessary to remove several dozen nuts from a hatch to gain entry to a personnel entry or single-filter housing. Not only is this too time consuming, but nuts tend to cross-thread or gall to the extent that it is often necessary to cut off the bolt to open a hatch; or the nuts get dropped and lost and are often not replaced, thus compromising the seal of the hatch. Sliding doors are not suitable because they will jam with any distortion of the housing wall (see Chapter 4, Section 4.4.17) and are difficult to seal.

- Maintenance and testing procedures specific to the system being tested should be well planned and rehearsed.

- There should be adequate space for materials and test equipment and access (through preplanned doors or panels) to both sides of filter and adsorber banks.

Construction

Designing for maintainability requires careful attention to the details of construction, including tolerances, surface finishes, and the location of adjacent equipment and service lines. Ducts and housings should have a minimum number of interior ledges, protrusions, and crevices that can collect dust or moisture, impede personnel, or create a hazard in the performance of their work. Prefilters at duct inlets will minimize the accumulation of dust and contamination in the ducts. If these are not provided and the hazard analysis permits, easily opened ports and hatches for inspection and cleaning must be provided at strategic and accessible locations in the duct. [Note: Easily opened ports and hatches are not appropriate for plutonium-bearing systems.] Duct runs should have enough mechanical joints to permit easy erection and dismantling. Otherwise, replacement of radioactively contaminated ducts can be an expensive and hazardous job.

Housings, ductwork, and component-mounting frames must be able to withstand anticipated system pressures and shock loadings without distortion, fatigue, or yielding that permits in-leakage or bypassing of the filters or adsorbers. These components must meet a pressure test in accordance with the requirements of ASME N509[29] and ASME AG-1.[4]

Interior surfaces and finishes warrant special attention. Regardless of the formulation when coatings are used, a primary factor in a long, dependable service life is proper preparation of the surface to be coated. Manufacturers' coating or paint instructions and plant procedures must be followed precisely. One alternative to the coating requirements is to build the housings and housing components from stainless steel or other harsh-environment-resistant materials. This reduces the need for frequent and costly repair to coatings that are damaged as a result of routine testing and maintenance.

2.4 Emergency Considerations

The ventilation and air cleaning systems of a building in which radioactive materials are handled or processed are integral parts of the building's confinement. In some cases, these systems may be shut down in the event of an operational upset, power outage, accident, fire, or other emergency. In other cases, they must remain operational to maintain the airflows and pressure differentials between building spaces and between the building and the atmosphere as required to maintain confinement. In some of these cases, airborne radioactive material may not be a problem until an emergency occurs. In all cases, however, a particular danger is damage to or failure of the final HEPA filters (and adsorbers in those facilities where radiolytic particulates could be released) that constitute the final barrier between the contained space (hot cell, glovebox, room, or building) and the atmosphere or adjacent building spaces. Even if the system can be shut down in the event of an emergency, protection of the final filters is essential to prevent the escape of contaminated air to the atmosphere or to allow personnel to occupy spaces of the building.

Consideration must be given to: (1) the possible effects of operational upsets, power outages, accidents, fires, and other emergencies on the ventilation and air cleaning systems, including damage to the filters and adsorbers from shock, overpressure, heat, fire, and high sensible-moisture loading; (2) the design and arrangement of ducts and air cleaning components to alleviate these conditions; (3) the means of switching to a redundant air cleaning unit, fan, or alternate power supply; and (4) the methods of controlling or isolating the exhaust system during failure conditions. To provide the necessary protection to the public and plant personnel, the air cleaning and ventilation system components on which confinement leakage control depends must remain essentially intact and serviceable under these upset conditions. These components must be capable of withstanding the differential pressures, heat, moisture, and stress of the most serious accident predicted for the facility, with minimum damage and loss of integrity, and they must remain operable long enough to satisfy system objectives.

2.4.1 Shock and Overpressure

Mechanical shock in an air cleaning system can be produced by an explosion in an operating area of the building, by an earthquake, or by rapid compression or decompression of the air inside a system caused by sudden opening or closing of a damper or housing doors. When pressure transients last for periods measurable in seconds, static pressure is primarily responsible for any destructive effect. For shocks that last only a few milliseconds with a nearly instantaneous pressure rise, as occurs in most chemical explosions, the extent of destruction is primarily a function of the momentum of the shock wave. Shocks produced by an earthquake or inadvertent opening or closing of a damper usually fall somewhere between these two extremes. Protection of the final filters and adsorbers against failure from shock can be accomplished by isolating them to prevent the transmission of destructive forces to them and by increasing the shock resistance of ducts, housings, mounting frames, and equipment supports.

The shock resistance of HEPA filters can be enhanced by faceguards and similar treatment may sometimes improve the shock resistance of prefilters. Most prefilters used today, however, probably have low shock and overpressure resistance, and a screen installed between them and the HEPA filters is recommended to prevent the condition shown in Figure 2.6. Adsorbers, both unit-tray and permanent single-unit types are generally of a robust construction that should be relatively unaffected by shock loadings if properly installed. Filter and adsorber mounting frames and housings designed in accordance with recommendations in Chapter 4 will probably have adequate shock resistance for most applications. The difference in the ability of the two fan installations, shown in **Figure 2.9**, to withstand a substantial degree of shock is readily apparent.

Protection of the primary air cleaning components can be achieved by using fast-acting isolation. Although turning vanes, dampers, moisture separators, and prefilters may be damaged by a shock wave, they may also serve to attenuate its force to some degree and thereby provide a measure of protection to the HEPA filters downstream. Damage to dampers, however, can result in inability to control flows or isolate branch lines. Sand filters are employed in some DOE facilities for protection of the final filters and to prevent loss of confinement in the event of explosion, earthquake, tornado, fire, or shock. As discussed in Chapters 3 and 9, sand filters are large deep beds of graded sand and gravel, installed in underground concrete enclosures. In some cases they are employed as final filters. Because of their size, a true efficiency test cannot be performed on a sand filter installation. Field tests have shown leakages comparable to HEPA filters. Their large mass bed size will dampen most conceivable explosions and deflagrations. Airflow is upward through the bed, and leakage caused by the explosion should be only momentary because of the great mass of sand and gravel comprising the filter. The disturbed sand should fall back to heal the breach. This large mass of sand and gravel also provides a substantial heat sink in the event of fire in a ventilated space. The disadvantages of sand filters are very high initial cost and high pressure drop.

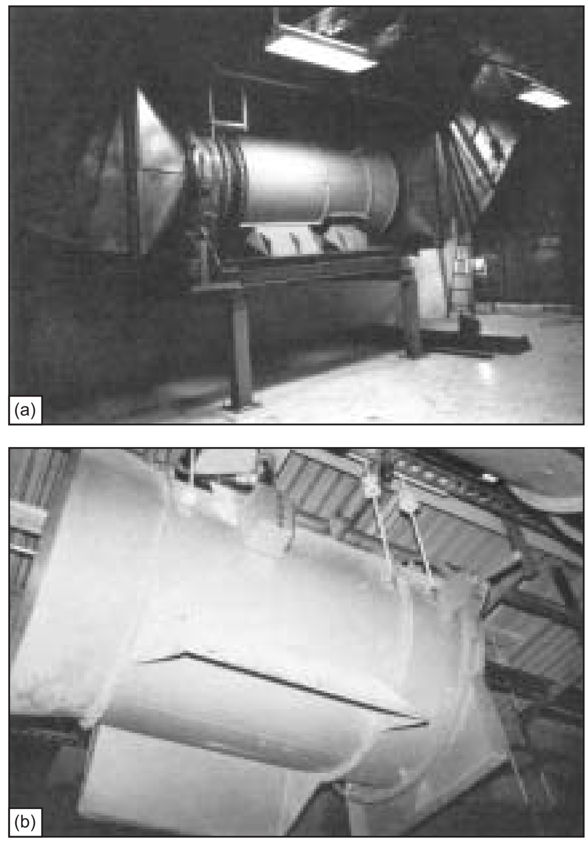

Figure 2.9 – Methods Employed for Installing Axial-Certrifugal Fans in Different Nuclear Reactor ESF Air Cleaning Systems—(a) Shock-Resistant Base-Mounted Fan; (b) Hanger-Rod Supported Fan. (Note anchor plates provided by Fan Manufacturer, but not used.)

Explosion in an operating area of a building is probably the most likely type of shock-generating incident that one can expect in radiochemical, laboratory, and experimental facilities. A chemical explosion is no more than a rapidly burning fire and therefore, in a confined space, can be arrested if a suppressant can be introduced quickly enough.

2.4.2 Power and Equipment Outage

Emergency plans must account for the probable occurrence of power and equipment (particularly fan) failures. Such failures, if not property planned for, can result in a contamination hazard to the public or operating personnel, particularly in buildings with zone ventilation where airflow must be maintained to preserve pressure gradients between zones and to prevent backflow to contaminated air to occupied spaces. Possible emergency measures include redundant fans, redundant fan motors (perhaps served from independent power sources), and alternate power supplies (e.g., steam turbine or emergency diesel-electric generator). Where continuous airflow must be maintained, facilities for rapid automatic switching to an alternate fan, power supply, or emergency source, or to a standby air cleaning unit, are essential. However, if brief interruptions of flow can be tolerated, manual switching may be permissible at less expense. In any event, visible and audible alarms should be provided, both locally and at a central control station, to signal the operator when a malfunction has occurred. In addition, indicator lights to show the operational status of fans and controls in the system should be provided in the central control room.

2.4.3 Air Cleaning System Layout Considerations

The layout and location of air cleaning facilities can have a direct bearing on the system's capability of effecting control under upset conditions and of limiting the adverse consequences of such an upset.

Compartmentation and Segmentation

A higher degree of control is required in the event of a fire, explosion, equipment outage, or other system upset if the air cleaning system is segmented or if the individual air cleaning units are compartmented. Segmentation permits isolation of a damaged unit and minimizes the chance that the entire system will become inoperable at the same time. Series compartmentation is employed in some potentially high-risk applications to permit further isolation of the less critical air-pretreatment facilities (demister, prefilters) from the more critical final HEPA filters and adsorbers. Series parallel arrangement of a central exhaust filter system that handles high-specific-activity alpha-emitting materials is shown in **Figure 2.10**. In the event of fire or equipment damage in any one housing of this system, or in the filters, the housing can be isolated and the remainder of the system kept in service. Also, any one of the housings can be isolated for testing or filter change (under normal operating conditions) without interruption of work being conducted in the building. NRC Regulatory Guide 1.52[27] recommends that the installed capacity of any one air cleaning unit be no greater than 30,000 cubic feet per minute (cfm) to permit more effective control in the event of an emergency and to permit more reliable surveillance testing of the HEPA filter and adsorber stages of the unit.[29]

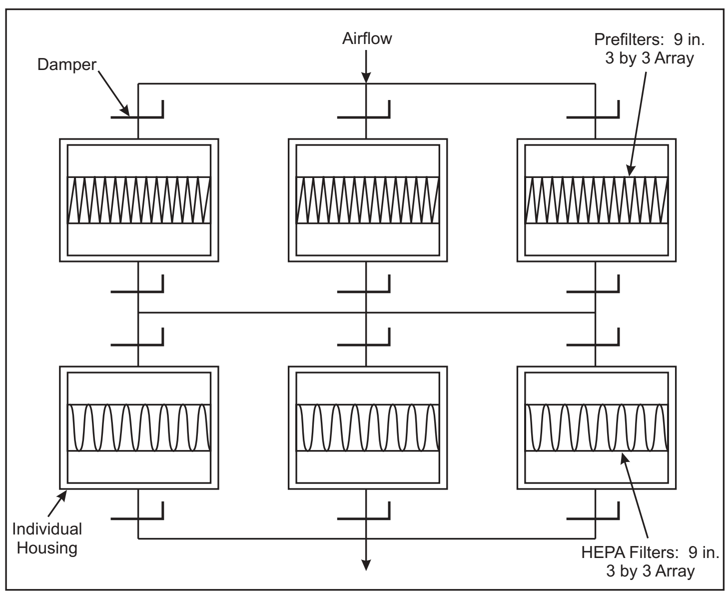

Figure 2.10 – Series-Parallel Arrangement of Central Exhaust Filter System of a High-Hazard Radiochemical Laboratory (Note: Dampers that Permit Isolation of Any Housing Without Stopping Exhaust Airflow)

Redundance

Redundant air cleaning facilities are often required in potentially high-risk operations, such as reactors and radiochemical plants, to ensure continuous ventilation in the event of failure of an online air cleaning unit. In the case of reactor post-accident cleanup systems, redundant air cleaning units are required even though the system is normally in a standby condition. **Figure 2.11** shows the segmented, redundant, normal offgas and building-exhaust air cleaning systems of an experimental water-cooled reactor with vented confinement. Of the two units of each system, which are normally online, one is capable of meeting exhaust requirements when the building supply fans are shut down in the event of an emergency. High-quality isolation dampers are essential in redundant systems, not only to protect the offline units when not in service, but to prevent bypassing of the air cleaning system through a damaged offline air cleaning unit.

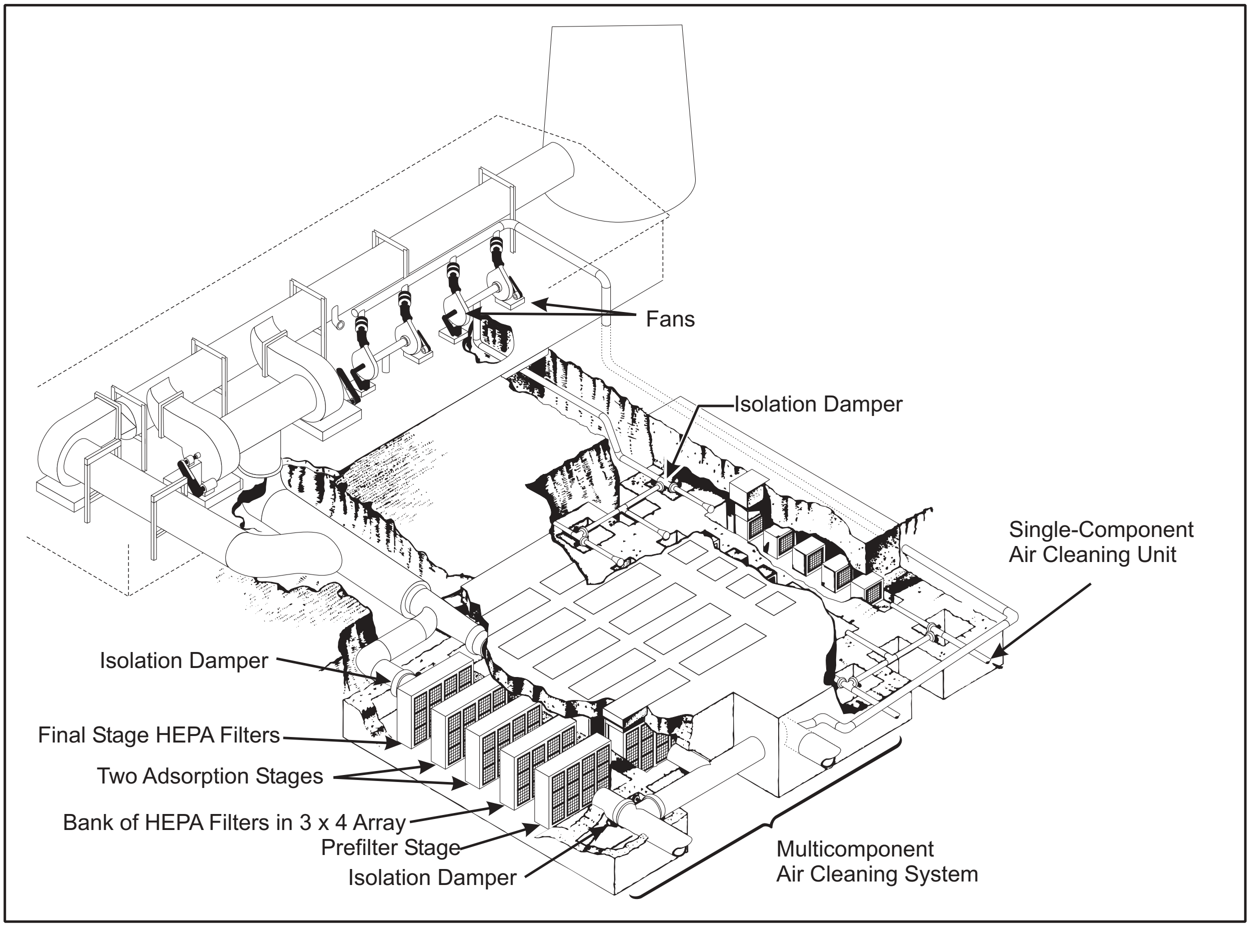

Figure 2.11 – Experimental Reactor

Location of Air Cleaning Facilities

The location of filters, fans, and other air cleaning components can play a major part in minimizing component damage and spread of contamination in the event of a fire, system upset, or other emergency. A common but undesirable practice has been to install such items in random locations in attics or unused building spaces. **Figure 2.12** illustrates a type of filter installation in which a wood-cased filter was simply clamped between two flanged duct transitions in an open attic space. There is no floor a catwalk adjacent to the filter, with the danger that service personnel risk falling through the ceiling to the room below. Access is limited by the adjacent hangers and ducts. Furthermore, because the location is in an open attic space, dropping a used filter during a filter change, or breach of the wood filter case in the event of a fire, would result in the spread of contamination throughout the entire attic, which would be difficult if not impossible, to cleanup. In-duct installations of this type, in which the wood filter case is part of the pressure boundary, do not conform with NFPA 90A.[29] For this reason, the design is not acceptable and a housing must be used.

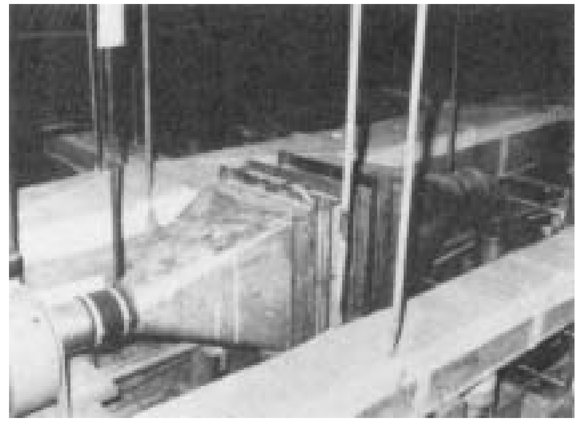

Figure 2.12 – An Illustration of Poor Filter Installation Practice

Figure 2.13 illustrates another example of poor filter installation and location. The location of the light troffer indicates that the air cleaning unit (which is provided for control room ventilation in a nuclear reactor) is located about 20 feet off the floor, and access is seriously impeded by hangers, cable trays, piping, and other equipment. This unit is a wood-cased chemical, biological, radiological (CBR) filter, which, like the filter installation shown in Figure 2.12 does not comply with NFPA 90A.[29] Again, this unit is located in an open and normally occupied building space where a serious spread of contamination could result if the filter were dropped during service or breached in an accident or fire. Furthermore, fire external to the filter could also breach the filter case and permit contamination to spread from the room to other portions of the building. **Figure 2.14** illustrates a better practice by showing an air cleaning facility installed in a large room that can be isolated as a radiation zone in the event of an emergency or spill without risking contamination of adjacent facilities.

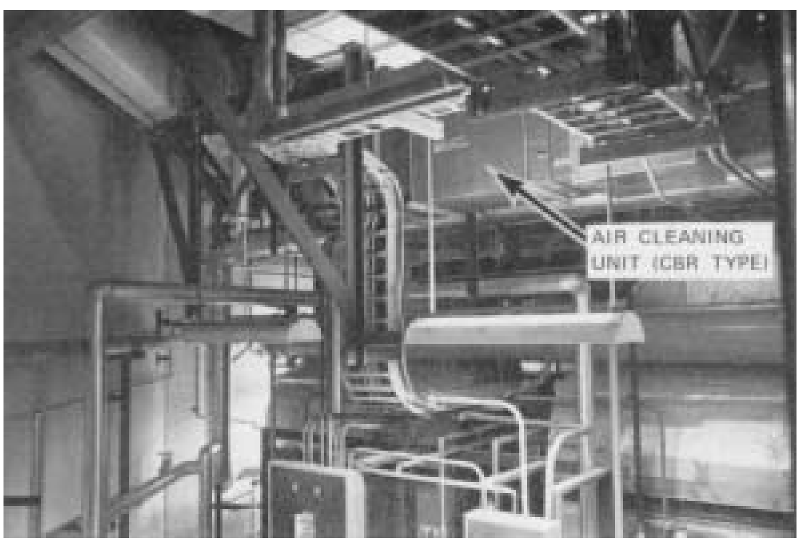

Figure 2.13 – An Illustration of Poor Filter Installation Practice

Another common practice has been to install ducts and filter housings on the roof of a building, which are accessible only over the roof. In the event a used filter is dropped during maintenance, there is a potential for contamination spread not only to a surface (the roof), which would be difficult to decontaminate, but to the atmosphere as well. For all systems, but especially for potentially high-hazard systems, it is recommended that all air cleaning components, including ductwork, be located inside a building space to provide a secondary

Figure 2.14 – Series-Compartmented Air Cleaning System

confinement against breach of the pressure boundary. Preferably, such building spaces should be heated to minimize condensation in the ducts during the winter months, and they should be easily accessible for inspection and service. Housings should be located in rooms that can be isolated during service or an emergency and that have walls and floors that can be easily decontaminated in the event of a spill. As a minimum precaution, the general areas surrounding the housing should be one that can be cordoned off as a contamination zone. Off-the-shelf bag-out housings of the type, shown in **Figure 2.15**, are being used increasingly for single-filter installations. Although the bag-in bag-out provisions of those housings offer a measure of protection against spills during service operations, the plastic bags employed can be torn by the sharp corners of steel-cased filter elements and adsorber cells. It is recommended, therefore, that these caissons be installed in isolable rooms or controlled building spaces, at least in those cases where intermediate to high-level radioactive material is, or could be, present in the duct. Additional information on caissons and bag-in bag-out filter installations is given in Chapter 6.

2.5 Multistage Filtration

Although a single stage of HEPA filters is sufficient to meet most decontamination requirements, two, three, or even more stages may be required to meet the stringent requirements of facilities in which plutonium and other transuranic materials are handled. Multistage HEPA filtration is also employed to increase system reliability through series redundancy.

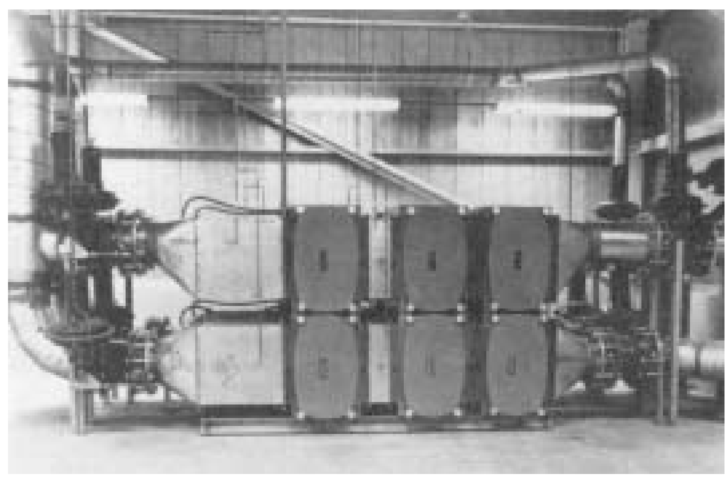

Figure 2.15 Exhaust Air Cleaning System of Radiopharmaceutical Company

2.5.1 Series Redundancy

Installations such as the DOE national laboratories and production facilities which have lived with radiation on a day-to-day basis for many years have found it necessary to employ series redundancy of HEPA filters in exhaust and air cleanup facilities for Zone I, and often Zone II, confinements. The purpose is to increase the reliability of the system by providing backup filters in the event of damage, deterioration, or failure of the first-stage filters. Each stage of filters must be individually testable if credit for redundancy is to be clamed. That is, if the stages are not individually testable, the combination of two or more stages must be considered as only a single stage from the standpoint of reliability. On the other hand, each untestable stage contributes to the overall filtration efficiency of the combination, although not to an extent equivalent to the nominal stage efficiency of 99.97 percent [decontamination factor (DF)=3333]; a maximum efficiency of 99.8 percent (DF=500) has been allowed in the past for untestable second- and third-stage filters, with full credit for the stage. For new systems, no credit should be assumed for non-tested filters.

Redundant stages should be well spaced, the first often being a duct-entrance filter in a room, glovebox, or hot cell, and the second being the final filters of a central exhaust system. In some systems, for example the ESF air cleaning units of nuclear power plants, the series-redundant filter banks are installed within the same housing. In any event, redundant stages should be spaced sufficiently far apart to allow for effective in-place testing and inspection of both faces of the filters; they should not be installed back-to-back or to other components of the system such as prefilters or adsorber cells.

2.5.2 Increased Decontamination Factor (DF)

The particle sizes of plutonium aerosols generated in chemical operations employed in nuclear fuel fabrication and reprocessing fall within the range of the size of maximum penetration (SMP) for HEPA filters, 0.07 to 0.3 µm light scattering mean diameter (LMD). Although 0.3 µm LMD is considered the SMP for dust and other unit-density particles, the SMP for high-density particles, such as plutonium, is substantially higher. The aerodynamic mean diameter of plutonium particles formed by condensation is thought to lie between 0.4 and 0.7 µm.[28] A HEPA filter, by definition, has a minimum filtration efficiency of 99.97 percent (DF=3333) for 0.3-µm particles (although most of the HEPA filters currently being validated by the DOE Quality Assurance Stations exhibit DFs on the order of 10^4). Current NRC Regulatory Guides recommend a total plant DF of at least 10^{11} for plutonium in gaseous effluents. Although some decontamination is effected by plant operations, the greatest portion must come from the HEPA filters, which means that two, three, or even more stages of filters may be necessary.

Theory predicts that the primary mechanisms in the arrestance of particles by a HEPA filter are diffusion and inertia; the effectiveness of these mechanisms varies with particle size, airflow velocity through the medium and, to a lesser extent, particle density as shown in **Figure 2.16**. Direct interception, or impaction, is a secondary mechanism that is independent of these parameters. As evident from Figure 2.16, these mechanisms combine to produce a statistical average DF, not an absolute value for a given particle size. For this reason, the effect of adding stages of HEPA filters is multiplicative and does not produce a screening effect that theoretically results in an absolute minimum DF for any given particle size. (In practice, however, some screening of particles substantially larger than the SMP can be expected.) In theory, therefore, the DF of a multistage HEPA filter installation would be DF^n_f, where DF_f is the definition DF of the HEPA filter (DF=3333) and n is the number of stages. Work at the Los Alamos National Laboratory suggests that this theory is essentially true[30]; DFs of 10^4 for stages one and two and of somewhat less than 5×10^3 for the third stage of a three-stage system, with an average DF of 5×10^3 for each of the three stages, were determined. These results were obtained in a small-scale test system (about 25 cfm) in which conditions were idealized by eliminating gasket leakage and employing filter units that exhibited a test efficiency (according to DOE Quality Assurance Station testing) of greater than 99.99 percent.

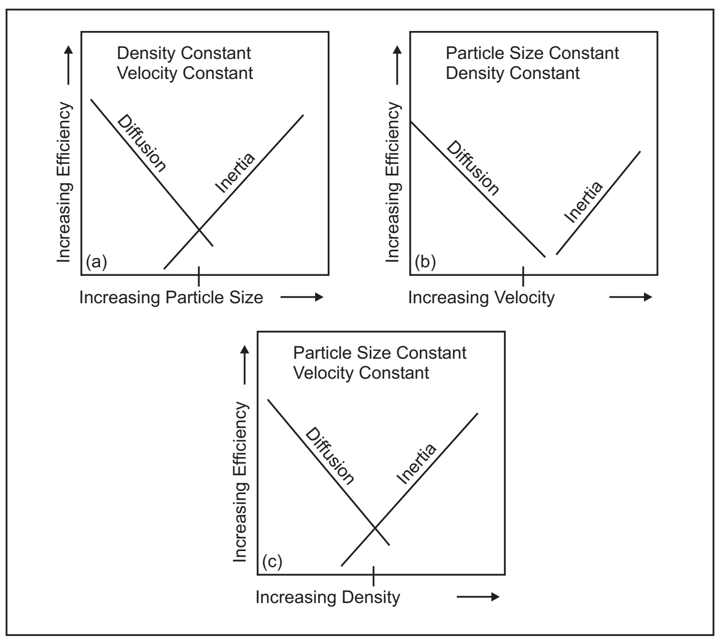

Figure 2.16 – General Effect of Principal Mechanisms that Affect the Arresting Efficiency of the HEPA Filter

Earlier less definitive tests and experience had indicated substantially lower values of DF in the second and third stages, and conservatism suggests that values lower than those obtained in the Los Alamos tests should be used in practice. Conservatism also suggests that a value no higher than DF 3333 be used for the first stage, and probably somewhat less to allow for filter degradation under service conditions. Although DF improves with dust lading of the filter, aging and exposure to moisture and corrodents may decrease the ability of the filter to maintain the higher DF under system upset conditions. For purposes of estimating the capability of a multistage HEPA filter installation under normal operating conditions, a DF of $(3 \times 10^3)^n$ can be safely used with systems that adhere to the design, construction, testability, and maintainability principles of this handbook or ASME N509.[33]

Accident analyses typically assume a first stage credit of 99.9 percent efficiency (DF of 10^3) for removal of plutonium aerosols. Second and subsequent stages typically assume an efficiency of 99.8 percent (DF of 5×10^2). These assumed efficiencies are based on the premises that: (1) the HEPA filters have successfully been through the DOE Filter Test Facility (FTF) at Oak Ridge; (2) they are installed and in-place leak tested to at least 99.95 percent[31]; (3) they are installed in a system built to the specifications of AG-1; and (4) are tested in accordance with national standards.

2.6 Passive Safe Shutdown of Systems

"Passive Safe Shutdown" (PSS) is an expression that describes a confinement concept in use at a hazardous nuclear facility, whereby potential air exhaust pathways are aligned through filtration components, but without a motive force pulling the air through. The concept is basically the same as a judicial arrangement of filtration assets during a facility blackout condition. The potential imminent failure of the exhaust filtration system may also warrant such an arrangement. The PSS concept can be applied as either a penultimate or a first response to an accident situation.

As a penultimate response, every hazardous facility manager should have such a prepared plan for what to do when the lights go out. This should include the arrangement of the facility in such a way that it poses the least threat possible to the facility workers, the environment, and the public. It may also be useful to enter this intentional "operational" mode under extenuating circumstances, such as the exhaust filtration system is in jeopardy of failure (e.g., from internal or external fire threats). However, the plan should also consider expeditious departure from the PSS mode after entry.

When PSS becomes the first, and sometimes only, response to an accident situation, additional attention must be given to potential leakage pathways and accident sampling. The reasons for this are simple. The accident itself could produce some unintended consequences when the PSS mode is entered and the facility is operating at, or greater than, atmospheric pressure. To understand these two potential challenges (i.e., potential leakage pathways and accident sampling) each will be examined in the context of a confinement, versus a containment concept.

Hazardous operations at DOE facilities are typically located inside a confinement. The confinement usually consists of the entire building structure and associated confinement ventilation system(s) (CVS). The building is maintained at a negative pressure relative to atmosphere by the CVS. The CVS is an assortment of several subsystems that cascades the building air from areas of lesser contamination to areas of greater contamination, with some intermediate contaminate removal via filtration. Prior to being exhausted from the building, the air undergoes filtration, sometimes through multiple stages of filters.

Air is supplied to the confinement building by various air supply systems. Typically, air is supplied at a rate slightly less than it is exhausted, such that a vacuum can be maintained throughout the facility. Air may also "leak" into the building through door seals or penetrations and account for the mismatch between supply and exhaust. Various dampers and valves are usually employed to direct the air to specific locations.

Theoretically, with the building maintained at a negative relative to atmosphere, all air that enters the building should exit only after it is filtered.

By contrast, in a containment concept, such as those employed at commercial nuclear power plants, air is bottled up inside an unfired code pressure vessel (the actual confinement) which is surrounded by a reinforced concrete structure, which provides the seismic resistance for the facility. Here there is no unintentional supply or exhaust of air expected during the course of the accident. Also, there is no cascading of air or vacuums relative to atmosphere. Actually, confinement pressures up to several atmospheres are expected. This is not to say that confinements are not found in commercial nuclear power applications, for they are. It's just that the containment is the primary retention device, and not a confinement.

For actual confinements, several factors may cause the building to either "breath" or "exhale." "Breathing" can be caused by the diurnal sun cycle which leads to the heating and cooling of the building and consequent expansion and contraction of the building air. Since the building seeks to remain at atmospheric pressure, it will breath, hopefully through a pre-established filtered pathway, to accommodate the expansion and contractions within the building. This pre-established filtered pathway is the very essence of the PSS concept. Changes in barometric pressure act in somewhat the same way.

The building can "exhale" by several mechanisms. Fires can cause the air to exhale from the building, as can the release of compressed gases, which hopefully are not flammable, inside the facility. Strong winds can create a vacuum on the leeward side of the building and pull air through various penetrations.

The purpose of the last two paragraphs is to demonstrate that there are mechanisms beyond our immediate control (i.e., diurnal cycling, barometric pressure swings, fires, compressed gas releases and strong winds) that can lead to undesirable releases from a structure that is in a passive state. Hopefully the releases will be through filtration devices, but this is dependent upon the integrity of both the structure and the exhaust pathway established.

The greatest threat to confinement, structural integrity, is an earthquake. At nuclear facilities, buildings and equipment, designated Safety Class or Safety Significant are specifically designed to withstand the effects of a design basis earthquake (DBE). This means the building should be structurally usable and the equipment able to perform its intended function after suffering the imparted motions of a DBE or one of lesser magnitude. Cracks and damaged penetrations may be significant in that they could provide potential unfiltered leakage pathways.

To gain some insight into the size of cracks that may be of interest, consider the following for diurnal cycling. A 2 million cubic foot building (200 feet long $\times$ 200 feet wide $\times$ 50 feet high) and a 25 degree Fahrenheit temperature increase, will lead to a 5 percent volume change over 10-hour period, leading to a leak rate of approximately 170 standard cubic feet per minute (scfm). Bypass leak rates of only a few volume percent have been shown in Documented Safety Analysis (DSA) reports to result in calculations that approach the exposure guidelines for the general public. The surface area represented by this building is approximately 80,000 square feet. Assuming a 10 square foot leakage pathway (i.e., an average size inlet duct), this represents a 17-foot-per-minute velocity from the pathway [or roughly 11.5-mile-per-hour (mph) velocity which is humanly perceptible]. At 100 square feet assumed surface area of cracks, that's down to 1.15 mph (not easily perceptible). A 10 square foot leakage pathway represents only 0.0125 percent of the surface area and could also be represented by a crack 960 feet in length and 1/8 of an inch wide. It is evident that even small holes and cracks are potentially extremely important to any confinement concept.

When it comes to building penetrations, doors are the most obvious. Under normal conditions, door seals will leak. Tell-tale air in-leakage marks have been observed at damaged facilities. Since air will follow the path of least resistance, if there is no impediment to in-flow during normal operations, there will be no impediment to out-flow during PSS conditions. Also, and most importantly, this may not be a filtered pathway. One facility, in response to establishing Technical Safety Requirements (driven by the importance of the bypass leakage assumptions to their DSA calculations), has actually measured the air in-leakage during normal facility operations and set an upper limit of acceptability and periodic surveillance requirements for operation. Doors, therefore, should be thoroughly analyzed for susceptibility to permanent distortion resulting from seismic events. This could occur at the door frame to building mounting as well as the door to the door frame mounting. The amount of expected distortion and resultant leakage pathway, should be taken into consideration in the safety basis for the facility.

The next obvious potential bypass leakage pathways are the inlet and exhaust duct penetrations. As with doorways, the attachment of the ductwork to the structure represents a potential failure point that should be analyzed. In addition to the penetration itself, the extension of the ductwork into the facility also offers a potential bypass leakage pathway, as the skin of the ductwork is actually an inward (or outward) extension of the confinement boundary. This boundary should end with a testable isolation valve or a seismically designed filtration system. A few facilities have actually fitted their inlets with HEPA filters, such that the facility can be alligned to breathe through both the inlet and exhaust HEPAs. Dampers should never be used for isolation purposes, as they are not designed for this purpose. Obviously, all penetrations through the ductwork up to the point of isolation represent potential bypass leakage pathways and should be limited and testable. Potential problem areas include fan shaft seals, boots on fans, valve and damper shafts, instrument penetrations, electrical penetrations, etc. All these should be considered in estimating potential bypass leakage. The seismically-designed ductwork supports should not be overlooked. Without them, the ductwork, that is expected to remain in tact, might not stand during a seismic event.

A not so obvious threat to a PSS confinement (or any confinement for that matter) is the storage of unsecured waste in large 100-cubic foot boxes or 55-gallon drums throughout the facility. During a seismic event, such unsecured items could move and possibly endanger the confinement boundary. The same is true for items stored inside filtration systems (i.e., ladders and tools used for filter testing and change outs). All these things must be considered.

Besides trash and testing tools, there is also concern for installed equipment that is not seismically designed or restrained. The potential interaction of nonseismically-designed equipment upon seismically-designed equipment is referred to commercially as “two over one” considerations. [Note: This is derived from the seismic level II (nonseismically-designed) and seismic level I (seismically-designed) designations used commercially.] This has led to cumbersome shield walls and restraints added to commercial designs. The bottom line is the potential motion of material and nonseismically-designed equipment and its resultant potentially detrimental impact on the confinement boundary should be taken into consideration.

Internal integrity may also be important if transport assumptions for zone-to-zone communications during potential accident scenarios effectively reduce the material at risk. All the concerns expressed for confinement boundary integrity (i.e., cracking, penetration, moving equipment, unsecured trash, etc.) now should apply to the zones themselves. This could become a calculational quagmire.

Besides bypass leakage considerations, the other significant challenge to the PSS concept involves post-accident sampling. Such sampling is necessary to adequately inform the facility management so appropriate and timely actions might be recommended for the protection of the public, workers, and the environment in the event of an accident. Without sample flow [because there is no power], installed instrumentation will not work because the electronics will divide the raw counts collected over a period of time (this is directly proportional to the amount of an assumed isotope released via the fixed pathway) by the average sample flow rate during the same period of time, which will lead (with division by zero) to meaningless numbers. It is also assumed that all the leakage is being directed past the monitor, which, as has already been discussed above, may not be the case.

The use of field sampling results for post-accident decisionmaking suffers from two serious deficiencies: accuracy and timeliness. With bypass leakage, it is impossible to determine, a priority just where the material will come from and at what flow rate. So, even though something may be measured, there is no assurance that it represents the total threat. Also, the time to gather and analyze a sample is too long compared to the time required for recommending protective actions. There is simply no substitute for directing a known flow quantity through a known pathway and past a monitor to assess the conditions emanating from inside an accident stricken confinement.

In conclusion, every hazardous facility should have a plan on how and when to best align for a blackout condition (i.e., a PSS plan) and on how and when to expeditiously exit a PSS state. That being said, a PSS concept for a post-accident condition requires both a detailed level of knowledge of the integrity of the confinement structure itself, all its penetrations, and potential equipment and material movements in the facility; and, development of reliable and timely sampling techniques. While such knowledge and development might be useful to pursue, it soon becomes obvious that it is overly burdensome to control all the potential threats to confinement integrity or to obtain reliable and timely estimates necessary for protection of the public, workers, and the environment. It is easier, more reliable, and practical to direct flow by force through a known pathway.

2.7 Air Cleaning System Design Considerations for Commercial Nuclear Power Plants

The purpose of this section is to introduce the reader to the lexicon and requirements for air cleaning systems at nuclear power plants. Except for those systems found in confinement, there are many similarities between the air cleaning systems used at nuclear power plants and those used at DOE facilities. The first difference is nomenclature (i.e., the names of components). At DOE facilities, the nomenclature used includes “safety class,” “safety-significant,” and “defense in depth,” or simply production support. Nuclear power plant systems and equipment are classified as either nuclear-safety-related, ESF, or nonnuclear-safety-related. In some cases, nonnuclear-safety-related systems and equipment are designated as “Balance Of Plant.” Some systems and equipment are referred to as “Important to Safety.” This term is not recognized by regulatory agencies and organizations, but certain situations exist where an air cleaning system must perform a function that has fewer requirements than those for a system that is fully nuclear-safety-related. One example is the Technical Support Facility Ventilation Air Cleaning System for commercial nuclear power plants. This area is used by plant management and technical support staff to support the operating staff in the control room during unusual events or accidents. The Emergency Operations Centers (EOCs) at DOE facilities are similar in both function and design to commercial nuclear power plants Technical Support Centers. These systems are required to: (1) be constructed, operated, and tested in accordance with the requirements of U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.140,[32] (2) be able to provide a positive pressure within the Technical Support Center when it is operational, and (3) be supplied with Class 1E emergency power. These systems are nuclear-safety-related, but are not an engineered safety feature.

2.7.1 Engineered Safety Feature and Nonnuclear-Safety-Related Systems

Air cleaning systems designed for ESF applications at commercial nuclear power plants must meet the requirements of Regulatory Guides 1.52,[28] and 1.78,[33] as well as applicable portions of the facility’s Standard Review Plan. These documents have been cited routinely by DOE, but generally are not mentioned in current DOE Orders. In addition, DOE cites numerous of its Orders that have special application to nonpower-related reactor activities. Many of these documents are site specific, and DOE is currently reviewing some of them for possible deletion and replacement (by reference) with consensus codes and standards.

Regulatory Guide 1.52[27] addresses ESF air cleaning system requirements. Regulatory Guide 1.140[32] addresses nonnuclear-safety-related air cleaning ("normal atmosphere cleanup") system requirements. Regulatory Guide 1.78[34] addresses climatic affects and requirements for outside air intakes.

For ESF applications, applicable regulations, codes, and standards must be combined with good engineering practice. Ease of maintenance, operability, testability, cleanability, and decontamination also must be carefully considered. In addition, air cleaning systems must be integrated into the overall plant or process design, including monitoring and control requirements. ESF systems are supplied with assured power from the plant Class IE emergency electrical power system.

Applicable Regulations and Standards for ESF Air Cleaning Systems

Air cleaning systems designed for ESF applications at commercial nuclear power plants must meet the requirements of ASME Standard N509, *Nuclear Power Plant Air Cleaning Units and Components*;[29] ASME Standard N510, *Testing of Nuclear Air Treatment Systems*;[23] ASME Standard N511, *In-service Testing of Nuclear Air Treatment Systems* (to be published)[35]; and ASME AG-1, *Code on Nuclear Air and Gas Treatment*.[4] It is good practice to implement the codes and standards referenced above for all nuclear-related air cleaning systems and components. All Safety Class and Safety Significant systems must be built to ASME AG-1 requirements.

Specific regulations, regulatory guides, Standard Review Plans (SRPs), and industry guidance and consensus standards govern the design criteria and operating characteristics for ESF air cleaning systems. Although these criteria are generated specifically for commercial nuclear generating stations, the principles can be adapted to other nuclear facilities.

Regulatory guides and SRPs provide more specific guidance and are considered acceptable ways of satisfying regulatory requirements. Regulatory Guide 1.52, *Design, Testing, and Maintenance Criteria for Post Accident Engineered-Safety-Feature Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water Cooled Nuclear Power Plants*,[27] details criteria for operating Control Room air cleaning systems in a post-accident environment. Environmental and system design criteria, component design criteria, qualification testing, maintenance, and in-place testing are discussed in detail.

The ESF systems designed to contain and mitigate DBAs must be redundant and physically separated so that damage to one does not cause damage to the other.

Redundancy requires two complete trains of equipment and components. There are cases where ductwork has not been completely redundant. A common space served by the redundant trains, such as control rooms, may not require 100 percent redundancy of the ductwork, as long as it can be demonstrated that no common mode failures would render both trains of equipment inoperable.

Separation is required, so that postulated accidents such as internal missiles, fire, and flood cannot render both trains of the redundant system inoperable from the same event. Separation can be achieved by physically locating the trains far enough apart that postulated accidents cannot render both trains inoperable, or by erecting a physical barrier, such as a concrete wall, for protection.

The SRPs are documents prepared by NRC staff to document application review procedures for construction and operation of nuclear power plants (NUREG-0800).[36]

The following criteria are applicable to ESF systems for all applications:

- A single active failure cannot result in loss of the system functional performance capability.
- Failure of nonseismic Category I equipment or components will not affect system operation.

- A suitable ambient temperature can be maintained for personnel and equipment.
- The system can detect and filter airborne contaminants before personnel enter the area.
- The system can detect and isolate portions of the system in the event of a fire.
- The ESF ventilation system will continue to function during all DBAs that require the building or area of the plant to be habitable and that require the essential equipment served by the ESF ventilation system to remain in operation.

Most nuclear power plants restrict the amount of zinc and aluminum that can be used inside the confinement structures. Zinc and aluminum both interact with the spray chemistry of the emergency core cooling systems to produce hydrogen, which can accumulate in the confinement and become an explosion hazard in the event of an LOCA. These materials must be tightly controlled, and an accurate inventory must be kept when they are used inside confinement structures.

Since most HVAC and air cleaning systems use galvanized steel for ductwork and equipment housings, alternate materials need to be considered for use inside confinement structures. One option is to use stainless steel for ductwork and equipment housings. Stainless steel is expensive, but its advantage is that it does not require any coating to prevent the corrosion or scratching that can occur during repair, maintenance, or testing/surveillance activities. In addition, it is easier to decontaminate than some other materials. Another, less costly option is to use steel coated with a material that is compatible with the confinement environment. The disadvantage of using coated steel is that it does not hold up well in environments involving high rates of ductwork or equipment repair, maintenance, or testing/surveillance activities. The coating also must be inspected and repaired when damaged, which can cause critical time delays during refueling or other time-sensitive activities.

Galvanized steel ductwork can be used successfully outside confinement, and at a lower cost than stainless steel. Galvanized steel has many of the same advantages as stainless steel, such as ease of decontamination, and it holds up well in areas that are subject to frequent repair, maintenance, testing, and surveillance activities. One caution should be noted, however: if the galvanized coating is severely damaged or removed, as in cases when welded duct construction is used and when supports are attached by welding, then the damaged areas must be recoated with a zinc-rich paint to prevent corrosion.

Radiation considerations can also present some material challenges, especially for those units that are normally in standby but function during and after a DBA and collect large quantities of radioactive materials. Radiation exposures of ten to hundreds of millions of rads are possible and need to be considered. At these exposure levels, the decomposition of some organic materials (e.g., gules, gaskets, binders) becomes possible. [Note: One common sealant, Teflon®, is particularly susceptible to radiolytic decomposition starting at approximately 1,000 rads of exposure. One decomposition product of note is hydrofluoric acid.]

2.7.2 Design Considerations

A clear definition of the design parameters is probably the most important, but often the least appreciated, requirement leading to the development of a satisfactory air cleaning system. The design parameters must consider basic performance requirements; physical limitations; regulatory, code, and standard compliance; and accident confinement and recovery. All of these parameters must be identified as an initial system design step because they form the basis for design. This is the responsibility of the facility owner, who is often assisted by an architectural engineering firm with experience in this type of plant design. See Table 2.1 for system environmental parameters.

Outdoor design conditions can be obtained from the ASHRAE Guide and Data Books,[37] from local weather stations, or from site meteorological data. It is important when selecting outside design conditions to use the *most extreme* data, particularly for nuclear-safety-related systems, as they must be capable of operating in these extremes.

The following examples of design basis accidents should be considered when designing an air cleaning system:

- Reactor coolant system LOCA (large and small breaks).

- Seismic Loading. [Note: the loads that must be considered when designing the air cleaning system will be different if the system has to remain operational during and after the event, or if the system only has to maintain its structural integrity; i.e., the system does not have to function during and after an event.]

- Fire, smoke, and hot air (see Chapter 10).

- Tornado/high winds. [Tornadoes can cause damage due to a significant pressure drop [approximately 3 pounds per square inch in gauge (psig), negative] as the tornado passes over the facility. Openings and items (e.g., air cleaning equipment, ductwork, etc.) that are exposed to this pressure transient can collapse if they are not protected by tornado dampers. In addition, tornadoes and high winds can convey missiles that can enter intakes and other unprotected openings and damage safety-related systems and equipment.]

- Internal and external missiles. (Internal missiles are usually generated by rotating equipment failure. External missiles are usually generated by a tornado or high wind.)

- Active equipment failure. [This refers to failure of any equipment that provides an "active" function (e.g., pumps, fans, valves, dampers, switches, etc.) and must be relied on to safely shut down the facility and/or maintain it in a safe configuration.]

- Loss of onsite and offsite power. (The facility must be designed to be safely shut down and/or be maintained in a safe configuration in the event of a loss of onsite and offsite power.)

2.7.2.1 System Design

Individual ESF air cleaning systems are limited by Regulatory Guide 1.52[27] to approximately 30,000 cfm. When the system airflow exceeds this limit, multiple systems must be used in parallel. ESF systems contain the following sequential components: (1) a moisture separator to remove entrained water droplets, (2) a heater to control relative humidity (RH) when the RH of the air entering the carbon adsorber exceeds 70 percent, (3) prefilters, (4) HEPA filters, (5) a charcoal adsorber, (6) HEPA filters downstream of the adsorbers, and (7) a fan. Ducts, valves, and dampers are also included for system isolation and flow control, as well as related instrumentation. When the moisture and dust loads are low for all credible operating modes, the prefilter and moisture separator may not be required.

As stated previously, ESF systems designed to contain and mitigate accidents must be redundant, and the redundant systems must be physically separated so that damage to one does not cause damage to the other. Instruments must make flow rates and pressures available to the Control Room as well as locally, and must provide visual and auditory alarms as indicated in ASME AG-1, Appendix IA-C, Table IA-C.[4] All instruments, including heater, damper, and fan controls should meet the requirements of IEEE 323, *Standard for Qualifying Class 1E Electrical Equipment for Nuclear Power Generating Stations*[5] and IEEE 344, *Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Generating Stations*.[6] Regulatory Guide 1.100, *Seismic Qualification of Electrical Equipment for Nuclear Power Plants*,[38] and Regulatory Guide 1.105, *Instrument Set Points*,[39] are also applicable. Instrument controls and control panels should meet the design, construction, installation, and testability criteria in Section IA of ASME Code AG-1.[4]

The design, construction, and test requirements of *ASME Code AG-1*[4] apply to the following ESF air cleaning components and are titled accordingly.

- Section AA, "Common Articles"
- Section BA, "Fans and Blowers" (Motors for fans and blowers must also meet the qualification requirements of IEEE 334,[40] IEEE 323,[5] and IEEE 344.[6])
- Section DA, "Dampers and Louvers"
- Section SA, "Ductwork"
- Section HA, "Housings"
- Section RA, "Refrigeration Equipment"
- Section CA, "Conditioning Equipment"
- Section FA, "Moisture Separators"
- Section FB, "Medium Efficiency Filters"
- Section FC, "HEPA Filters"
- Section FD, "Type II Adsorber Cells"
- Section FE, "Type III Adsorber Cells"
- Section FF, "Adsorbent Media"
- Section FG, "Frames"
- Section FH, "Other Adsorbers"
- Section FI, "Metal Media Filters"
- Section FJ, "Low-Efficiency Filters"
- Section FK, "Special Round and Duct Connected HEPA Filters"
- Section IA, "Instrumentation and Controls"
- Section TA, "Field Testing of Air Treatment Systems"

2.7.2.2 Structural And Seismic Design

The structural design of ESF air cleaning systems must consider the service conditions that components and their housing may experience during normal, abnormal, and the accident conditions contained in Section AA of ASME AG-1.[4] The ESF air cleaning system must remain functional following dynamic loading events such as an earthquake. The ESF air cleaning systems, including all components, must have their structural design verified by analysis, testing, or a combination of both. Qualification criteria are contained in Section AA of ASME AG-1.[4] The design requirements for determining housing plate thickness and stiffener spacing and size are contained in ASME AG-1, Section AA, "Structural Design," Sections SA, "Ductwork," and HA, "Housings." [4]

The maximum allowable deflections for panels, flanges, and stiffeners for the load combinations are contained in ASME AG-1, Section SA, "Deflection Criteria."[4]

2.7.2.3 Equipment Qualification

The fundamental reason for qualifying equipment is to provide adequate levels of safety for the life of the facility. Equipment qualification assures the ESF system will satisfy two characteristics:

- The equipment will resist common mode failures due to aging degradation.
- Nonmetallic materials will survive anticipated environmental stresses.

Generic or Application-Specific Qualification

Qualification may be generic or application specific. Generic qualification is probably best applied by the original equipment manufacturer. This type of qualification program requires test parameters that may exceed the needs of the specified requirements to be able to use the qualified equipment in a variety of applications and environments. An application-specific qualification limits the use of the component or system to those with the same or lesser environmental parameters.

Mild or Harsh Environment Qualification

A mild environment qualification can usually be accomplished without determination of a qualified lifetime (per Section 4 of IEEE 323),[5] whereas a harsh environment program usually requires testing to verify performance under extreme accident conditions. Simulated aging is necessary to arrive at "end of life conditions" prior to accident condition testing.

Determining Mild or Harsh Environment

When the answer to all of the questions below is "Yes," the equipment should be assumed to be subjected to a mild environment and treated accordingly.[27] Otherwise, it should be treated under the assumption that it is subjected to a harsh environment.

- Will the environment where the equipment is located be unaffected during and after a DBA (i.e., will there be no significant changes in temperature, radiation)?
- Will the equipment perform its safety-related function *before* the environment becomes harsh?
- Will failure of the equipment in a harsh environment after it has performed its function:

- Result in misleading information?
- Affect the functioning of other safety-related equipment?
- Cause a breach of pressure boundary integrity?

Safety or Non-Safety-Related Function

It is necessary to determine whether the components are designated as safety-related or nonsafety-related. Nonsafety-related items can often be excluded from the qualification process when it can be shown that failure of that component would have no adverse effect on the safety function of the overall equipment.

Equipment Qualification Plan

The Qualification Plan must be developed in accordance with IEEE 323[5] and must include a determination of the qualification method, listing of the environmental service conditions, description of any required aging programs, protocol of the test sequence, and definition of the accident test profiles.

An aging program consists of all stress factors, including thermal aging, mechanical/cyclic aging, radiation exposure, and mechanical vibration. All are designed to simulate conditions that would be encountered during the expected life of the test specimen prior to an accident condition or test such as seismic pressure or LOCA.

Equipment Qualification Methods

Three equipment qualification methods are described below.

- Type Testing:
  - Accounts for significant aging mechanisms;
  - Subjects the equipment to specified service conditions; and
  - Demonstrates subsequent ability to perform safety function.
- Operating Experience:
  - Must be compared to equipment with the same generic design; and
  - Depends on documentation of past service conditions, equipment performance, maintenance, and similarity for its validity.
- Analysis:
  - Requires logical assessment or mathematical model of the equipment;
  - Requires the support of test data, operating experience, or the physical laws of nature; and
  - Must be documented to permit verification by a competent third party.

A combination of any of the above qualification methods is recommended.

2.7.2.4 Air Cleaning System Integration with the Entire Facility

A critical design consideration that is often overlooked is the question of how the air cleaning system interrelates with other air handling systems and the entire facility. Often areas of a facility are directly connected to more than one air handling system. There are an unlimited number of possible combinations, but some of the most common are:

- An ESF air cleaning unit exhausting an area supplied by a non-safety HVAC system;
- An ESF air cleaning unit in an area normally exhausted by a large fan that may or may not shut down when the safety system is activated;
- A Control Room ESF air cleaning unit designed to provide a positive pressure in an area served by other ESF and/or non-ESF systems;
- The maintenance of graduated levels of negative pressure in concentric rings in fuel plants or plutonium facilities; and
- Gloveboxes, hot cells, and laboratory hoods with independent filtration systems in rooms served by ESF or non-ESF systems.

These examples illustrate the need to consider the entire facility when designing an ESF system. Two questions must be addressed: (1) how can the system under design affect other systems and areas, and (2) how can the remainder of the facility affect this system?

2.7.2.5 Design Areas Requiring Special Attention

There are system characteristics that apply to all air cleaning systems regardless of their specific function or the nature of the facility. One is that they must be capable of continuing to meet quantifiable test criteria to provide evidence of maintaining acceptance limits over the life of the installation. Therefore, the ability to maintain and test systems is as important as the ability of the systems to meet the initial performance criteria. The following are samples of some of the factors that apply to all systems and must be addressed:

- Airflow distribution in the ducts and housings;
- Airflow balance through the inlet and/or outlet ducts;
- Fan balance, leaktightness, and a capacity to provide adequate pressures at all design flows;
- Access for inspection, maintenance, and replacement; and
- Instrumentation that integrates the overall control and monitoring requirements of the facility.

2.7.2.6 Location and Layout

The ducts of ESF air cleaning systems that pass through clean areas should be designed at a higher negative pressure, and the length of any air cleaning unit positive pressure discharge ducts that must pass through a clean space should be kept as short as possible. When an ESF air cleaning system is a habitability system, ducts carrying outside air that are routed through clean space should be designed at a negative pressure. Housings handling recirculated habitability air should be at a positive pressure when located in a contaminated space. Negative pressure ducts located in a contaminated space should be avoided. When this is not possible, all-welded duct construction should be used. The length of positive pressure ducts outside the habitability zone should be kept as short as possible.

Generally, the direction of airflow should be from less contaminated spaces toward areas with a higher level of contamination. All ducts and housings containing a contamination level higher than surrounding areas should be maintained at a negative pressure. Ducts and housings with lower concentration levels than surrounding areas should be at a positive pressure. Allowable leakage depends on the difference between duct/housing concentrations and surrounding area concentrations. For example, a once-through contaminated exhaust filter housing serving a radioactive waste handling area in a nuclear power plant may have the exhaust fan located downstream of the filter housing when the housing is located in a space that is cleaner than the air entering the housing. The benefit of this system configuration is that the air cleaning system is under a negative pressure up to the fan. Therefore, leakage will be into the housing, and the potential impact of contaminated leakage on plant personnel during system operation will be minimized.

Such a system configuration does not mean that leakage can be ignored. Where it is crucial to personnel habitability, acceptable limits should be established and periodically verified by testing and surveillance. Rather, it means the potential for exposure has been reduced to ALARA levels by system design. When the space in which an air cleaning system housing is located is more contaminated than the air entering the housing, it would be better to locate the fan on the inlet side of the housing to eliminate in-leakage of more contaminated air.

When the housings of habitability systems are located within a protected space, the fan should be located downstream of the filter unit to ensure that only cleaner air can leak into the housing. When the housing of a habitability system is located in an area outside a protected space, the fan should be located upstream of the filter unit to ensure that contaminated air cannot leak in downstream of the filter unit.

Location of fans and housings should be accomplished by assigning a positive designation to the atmosphere in the cleaner area or duct, and a negative designation to the more contaminated area or duct. When the pressure difference within an air cleaning housing or duct is positive (+), the fan should be on the contaminated air-entry side; when the pressure difference is negative (-), the fan should be on the "clean air" exit side.

Serviceability and maintainability are major considerations when designing an ESF air cleaning system. Access for servicing the inside and outside of the housing for filter replacement, maintenance, and testing must be provided. Housings should not be situated among machinery, equipment, and ductwork with any means for ready access. There must also be sufficient space in the access corridors and adjacent to the housing to allow handling of filters during change-outs, including space for stacking filters adjacent to the work area. Dollies are often needed to transport filters through the access corridors. When Type III carbon adsorbers are used, access to the area must be provided for the mobile carbon transfer equipment. Note that the fill method must be qualified to ensure adequate packing density. Hand filling is not acceptable. Recommended service clearances are given in ASME N509.[29]

2.7.2.7 Air Cleaning System Design Considerations for Commercial Nuclear Power Plant Control Rooms

The operation of a nuclear power plant is complex and must be performed with great care. Although there are a number of locations where control over operations is exercised at a nuclear power plant, the center of activity is the Control Room. Broadly described, the Control Room is a dedicated area at any type of nuclear facility where the plant operations controls are located.

Nuclear power plant operators are highly trained licensed individuals. Their primary function is to control the nuclear reaction to ensure the reactor is operated safely under both normal and abnormal conditions. Therefore, the Control Room design must ensure that environmental conditions allow achievement of this goal. Both Control Room operators and equipment (electrical equipment, cables, gauges, instruments, controls, and computers) must be protected from the radiation and radioactive material present during normal operation and during abnormal or accident situations, as well as toxic gases, fires, explosions, missiles, earthquakes, tornadoes, and floods. An environment must be provided where both temperature and RH are maintained to ensure the continuing performance of Control Room equipment and to provide reasonable standards of human comfort for the operators. The primary means of achieving these conditions are air cleaning, ventilation, and air-conditioning systems that are appropriately designed, tested, maintained, and operated in conformance with the facility design criteria and best engineering practices. In addition, to enhance operator performance, the Control Room environment must be free from excessive noise, equipped with adequate lighting, and be designed with easy accessibility to equipment controls.

Control Room System Design Criteria

The basic regulation applicable to nuclear station Control Room systems is 10 CFR Part 50, Appendix A, "General Design Criterion 19."[41] The regulation states, "A Control Room shall be provided from which actions can be taken to operate the nuclear power unit safely under normal conditions and to maintain it in a safe condition under accident conditions, including loss-of-coolant accidents. Adequate radiation protection shall be provided to permit access and occupancy of the Control Room under accident conditions without personnel receiving radiation exposures in excess of 5 rem whole body, or its equivalent to any part of the body, for the duration of the accident." Control Room habitability during a postulated hazardous chemical release also is the subject of two regulatory guides. Regulatory Guide 1.78, *Assumptions for Evaluating the Habitability of a Nuclear Power Plant Control Room During a Postulated Hazardous Chemical Release*,[34] identifies chemicals which, when present in sufficient quantities, could result in the Control Room becoming uninhabitable. Design considerations to assess the capability of the Control Room to withstand hazardous chemical releases either onsite or within the surrounding area are covered. SRP 6.4, *Control Room Habitability*,[36] contains guidance for reviewing Control Room ventilation systems and control building layouts, and is intended to assure that plant operators are protected against the effects of accidental releases of toxic and radioactive gases. The area served by the Control Room emergency ventilation system must be reviewed to verify that all critical areas requiring access in the event of an accident are included within the area (Control Room, kitchen, sanitary facilities, and computer facilities). The ventilation system layout and functional design must be reviewed to determine whether flow rates and filter efficiencies will be adequate to prevent buildup of toxic gases or radioactive materials inside the Control Room after an accident. Outside air intake locations for the Control Room must be reviewed to determine the potential release points of hazardous airborne materials to assure that such airborne materials cannot enter the Control Room.

The details of the ESF atmosphere cleanup system, including the credit to be assigned to the filtration system for iodine and particulate removal for use in dose calculations, are covered in SRP 6.5.1.[36] This information is identical to the information specified in Regulatory Guide 1.52.[27] The remainder of the Control Room area ventilation system is reviewed under SRP 8.4.1.3[36] A functional review of this system must be performed, including components such as air intakes, ducts, air-conditioning units, filters, blowers, isolation dampers or valves, and exhaust fans.

Control Room fire protection (for fires occurring either inside or outside the Control Room) is described in SRP 9.5.1.[36] Section 6.4 presents specific details concerning the applicability of fire protection features to assure Control Room habitability under all required operating conditions.

SRPs 12.3 and 12.4[36] provide guidance for radiation protection design features. Occupational radiation exposures are to be kept within ALARA limits by using appropriate shielding and air cleaning. Additional details on this subject are provided in Chapter 11.

The criteria for the design, installation, operation, testing, and maintenance of Control Room air cleaning systems have a single objective: to provide a safe environment in which the operator can keep the nuclear reactor and auxiliary systems under control during normal operation and can safely shut down these systems during abnormal situations to protect the health and safety of the public and plant workers.

Basic Control Room Layout

The entire Control Room envelope is serviced by the Control Room emergency ventilation system. All areas that require access in the event of a nuclear accident are included within this envelope. The Control Room emergency zone includes all of the instruments and controls needed for safe shutdown, the critical reference files, the computer room (when used as an integral part of the emergency response plan), the shift supervisor's office, a washroom, and a kitchen. Battery rooms, cable spreading rooms, switchgear rooms, motor control center rooms, and other spaces that do not require continuous or frequent occupancy after an accident are generally excluded from the Control Room emergency zone. However, these areas need to be provided with nuclear-safety-related cooling for essential equipment during and following DBAs. While these areas usually do not require the same level of protection from radiation and contaminants as the Control Room, their cooling systems (air handling and water cooling) should meet all of the other requirements.

Control Room General Ventilation Criteria

Control Room ventilation criteria are based on the premise that contaminants must be kept outside the Control Room. Therefore, Control Rooms are maintained at a positive pressure with respect to their immediate environs to assure that all air leakage flows out of the Control Room. The ventilation system should be capable of providing fresh outside air at a rate sufficient to dissipate any internally generated carbon dioxide or other noxious fumes.[42] The system also should be capable of providing sufficient cfm per occupant to maintain human comfort. There should be no noticeable drafts to disturb operators or documents. In addition, the ventilation system must take care of the Control Room cooling and heating loads.

Control Room Temperature and Relative Humidity

The Control Room HVAC system must be capable of maintaining a comfortable temperature and RH range, generally considered to be 73 degrees Fahrenheit (23 degrees Celsius) to 78 degrees Fahrenheit (26 degrees Celsius), and 20 to 60 percent RH (ASHRAE Comfort Standard 55-74).[42] A secondary criteria is that the air temperature at floor and head levels should not differ by more than 10 degrees Fahrenheit (5.6 degrees Celsius).

Effective temperature, which takes into account dry-bulb temperature, RH, and air velocity, is commonly used as a measure of maximum limit for reliable human performance. The maximum effective temperature for reliable human performance is believed to be 85 degrees Fahrenheit (29 degrees Celsius). As extremes, this effective temperature can be achieved with 100 percent humid air at 85 degrees Fahrenheit (29 degrees Celsius), or with 20 percent humid air at 104 degrees Fahrenheit (40 degrees Celsius). Air velocity under 100 fpm (30.5 m/min.) has a negligible effect on effective temperature. Effective temperature is not intended to be used as a design criterion, only as a guideline for limiting operating conditions. Because RH is not normally measured in a Control Room, a worst-case condition should be assumed, implying that a dry-bulb temperature of 85 degrees Fahrenheit (29 degrees Celsius) should be the maximum temperature for a Control Room. This temperature should not be exceeded for longer than 1 hour, after which steps should be taken to reduce the temperature. Previous regulatory requirements in this area were based on equipment qualification only, and required temperatures were to be kept under 120 degrees Fahrenheit (49 degrees Celsius). This is too extreme for an operator to function efficiently and has been revised.

Control Room Air Composition

Clean air breathed by operators can be compromised by radioactive and chemically toxic gases. Chlorine is used extensively at nuclear power plants, and is the principal toxic gas of concern. With respect to radioactive materials, the air composition is specified in 10 CFR 20, Appendix B, Table 2.[43] The limits specified for every radionuclide are given as the maximum allowable airborne radioactive material concentrations to occupational workers during normal operations. During an accident, the HVAC system must be designed to limit the dose to the Control Room operator to 30 rem thyroid exposure.

Control Room Noise Levels

Verbal communication is necessary for efficient Control Room operation. Background noise, particularly from HVAC systems, should not impair this communication. Background noise levels should not exceed 65 Decibels A-weighted (dBA), and sound absorption should be sufficient to limit reverberation time.

Control Room Fire Protection Criteria

Fire Events Inside the Control Room. For fire events inside the Control Room, the design must ensure that plant shutdown capability, independent of the Control Room, is provided. With respect to ventilation, means should be provided to remove combustion products from the Control Room. Smoke detectors are necessary to alert Control Room operators of a fire and should be located in Control Room cabinets, consoles, and air intakes. The location of air supply intakes must be remote from all exhaust air and smoke vent outlets. The outside Control Room air intakes and all recirculation portions of Control Room ventilation systems require manual-isolation fire and smoke dampers. Peripheral rooms within the Control Room emergency ventilation zone should have fire dampers that close when the fire detection or fire suppression system begins operation.

Fire Events Outside the Control Room. The Control Room complex should be separated from the remainder of the plant by fire dampers. Important HVAC fire protection features, in addition to detection, include:

- Fire suppression,
- Qualified penetration seals for all penetrations,
- Portable blowers for smoke removal, and
- Location of all ventilation intakes and exhausts in relation to fire hazard.

2.7.2.8 Control Room Ventilation System Arrangements

The influx to a Control Room of radioactive and other contaminants can be eliminated by a ventilation system designed to filter the inlet air and by pressurizing the room to ensure that any leakage will be out-flowing. Design alternatives include one-pass purified outside air, recirculation purified air, stored bottled air, and a choice of dispersed air inlets.[44] Each system has a different application, with advantages and disadvantages. This section will discuss the four types, present models for calculating doses to the Control Room operators, and associated air cleaning requirements.

Control Room Infiltration

Infiltration is defined as unintentional leakage of air into the Control Room caused by pressure differences across the boundary of the Control Room air space. Typical leak paths are cracks around doorframes; duct, pipe, and cable penetrations; structural joints; and damper seals. Good Control Room design minimizes leakage paths by using gaskets, weather stripping, and sealing techniques. However, continuous distributions of microscopic capillaries and pores in concrete are possible, making complete elimination of infiltration difficult.

Pressure differentials may be due to natural phenomena such as wind and temperature or barometric differences. Pressure differences can also occur when there are flow imbalances between the Control Room and adjoining spaces.

Precise evaluation of Control Room infiltration is difficult to predict in the design phase because of the many variables (e.g., wind direction and speed, building geometry, Control Room leaktightness, and internal building pressure distribution) that can combine in different ways. In addition, the degree of Control Room isolation after an accident associated with ingress/egress traffic further compounds the situation. One approach is to measure infiltration at a number of Control Rooms and analyze the data. An isolated Control Room can be pressurized to determine the pressurization flow rate required to maintain a constant pressure. Tracer gases may also be used in a series of concentration decay measurements under various atmospheric conditions to establish empirical correlation between Control Room configuration, construction quality, ventilation characteristics, and infiltration characteristics. A study performed at the Zion Generating Station in Zion, Illinois using sulfur hexafluoride, provided extremely useful results. Sulfur hexafluoride was used because it is nontoxic, nonreactive, inert, and easily detectable by electron capture gas chromatography. With a measured makeup flow of 1,700 cfm, total infiltration leakage was experimentally determined to be 150 cfm. This was reduced by 50 percent when simple corrective measures were taken (new gaskets).

Air Cleaning Criteria

The most important feature of a Control Room air cleaning system is its ability to deliver sufficient quantities of clean air to the Control Room so that operators can perform their assigned duties in comfort and safety.

During normal operations, the Control Room ventilation system keeps out dust and noxious contaminants and maintains effective temperature at acceptable levels. It also keeps the Control Room pressurized to 1/4 in.wg to prevent in-leakage. During an accident situation, the Control Room air cleaning system must continue to function and provide a habitable environment for the operators. The system must be designed to seismic Category I and must be redundant to satisfy the single failure criterion. Automatic activation is necessary. Design features and the qualification requirements of an ESF Control Room air cleaning system are contained in Regulatory Guide 1.52[27] and ASME Code AG-1.[4] The components included in each of the redundant filter trains are: (1) demisters to remove entrained moisture, (2) prefilters to remove the bulk of the particulate matter, (3) HEPA filters, (4) iodine adsorbers (generally, activated carbon), (5) HEPA filters after the adsorbers for redundancy and collection of carbon fines, (6) ducts and valves, (7) fans, and (8) related instrumentation. Heaters may be used to reduce the RH entering the carbon beds to maximize performance and remove radioiodine species. **Figure 2.17** is a schematic of a typical ESF air cleaning system.

Subsystems

Cable Spreading Rooms. These rooms contain the cables that are routed to the Control Room. They are normally cooled by a 100 percent recirculation air conditioning unit that is nuclear-safety-related and has an assured (nuclear-safety-related) source of cooling to maintain the space temperature for all applicable design basis events. This unit may be a part of the control complex HVAC system.

Emergency Electrical Switchgear Rooms. These rooms contain the essential switchgear for the plant. They are normally cooled by a 100 percent recirculation air conditioning unit that is nuclear-safety-related and has an assured (nuclear-safety-related) source of cooling to maintain the space temperature for all applicable design basis events. This unit may be a part of the control complex HVAC system.

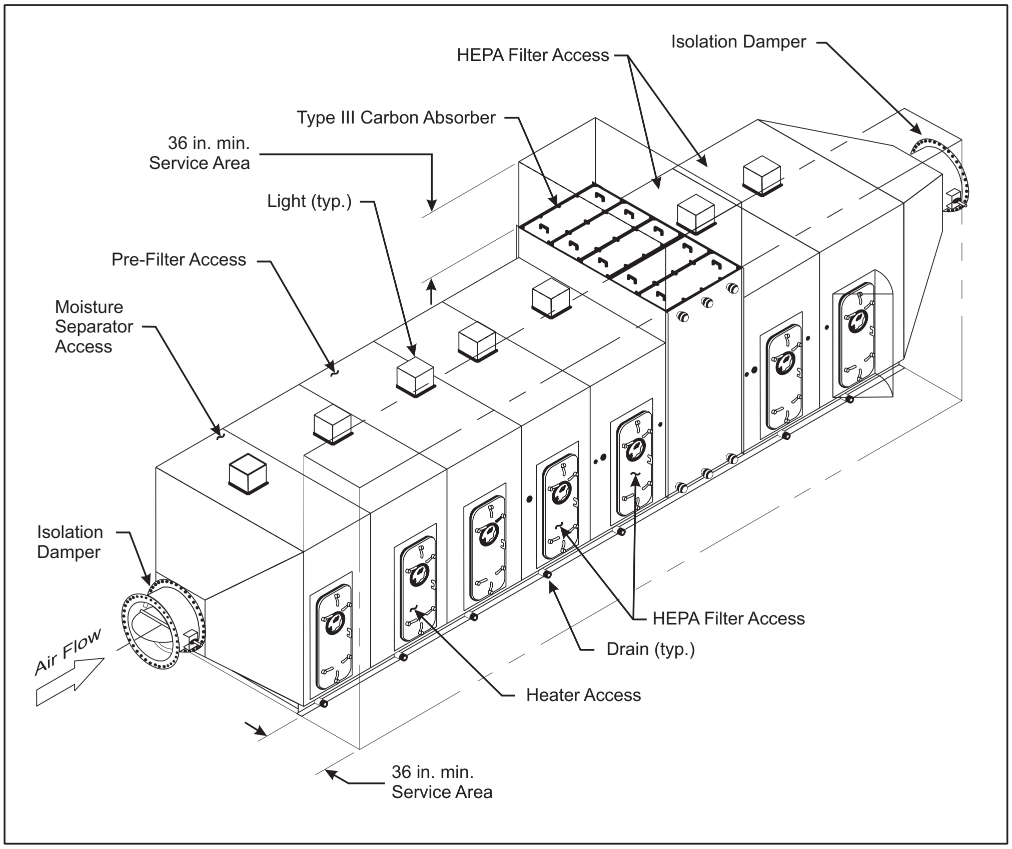

Figure 2.17 – Typical Air Cleaning System for Nuclear Power Plant Applications

Battery Rooms. The essential battery rooms contain the batteries that provide backup power for certain design basis events. They should be designed for a maximum room temperature of 77 degrees Fahrenheit (25 degrees Celsius) per IEEE Standard 484[43] and should be provided with an assured (nuclear-safety-related) source of cooling. These batteries also produce hydrogen when they are being charged. Therefore, a nuclear safety-related exhaust system is required that provides a minimum of five room air changes per hour. Also, the exhaust pickup points must be located at the ceiling of these rooms because hydrogen is lighter than air and will pocket at the highest point in the room.

Testability

Qualification testing and quality assurance of individual components by manufacturers in accordance with ASME N509,[29] ASME Code AG-1,[4] and ASME NQA-1[44] are required. After installation, pre-operational tests on individual components and the complete system are necessary. Deficiencies need to be repaired prior to accepting the system for operation and subjecting the system to radioactive contamination. An operating system must undergo periodic surveillance testing to verify that it can continue to perform its intended function. Technical Specifications, a part of the license for each nuclear power station, define the limiting conditions for operation (LCO) and the surveillance requirements for satisfying the LCOs. The LCOs specify which actions must be taken if the system becomes inoperable. The surveillance requirements are contained in Regulatory Guide 1.52,[29] ASME N510,[23] and ASME Code AG-1.[4]

Inspections of Control Room ventilation and radiation protection provisions for Control Room personnel are performed during the construction, pre-operational, and operational stages. In the United States, regional staffs perform this function at nuclear power plants. Inspection guidance is contained in manuals in the form of inspection modules. Inspections are performed to ensure that all systems will perform their intended functions, that operating procedures are in place, and that training has been provided.

Licensee Event Reports (LERs) submitted to the NRC by operators of commercial nuclear power plants are a useful source of information on the performance of habitability systems in Control Rooms, as well as other air cleaning systems. It is important to evaluate them and factor the lessons-learned into future activities. Owners of commercial nuclear power plants evaluate LERs through their Operating Experience Program.

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CHAPTER 3

FILTERS FOR THE NUCLEAR INDUSTRY

3.1 Introduction

Filters are widely used in nuclear ventilation, air cleanup, and confinement systems to remove particulate matter from air and gas streams. Air filters are defined as porous structures through which air is passed to separate out entrained particulate matter. The word "filter" is derived from a word for the fabric called felt, pieces of which have been used for air and liquid filtration for hundreds of years. The porous structures of a filter may also be composed of granular material such as sand or fibers derived from cotton, minerals (glass, asbestos), metals, or a wide selection of plastic materials. For filtration purposes, the fibers may be woven or felted into a cloth or formed into a paper-like structure. Filters may also be constructed in the form of highly porous fibrous beds of considerable depth. Other kinds of air cleaning devices (e.g., adsorbers, liquid scrubbers, electrostatic precipitators) are sometimes referred to as "filters" because they are capable of removing particles from an airstream. For clarity, the strict definition of a filter (given above) will be used in this chapter.

High-efficiency particulate air (HEPA) filters are components of a nuclear treatment system that degrade with service. The user/owner of the facility shall incorporate written specifications on the service life of the HEPA filters for change-out criteria. Appendix C provides guidance on determining the acceptable service life for each application pf HEPA filters.

Air Filter Types

Air filters of many types and materials of construction have been designed, manufactured, and applied to meet a wide variety of industrial and commercial requirements for clean air (e.g., the nuclear industry makes full use of all filter types). Commercially available filters are divided into three distinct categories based on how they operate to remove suspended particulate matter from the air passing through them. The largest category, often referred to as ventilation or heating, ventilation, and air conditioning (HVAC) filters, is composed of highly porous beds of resin-bonded glass or plastic fibers with diameters ranging from 1 to 40 micrometers (µm). The fibers act as targets for collecting airborne dust. As their name indicates, HVAC filters are widely used for air cleaning in mechanical ventilation systems. They are almost all single-use, disposable items, and are used in all sectors of the nuclear industry, including as prefilters that reduce the amount of coarse dust reaching more efficient filters located downstream.

A second category also is comprised of single-use, disposable filters called HEPA filters. By definition, a HEPA filter is a throwaway, extended-medium, dry-type filter with: (1) a minimum particle removal efficiency of no less than 99.97 percent for 0.3-µm particles, (2) a maximum resistance, when clean, of 1.0 inches water gauge (in.wg) when operated at 1,000 cfm, and (3) a rigid casing that extends the full depth of the medium[1] (**Figure 3.1**). [Note: Filters of different flows and resistances are allowable by the AG-1 Code.] [2] A filter of identical construction and appearance, but having a filtering medium with a retention of 99.9995 percent for 0.1 µm particles, is referred to as an ultra-low penetration aerosol filter (ULPA). The filtering medium of HEPA filters is thinner and more compressed, and contains smaller diameter fibers than HVAC filters. HEPA filters are widely used throughout all phases of the nuclear industry.

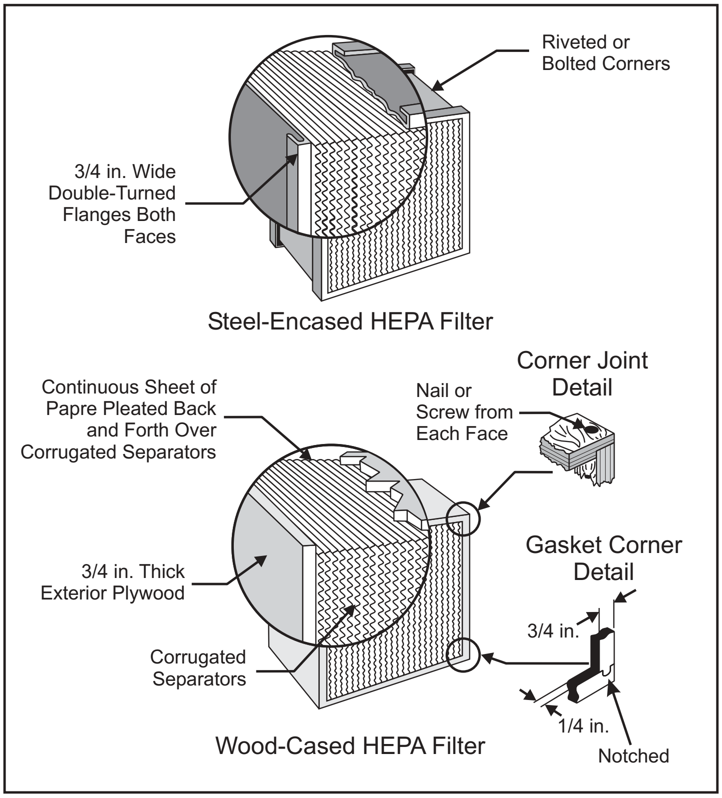

Figure 3.1 – Filter Casing

A third category of commercial air filters is known as industrial cleanable cloth filters. As the designation indicates, these filters have built-in mechanisms for periodically cleaning the filtering surfaces of accumulated dust. Unlike the first two types, industrial cleanable cloth filters rely on building a thick layer of dust on the surface of the cloth to provide a high-efficiency filtering medium. This type of filter is used in the nuclear industry for ore processing and refining and for similar tasks involving high concentrations of coarse mineral dusts.

Further, this third category includes special types of particulate filters for chemical and combustion operations. These include deep beds of sand in graded granular sizes, deep beds of glass fibers, and stainless steel membranes formed from compressed and sintered granules or fibers. Stainless steel membrane filters operate like industrial cleanable cloth filters in that they depend on a dust layer for high-efficiency particle removal and must be cleaned periodically, usually by reverse compressed air jets.

3.2 Filtration

The porosity of air filters has been noted. High porosity is associated with low resistance to airflow (e.g., low-resistance HVAC filters contain approximately 97 percent voids). In a uniformly dispersed filter medium, the individual fibers are relatively far apart—so far apart that the gaps between them are larger than the particles removed from the air. This means that sieving (particle removal via openings that are smaller than the particle dimensions) is not an important filtration mechanism. In fact, a sieve would make a poor air filter, even one containing submicrometer openings, because each collected particle closes up a sieve opening so that very soon no air can pass through. In contrast, filters collect particles from air and gas streams in a number of well-defined ways that are associated with the dynamic properties of airborne particles. The filters respond to the physical forces present as an aerosol passes through a porous medium composed of small granules, fibers, or other shapes.

3.2.1 Particle Collection by Filters

Figure 3.2 shows the streamlines around a spherical granule or a single filter fiber lying normal to the flow direction. A particle entering the flow field surrounding the fibers must follow the curved path of the streamlines so it can pass around the obstacle. When particles possess sufficient inertia, they resist following the curvature of the airstream and come in contact with the fiber because of their higher momentum relative to that of the conveying gas molecules. The capturing effect of *inertial impaction* (see I in Figure 3.2) becomes greater as both aerodynamic equivalent diameter and the velocity of the air approaching the fiber increase.

When suspended particles are very small, however, they tend to follow the curved streamlines closely; that is, they have little inertia, but are in vigorous, random motion (*Brownian motion*—see II drawing in Figure 3.2). Therefore, when a streamline passes close to the fiber surface, the random movements around the streamline may result in some of the particles contacting the fiber and adhering to it. This sets up a concentration gradient between the zone close to the fiber and the bulk of the aerosol which, in turn, results in particle diffusion in the direction of the fiber surface. The smaller the particles, the more vigorous their Brownian motion and the more effective their filtration by *diffusion*. Because the rate at which small particles cross streamlines under the influence of diffusional forces is slow compared to rate of the effects of inertial force on large particles, separation of small particles by diffusion is enhanced by slower velocities through a filter.

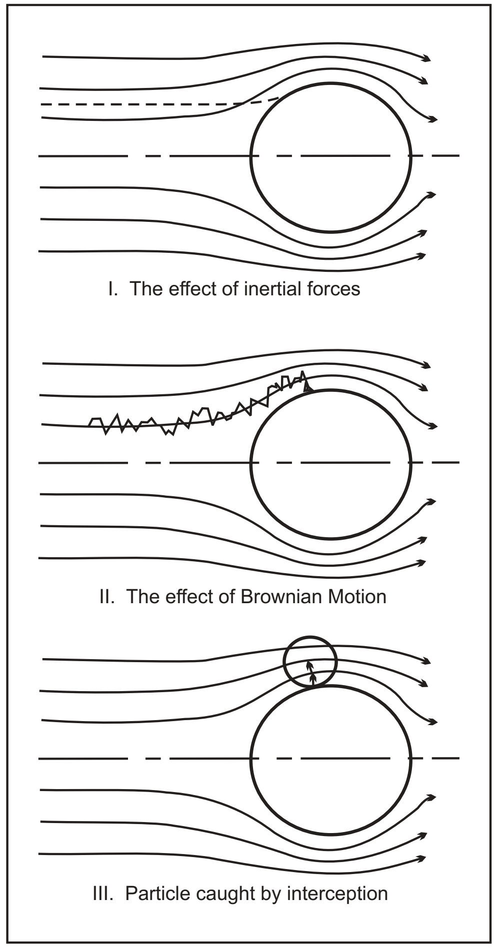

Figure 3.2 – Streamlines Around a Filter Fiber

Particle collection by *interception* (III in Figure 3.2) occurs when a particle traveling in a streamline that approaches a fiber within one particle radius makes contact with the fiber and adheres to it. Interception is independent of flow velocity and is enhanced when the diameter of the collecting fiber or granule approaches the geometric diameter of the particle.

The several filtration mechanisms of importance are shown together in **Figure 3.3**, where penetration (equal to 100 minus collection efficiency) is plotted against particle size. The penetration lines are not cumulative, as particles can be collected but once; however, the net effect can be approximated by the "dashed" summation curve. Figure 3.3 makes it clear there is a particle size where both inertial and diffusional forces are minimal and only interception is unaffected. This explains the concept of a minimum filterable particle size. The exact minimum size depends on fiber diameter, filter construction, and flow velocity. The minimum filterable particle size for currently manufactured nuclear grade HEPA filter papers is close to 0.1 μm when operated at the design flow rate of 1 foot per second. The effect of flow velocity on particle penetration for HEPA filter paper also shows a minimum efficiency point.

3.2.2 Particle Retention in Filters

After an airborne particle contacts a filter element, retention forces prevent re-entrainment under the influence of the drag of the air. For small particles, the principal retentive force is a surface phenomenon called the Van der Waals force, which is proportional to the total area of contact. For small spherical particles, the fraction of the total surface area in contact with a filter fiber will be relatively large, resulting in a retention force that exceeds the re-entrainment force of the air drag.

3.2.3 Airflow Resistance of Filters

Filter resistance is directly related to airflow rate and filter construction details. Decreasing the diameter of filter fibers or granules produces higher resistance for the same overall unit volume of the solid fraction of the filter medium. Greater filter depth at the same porosity increases resistance in proportion to the increase in depth. Within limits, compressing a highly porous filter medium decreases porosity and increases flow

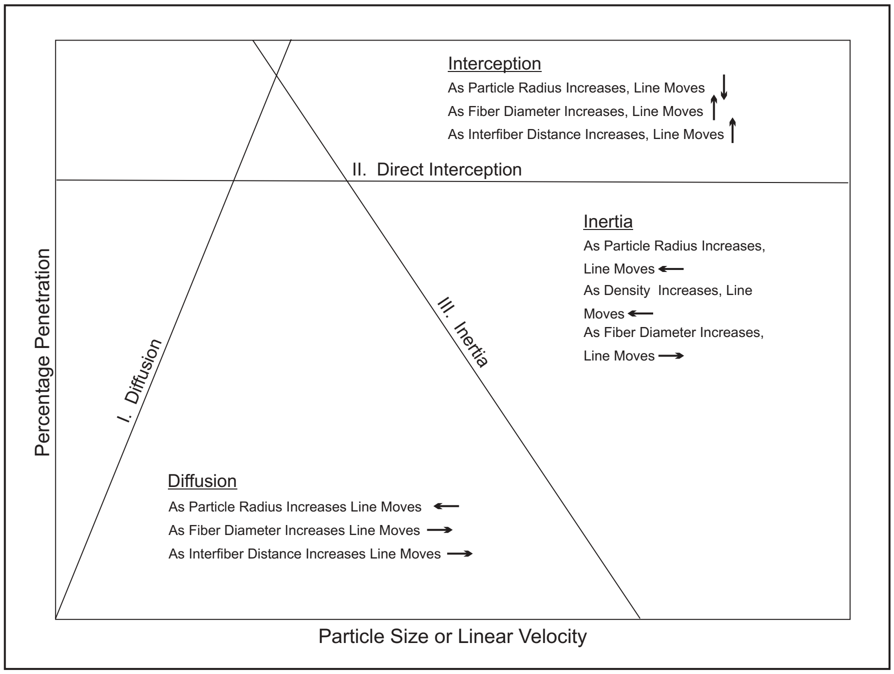

Figure 3.3 – The Effects of Inertia, Diffusion, and Interception on the Penetration-Velocity Curve

resistance, but it does not have much influence on particle removal efficiency until the medium becomes highly compressed.

The text in Section 3.2.1 that describes how fine particles are collected by filter elements applies to new clean filters. As particles collect on the surfaces of fibers or granules, or become entrapped in the interstices between upstream elements of the filter, the collected particles tend to form a coherent dust layer known as a filter cake. When this occurs, particle collection gradually shifts from media filtration (i.e., particle removal by individual filter fibers or granules) to cake filtration, and the filter shares the characteristics of the industrial cloth filter because the original structure now has the sole function of providing support for the filter cake and the filter cake completely takes over the particle separation function. This transformation produces two important changes: (1) efficiency increases in proportion to the increase in thickness of the cake; and (2) after formation of a coherent filter cake, resistance of the filter to airflow, which initially increased at a slow, steady rate as particles accumulated, now increases at an accelerating rate in response to additional particle deposition and narrowing of the pathways. When cake filtration begins, the filter rapidly reaches its terminal design airflow resistance. **Figure 3.4** shows typical pressure rise curves for two HEPA filters exposed to atmospheric dust. As shown, the long, slow pressure rise is clearly followed by a rapidly accelerating increase. The reason for the abrupt change is the onset of sieving, which takes over when the collected particles form a structure containing less space between the particles than the characteristic diameter of the particles being collected. When HEPA filters reach this stage, they must be replaced.

3.3 HEPA Filters

The original specifications for HEPA filter media and cased filters were concealed under a veil of military secrecy because of their use for chemical, biological, and radiological defense purposes. Following World War II, the Atomic Energy Commission (AEC) chose the military's HEPA filters as their principal device for particle removal in all exhaust air systems of nuclear facilities. Eventual expansion of the use of HEPA filters for nonmilitary applications required declassification and release of information about HEPA filter components and manufacturing methods (see Chapter 1). For this reason, military standards MIL-F-51068[3], MIL-F-51079[4] (filter construction and filter medium preparation), and MIL-STD-282[5] (filter testing) were issued in an unclassified format.

MIL-F-51068[3] and MIL-F-51079[4] have now been withdrawn by the Department of Defense and replaced by the American Society of Mechanical Engineers (ASME) *Code On Nuclear Air and Gas Treatment*, AG-1[2] and U.S. Department of Energy (DOE) Standard (DOE-STD-3020-97).[6] While MIL-F-51068[3] and MIL-F-51079[4] were active, the Edgewood Arsenal in Maryland prepared a procurement guide for military and nuclear agencies, the *Qualified Products List* (QPL), which is based on exhaustive tests of manufacturers' filter media and filters. The QPL referenced available American Society for Testing and Materials (ASTM), Technical Association of the Pulp and Paper Industry (TAPPI), and other standard test procedures and equipment in its documentation of products. Edgewood no longer maintains the QPL, and only issues letters to manufacturers after qualification testing. Standards incorporating the major provisions of these military specification and qualification standards have been issued. Besides AG-1,[2] those most relevant to nuclear service applications include two standards administered by the ASME Committee on Nuclear Air and Gas Treatment (CONAGT), with participation from DOE and the U.S. Nuclear Regulatory Commission (NRC). These standards relate directly to HEPA filter applications in the nuclear industry (i.e., ASME N509, *Nuclear Power Plant Air Cleaning Units and Components*,[1] and ASME N510, *Testing of Nuclear Air Cleaning Systems*.[7]) The requirements of Nuclear Regulatory Guide 1.52 have been incorporated into these standards.[8] DOE prepared a series of filter standards to establish the performance and physical requirements for the filter media and cased filters used in DOE environmental protection applications and to set policy and quality assurance procedures for DOE filter test facilities (FTF).[6, 9, 10, 11]

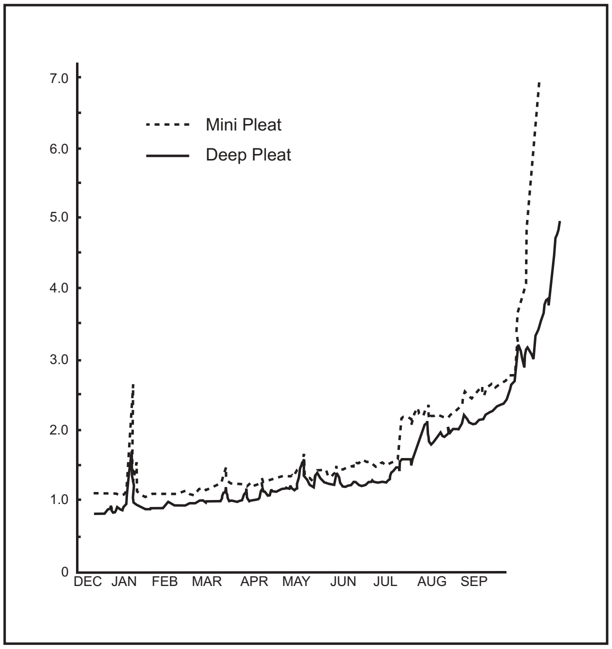

Figure 3.4 – Pressure Rise With Operating Time for Deep-Pleat and Mini-Pleat HEPA Filters

While HEPA filters and their properties are discussed in this section, the same facts apply to ULPA filters (except for differences in penetration, resistance, and media test velocity).

3.3.1 Filter Medium

Filtration theory implies that filter fibers must have diameters that are approximately the same as the aerosol particles to be removed. Therefore, the standard HEPA filter medium must have fiber diameters of 0.2 to 0.5 µm to remove submicrometer particles, and even smaller fiber diameters are necessary for the ULPA filter medium. All high-efficiency filters are now made from a mixture of glass fibers with carefully graduated diameters that provide the required particle retention efficiency without exceeding the maximum airflow resistance criterion and meet a wide variety of physical and environmental requirements. Typical glass fiber sizes used to manufacture HEPA filter media are shown in **Table 3.1**. Small amounts of chemicals are usually added to the glass fibers at the finish stage or after the medium is formed to impart desirable properties to the product (e.g., mildew resistance, water repellency, increased tensile strength of the glass paper). Plastic fibers in amounts less than 7 percent are sometimes added to the glass fibers to increase acid resistance. The ASME AG-1[2] Code for the HEPA filter medium is now a universal standard. This is primarily a performance standard, and the mixture of fiber sizes and specific additives and concentrations vary among manufacturers. Each filter manufacturer has a proprietary formula that qualifies the product for nuclear applications. Other nations have well-established criteria for HEPA filter paper that differ only to a minor degree from the current U.S. standard. Microfibers of plastic materials such as polystyrene, polycarbonate, and polyvinyl chloride also have been used for manufacturing HEPA filter media. Claims have been made that triboelectric charge effects, which are induced on these plastic materials during manufacturing, enhance filtration performance and save energy. Filters from these materials have found some acceptance in European markets, but have been rejected by the nuclear industry because of flammability, high cost, and loss of performance under conditions such as high humidity, ionizing radiation, and exposure to atmospheric contaminants. A HEPA filter medium made from polyvinyl chloride fibers has been used in East European installations, but has been found unacceptable elsewhere for the reasons noted above.

Table 3.1 – Sizes of Glass Fibers for HEPA Medium

Glass Fiber Industry Code	*Average Fiber Diameter (micrometers)*
112	2.60 - 3.80
110	2.50 - 4.00
108B	1.20 - 2.40
108A	0.69 - 1.10
106	0.54 - 0.63
104	0.39 - 0.53
102	0.33 - 0.38
100	0.29 - 0.32

[Note: Glass Fiber Industry Code Numbers 100-110 were determined by the William Freeness Test. Code 112 was determined by the Manville Micronaire Test FG-436-202 and calibrated by the Brunauer, Emmett, and Teller Test (BET) Surface area.]

In addition to a limit on the organic material content of these filter papers (for fire and smoke control), other qualification criteria include:

- Not less than 99.97 percent retention of 0.3-μm test aerosol particles at a flow rate of 32 liters per minute through a paper area of 100 square centimeters;

- Clean airflow resistance not exceeding 40 millimeters of water at a filtration velocity of 320 centimeters per minute (0.053 meters per second);

- Average tensile strength of not less than 179 g/cm of width in either direction after exposure to 6.0 to 6.5×10^7 rads;

- Resistance to excessive strength degradation after exposure to high temperature [698 ± 82.4 degrees Fahrenheit (370 ± 28 degrees Celsius)] for 5 minutes and to wetting by immersion in water for 15 minutes; and

- Paper thickness of approximately 0.38 millimeters.

HEPA filter papers used for nuclear service currently provide collection efficiencies greater than 99.99 percent when tested with a 0.3-μm-diameter aerosol by the official U.S. test method contained in MIL-STD-282.[5] By increasing the fraction of fine glass fibers in the paper that are less than 0.25 μm in diameter, it is possible to obtain efficiencies in excess of 99.999 percent for 0.1- to 0.3-μm particles with a modest increase in filter resistance—typically about 25 percent. Performance standards for filter papers that are acceptable for use in nuclear-grade HEPA filters (as distinguished from performance standards for fabricated filter units that contain such materials) have not been considered important by some nuclear authorities. This view is based on the assumption that, unless the glass fiber filter paper has the required characteristics, the completed filter unit will not meet the acceptance criteria. This approach is reasonable, provided the filter paper is subjected to equivalent stresses after fabrication (e.g., shock, ionizing radiation, heat, fire).

The filter media production usually constitutes the definition of a batch for HEPA filter manufacturing. Typically, a batch of media can be used to make a lot of only 6 to ten 24- × 24- × 11 1/2-inch HEPA filters. Any selective filter testing (as opposed to 100 percent testing at the manufacturers' or FTF) should be done in accordance with ASQC-Z 1.4-1993, with the batch size set by the media batch production capability of the manufacturer. To utilize this standard, the user must also select the appropriate reliability. A value of 90 percent or greater is appropriate for nonsafety class HEPA use.[12]

3.3.2 HEPA Filter Construction

Most HEPA filter units are constructed the same way—a continuous length of filter paper is folded back and forth into pleats and corrugated separators are inserted between each fold. The assembly is then sealed into a rigid, open-faced rectangle. The components of a fabricated HEPA filter include: (1) extensively pleated filter medium, (2) separators that provide air passages and keep adjacent pleats apart, (3) a rigid filter case that encloses and protects the fragile filter medium, (4) sealants used to bond the filter pack (consisting of the assembled pleated medium and separators) to the filter case and to eliminate leak paths between filter pack components, and (5) gaskets attached to the filter case on one or both open faces to provide an airtight seal between the filter and the mounting frame. Some filter construction methods form the filter paper on the papermaking machine using an interval means to keep the adjacent folds apart, thereby eliminating a need for corrugated separators. These filters are called separatorless HEPA filters (see Section 3.3.3). **Figure 3.5** shows the assembled components of an open-face, deep-pleat HEPA filter with corrugated separators.

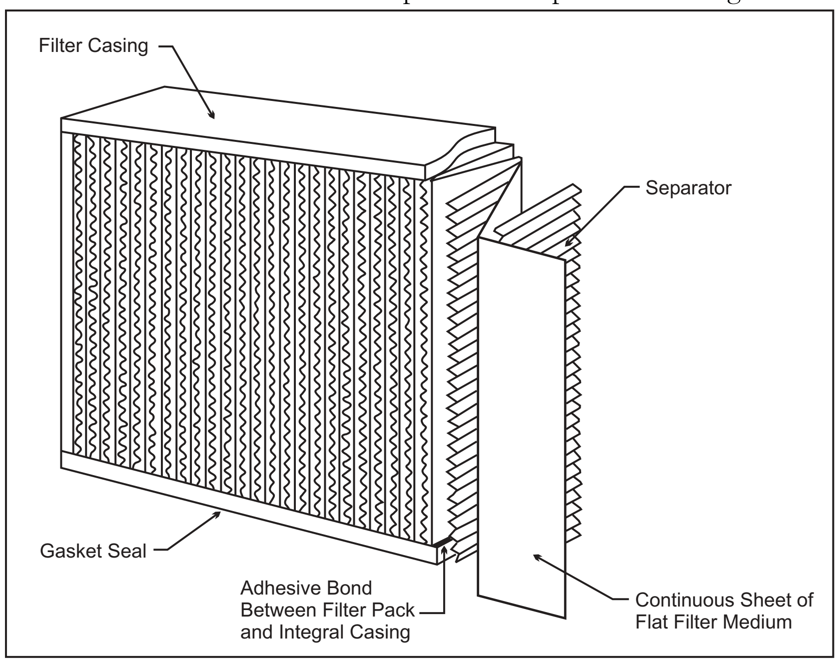

Figure 3.5 – Open-Face Deep-Pleat HEPA Filter-Type A Filter Pack

3.3.2.1 Separators

The most widely used material for the interleaved corrugated separators is tempered aluminum foil. The aluminum foils currently used for separators are identified as ASTM B209, *Standard Specification for Aluminum and Aluminum Alloy Sheet and Plate*,[13] alloys 1145-H19, 3003-H19, or 5052-H39, and are a minimum of 0.035 mm thick. When corrugating the aluminum sheet into separators, edges are often hemmed (turned back on themselves) to prevent the sharp edges from puncturing or tearing the part of the filter medium folded around the separator. Examination of disassembled filters aged up to 10 years showed deterioration of uncoated aluminum spacers to be common to all operating environments. Corrosion leads to adhesion of the spacer to the glass fiber medium. Levels of radioactive contamination on the evaluated filters appeared not to have affected the aging process. When greater chemical resistance is required, a plastic coating of an epoxy, thermo-set vinyl (or a similar compound) is applied to the aluminum sheet. [Note: If significant radiation is a concern, the use of organic materials may not be appropriate.] A dye is usually added to clear coating materials so that defects in the plastic coating can be easily detected. After drying to a film, the coating must be 0.0025- to 0.0050-mm thick, with no cracking, peeling, or delamination after corrugation. Experiments to determine the corrosion-resistance of certain all-plastic separators have been conducted and have generally found them to be unacceptable because the corrugations tend to reflatten due to "plastic memory," particularly after exposure to moderately high temperatures. ASME AG-1[2] details additional requirements for corrugated aluminum separators.

3.3.2.2 Filter Case

The filter case is constructed of materials that correspond to the specific application, decontamination requirements, and considerations of disposal ease and cost. Commonly used case materials include fire-retardant plywood, chromized carbon steel, and alloys UNS S30400 and UNS S40900 stainless steels. The minimum thicknesses required to maintain rigidity under compressive loads ranging up to 1,400 pounds when the filter is clamped to a mounting frame, are 3/4 inch for wood and manufacturer's standard steel sheet gauge for steel. Grade A-C, American Plywood Association (APA) PS-1 fire-retardant-treated plywood is acceptable, but the "A" face must be on the inside, facing the pack, and should be assembled with this face completely coated with a sealant to close off any leak paths. The outer face should be filled and sanded as smooth as possible (for plywood). This is particularly important for nuclear plant workers whose gloved fingers and hands must not be punctured by splinters from a wooden frame when replacing filters in a contaminated area. For wooden case filters, case panels are to be joined with rabetted joints, which are assembled by gluing with an adhesive and double nailing or doubling screwing with coated box nails, corrosion-resistant plated screw nails, or flat-head wood screws. The end points of the fasteners must not penetrate the inside or outside surfaces of the case. Metal cases should be used in instances of potential wetting or high humidity at elevated temperatures and when the filter will be exposed to corrosive chemicals.

3.3.2.3 Sealants

Sealants used to provide a leak-free bond between the filter pack and case must be resistant to heat and moisture, noncombustible, fire-resistant, or self-extinguishing, as well as capable of maintaining a reliable seal under continuous exposure to design operating conditions. Rubber-based adhesives compounded with chlorine or bromine to ensure self-extinguishing when exposed to ignition are acceptable, but catalytically cured solid and foamed polyurethanes containing additives for combustion suppression are the sealants of choice for most filter manufacturers. Sealants should maintain their integrity over a wide temperature range. Filters designed to operate at temperatures above 392 degrees Fahrenheit (200 degrees Celsius) have been sealed with compression-packed glass fibers and with ceramic cements reinforced with glass fibers, and have been hardened thermally. Compression-packed glass fiber seals are sometimes found to be damaged after shipment. The ceramic seal is often too brittle to withstand commercial shipment. Room temperature vulcanizing silicone rubber sealants have been used successfully at operating temperatures only slightly lower than 392 degrees Fahrenheit (200 degrees Celsius).

3.3.2.4 Gaskets

Filters must be installed so that even the smallest volume of air or gas does not escape filtration; therefore, gaskets and alternative methods of sealing filter units to the mounting frames play a critical role in the satisfactory operation of HEPA filters. The most widely used sealing method is a flexible gasket attached to the open face of the filter case and pressed against the flat face of the mounting framework. The second most popular method is referred to as a "fluid seal." This method uses a channel formed or routed in the peripheral face of the filter case that is filled with a highly viscous, very low volatility, nonflammable (or self-extinguishing), odor-free, non-Newtonian fluid such as a silicone. The fluid flows around and over imperfections, but does not relax or separate from the surfaces it contacts. For installation, the matching framework face is equipped with a continuously protruding knife-edge that mates with the fluid-filled channel in the filter case. The reverse arrangement of a protruding knife-edge on the filter and a fluid-filled channel on the mounting frame also may be employed. These two mounting methods do not have interchangeable parts, so hybrid sealing systems are not feasible.

Gaskets must be oil- and ozone-resistant.[14] Closed-cell sponge gaskets composed of synthetic rubber (neoprene) that conforms to grade 2C3 or 2C4 of ASTM D1056, *Sponge and Cellular Rubber Products*[15] have been widely used. Gaskets should have a minimum thickness of ¼ inch and width of ¾ inch. The gasket face attached to the filter case should be free of any adhesion-resistant mold-release contaminant that may have been acquired when the gasket material was molded. To ensure an absence of residual mold release chemical, only cut surfaces are permitted on both gasket faces. Gaskets may be cut out of a sheet of stock as a single piece or may be made of strips joined at the corners by dovetail or other interlocking arrangement. Joints are sealed against air leakage with a rubber-base adhesive, usually the same adhesive used to attach the gasket to the filter case. Manufacturers of neoprene gaskets recommend a shelf life not to exceed 3 years.

3.3.2.5 Faceguards

To guard against damage from careless handling and faulty installation procedures, a recessed faceguard should be installed across both faces of the filter during fabrication. Woven or expanded metal with square openings approximating 1/3 inch to 1/2 inch on a side have proven satisfactory in largely preventing the inadvertent intrusion of hands or other objects into the filter pack. In addition, a metal mesh faceguard provides added strength to the filter unit, increasing resistance to transportation damage and shock overpressure. Faceguards should conform to either galvanized steel ASTM A740[16] or 304 stainless steel ASTM A580.[17]

3.3.3 Separatorless HEPA Filters

A separatorless HEPA filter design,[18] shown in **Figure 3.6**, is constructed without corrugated spacers inserted between the folds of the filter paper. Instead, a continuous sheet of filter paper is molded on the papermaking machine with corrugations at intervals. When it is folded back and forth upon itself, it becomes a self-supporting pack where the peaks of the interval corrugations of successive layers contact each other to form a honeycomb-like filter pack. For the same filter frame size, a separatorless filter contains more useful filter paper surface than the corrugated separator type, and thus provides greater airflow capacity at equal resistance.

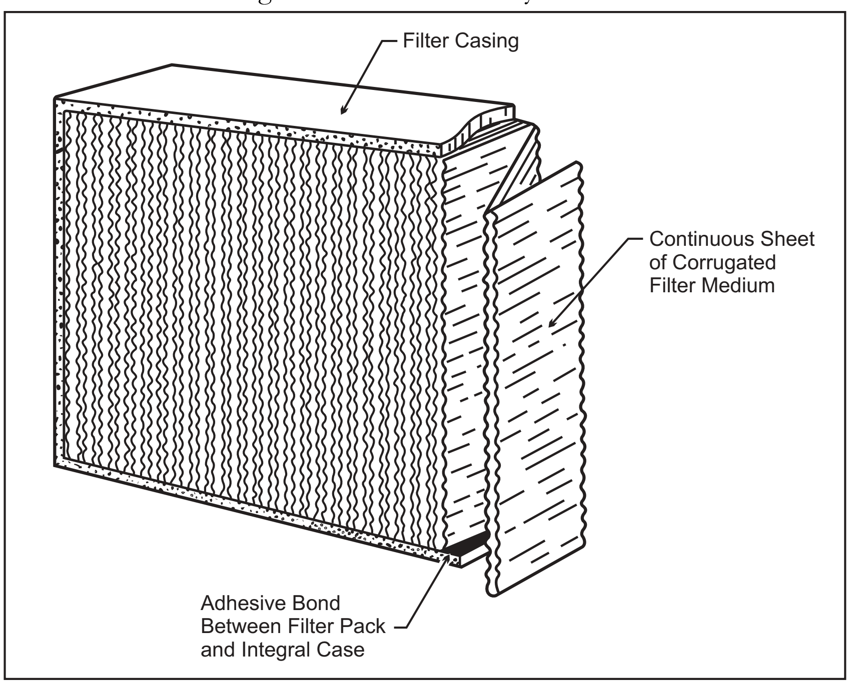

Figure 3.6 – Separatorless Style Filter-Type C Filter Pack

3.3.4 Mini-Pleat HEPA Filters

Mini-pleat filter construction methods utilize 7/8 to 1 1/4-inch-deep pleats with very narrow air spaces (1/8-inch) between, making it possible to pack more filter paper into the standard frame sizes than can be done with deep-pleat, corrugated separators, or even by using separatorless construction methods. Abutting folds are separated by threads, ribbons, tapes, strips of medium, or continuous beads of glass, foam, or plastic spaced across the width of the medium. Mini-pleat filters contain almost twice as much filter paper as deep-pleat, corrugated separator filters of equal frame size (**Figure 3.7**) (see Section 3.3.2.3). They are rated to have an airflow resistance of 0.25 Kilopascals (kPa) when operated at 3,060 cubic meters per hour (m^3/hr), compared to the same resistance for a flow rate of 1,700 to -2,040 m^3/hr for deep-pleat corrugated separator filters. This gives the user of mini-pleat filters the option of utilizing space-saving higher airflow rates or extending filter life by operating at lower than rated airflow capacity. This is called downrating a filter.

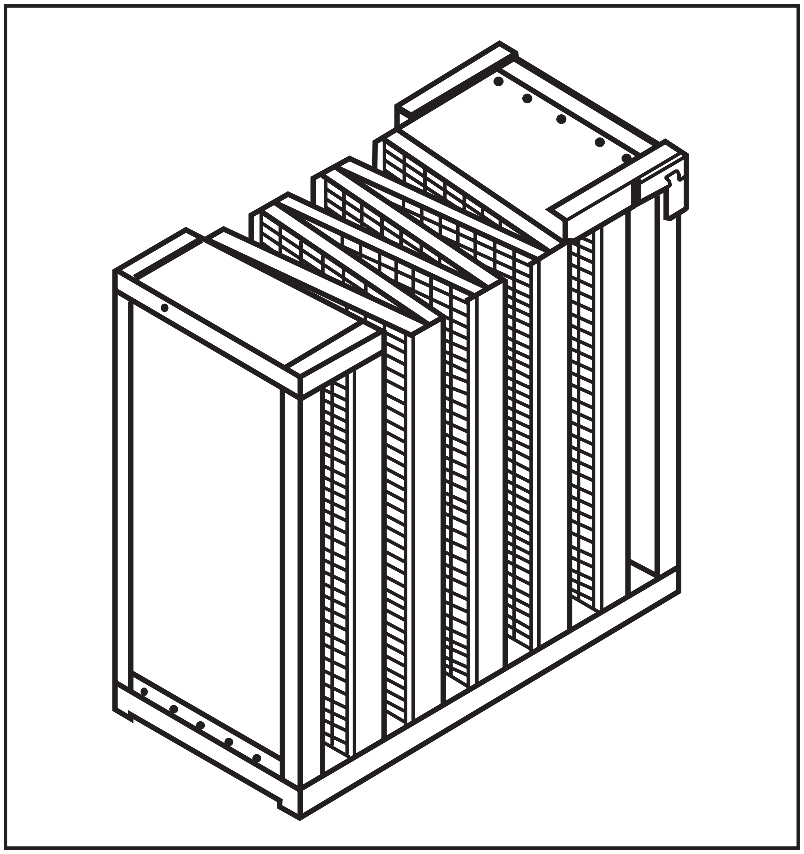

Figure 3.7 – Mini-Pleat (Thread Separator) Filter-Type B Filter Pack

When a mini-pleat filter rated for 3,060 m^3/hr is downrated to service at 1,700 m^3/hr, it theoretically should extend service life more than threefold before it reaches its final permissible resistance increase. In practice, filter life extension was found to be merely 1.6-fold because of dust bridging across the very narrow air passages between the paper pleats to form a filter cake covering the face area. An efficient prefilter might be used to prevent the formation of a surface filter cake and extend the service life of the mini-pleat filter.

Cased mini-pleat HEPA filters are formed from subcomponents assembled in a continuous "V" array. The subcomponents are panels that hold the pleated filter paper in metal frames approximately 23.62 inches wide, 11.81 inches high, and the depth of the paper pleats. A seal is made between framed filter packs and the standard frame using rubber-based adhesives, polyurethane, or some other plastic-based material, all of which are chemically compounded to inhibit their support of combustion.

Another mini-pleat filter design is formed by molding narrow longitudinal ridges into the wet filter paper at approximately 1-inch intervals while the paper is still on the papermaking machine, then folding the paper as it comes off the machine into mini-pleats that may be 2, 4, or 6 inches deep.[18] The filter pack is mounted into the filter case perpendicular to the airflow direction instead of mounting a number of shallow panels arranged inside the filter frame in a series of "V" formations The 6-inch-deep mini-pleat separatorless filter contains the same area of filter paper as the 12-inch-deep separator type. This type of filter has been placed into service, but there is no experience to report for nuclear applications.

3.3.5 HEPA Filter Classes and Sizes

In addition to being the workhorse filter for the nuclear industry, HEPA filters have found many important applications in the industrial, medical, pharmaceutical, and microelectronic sectors. These diverse applications have resulted in a number of industrial and governmental specifications. In general, these specifications can be grouped into five construction grades and three performance types that provide a range of materials, manufacturing techniques, performance characteristics, and costs for different applications and user preferences. A standard covering the grades and types of HEPA filters has been issued as IEST-RP-CC001.3 by the Institute of Environmental Sciences and Technology.[19] This standard lists the following classifications.

3.3.5.1 Filter Construction Grades

Grade 1 – Fire-Resistant Filters. Filters of this grade must contain fire-resistant materials that may ignite when the filter is exposed to hot air or fire, but will not continue to burn once the ignition source is removed. The filter must exhibit a specified retention efficiency after exposure to no more than 700 ± 50 degrees Fahrenheit (371 ± 10 degrees Celsius). These filters comply with ASME AG-1, Section FC.[2]

Grade 2 – Semicombustible Filters. This grade costs less, but provides a lower level of protection against elevated temperature than Grade 1. For this reason, the user should evaluate application of this filter grade with the individual fire propagation hazards in the area of use. This filter type will fail at temperatures much lower than Grade 1. These filters comply with UL 586.[20]

Grade 3 – Combustible Filters. This grade covers filters required for certain service requirements that permit acceptance of the combustibility hazard. Grade 3 filters are readily combustible and are used only where high-value product recovery by incineration is desirable, disposal of volumes are critical, or exposure to chemical atmospheres might be incompatible with the use of a HEPA filter incorporating a medium of glass fibers. It should be noted that manufacture of a combustible HEPA filter medium formulated from asbestos and cellulose has been discontinued for more than a decade because of the hazards associated with its use and the resulting low demand. Specialty filter media for recovery of precious metals by incineration are still available. These filters comply with UL 900, Class 1.[21]

3.3.5.2 Filter Performance Levels

IEST-RP-CC001.3[19] classifies filter performance levels as:

Type A Filter Performance. Sometimes referred to as industrial types, these filters are tested for overall penetration at rated flow only. The filter retention (inverse of penetration) must exceed 99.97 percent for 0.3-μm particles. ULPA filters greater than this value can be obtained upon agreement between the buyer and seller.

Type B Filter Performance. In addition to the basic requirements for Type A filters, Type B units are certified free of significant pinhole leaks that would cause penetration at low flow rates. This type is tested at 20 percent of rated airflow with the filter encapsulated to disclose casing or gasket leaks. This type is sometimes referred to as "nuclear-type."

Type C Filter Performance. In addition to the performance required of Type A filters, Type C filters, are tested with the use of air-generated test aerosols at 80 to 100 feet per minute (fpm) face velocity. The units are fully face-scanned to detect and eliminate all significant leakage streams greater than 0.01 percent of the upstream test aerosol concentration to which the filter is subjected. This type is infrequently called "laminar-flow type."

Type D Filter Performance. In addition to the testing required for Type C filters, Type D filters should be retested at their rated airflow and penetration, which should be no more than 0.001 percent of the upstream concentration. The filter unit should be encapsulated so that all components, including the filter pack, frame, and gasket, are subjected to testing. In the U.S., laser spectrometers are used to measure efficiencies of ULPA filters (>99.99999 percent).

Type E Filter Performance. Type E filters are designed, constructed, and tested in strict accordance with military specifications for HEPA filters intended for biological use.[22] This type is for application in air cleaning or filtering systems involving toxic chemical, carcinogenic, radiogenic, or hazardous biological particulates. This type is referred to as a "biological unit."

UL Class 1,[21] Type B filters are recommended for most nuclear applications, particularly in single-pass systems. These units comprise a large part of those manufactured by industry and are used extensively in nonnuclear industries as well. UL Class 1, Type C filters are common in clean room applications where laminar flow requirements are coupled with low particle penetration.[23] UL Class 1, Type D filters presently are used in printed-circuit or microprocessor clean rooms.

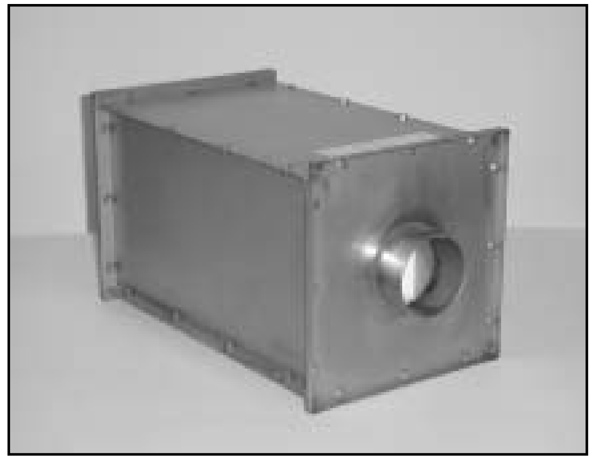

Figure 3.8 – Enclosed HEPA Filter

3.3.5.3 Enclosed Filters

Most HEPA units are used in the open-face configuration (Figure 3.1). When used in this manner, the filter is secured firmly to a rigid framework by a pressure device such that a leak-free seal exists between the unit and the framework. The HEPA filter may also be placed completely within an enclosing casing that is equipped with nipples at both ends for attachment to existing ventilation ducts (**Figure 3.8**). Enclosing casings may be metal or plywood, but care must be taken to ensure the casing material is compatible with Underwriters Laboratories, Inc., (UL) requirements for resistance of the filter to heated air and flame.[22] The enclosing casing forms the leak-free pressure boundary in addition to the filter case, and care must be taken to ensure that it is treated as an encapsulated design for both performance and leak-acceptance testing. Enclosed HEPA units have significantly higher resistance to airflow than the open-faced design because of the added restrictions of the duct transitions.

Enclosed filters are sometimes referred to as encapsulated (nipple-connected, closed-face, or self-contained) HEPA filters. They are not recognized by applicable codes (i.e., AG-1[2]) and standards and fail to meet all the requirements contained in DOE Standard DOE-STD-3020-97[6]. The most serious deficiency is failure to meet the requirement for uniform velocity across the filter face. This can invalidate the in-place filter leak test.

Figure 3.9 – Open-Faced Cylindrical Axial Flow HEPA Filter

The enclosed filter and its casing are often misused as part of a nuclear ventilation system pressure and confinement boundary. Enclosed HEPA filters are not specifically designed, analyzed and tested to meet either the housing or the ventilation ducting containment requirements of nuclear codes. When designing and constructing new nuclear facilities, enclosed HEPA filters should not be used in nuclear ventilation systems. When an installed ventilation system is being modified or upgraded, consideration should be given to replacement of enclosed HEPA filters with nuclear grade housings containing ASME AG-1 certified filters. A technical justification should be developed where the enclosed filter is not replaced with a housing.

3.3.5.4 Cylindrical Filters

Cylindrical filters may be either open-faced cylindrical axial (**Figure 3.9**) or radial flow (**Figure 3.10**). Filters fabricated with cylindrical cases appear to offer substantial advantages such as easier mounting in circular ducts, but in practice they have been found to have disadvantages attributable to manufacturing difficulties, escalated costs, and increased susceptibility to leakage. However, cylindrical filters offer significant advantages regarding simplified gasketing and automated filter-changing techniques. In the United Kingdom, a "push-through filter system" has been developed that permits changing of cylindrical filters by loading a clean filter that has gaskets on the top and bottom filter flanges into the filter housing tube from the "clean side," then pushing it through until it ejects the old contaminated filter into the "dirty side" of a cell or glovebox. A cylindrical filter of somewhat different design, but with similar characteristics, has been developed in the United States.

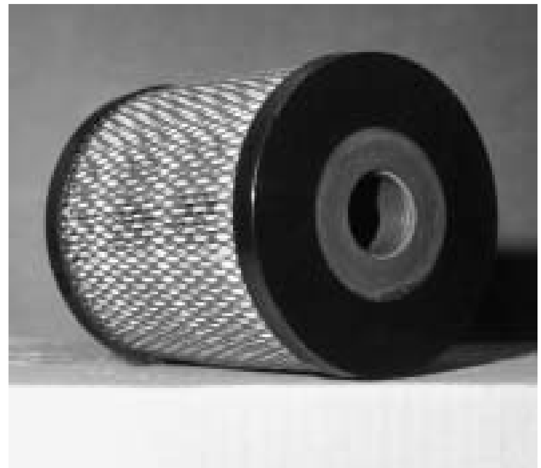

Figure 3.10 – Radial Flow HEPA Filter

3.3.5.5 Filter Sizes

The physical dimensions shown in **Table 3.2** have been standardized for the HEPA filters currently used in nuclear service and by U.S. Government agencies. [Note: DOE STD-3020-97 addresses more sizes than are indicated here, and may be used in addition to the table shown below.] Other sizes can be manufactured and purchased, but are considered "special orders." Nonnuclear applications (clean rooms, biological safety cabinets, medical facilities) generally use the same filter height and depth dimensions shown in Table 3.2, but may have lengths up to 72 inches. Special HEPA filter configurations for computer applications use many different sizes and shapes depending on the volume available within the computer cabinet. As many as 1,000 different configurations exist, each specific for a respective manufacturer, model, type, or size of computer.

Table 3.2 – Nominal Sizes and Ratings

Number Designation	Size		Minimum Rated Airflow		Maximum Resistance	
	Inches	Millimeters	Standard Cubic Feet per Minute (scfm)	m^3/hr	Inches Water Gauge (in.wg)	Pascal (Pa)
1	8 × 8 × 3 1/16	203 × 203 × 78	25	42	1.3	325
2	8 × 8 × 5 7/8	203 × 203 × 149	50	85	1.3	325
3	12 × 12 × 5 7/8	305 × 305 × 149	125	212	1.3	325
4	24 × 24 × 5 7/8	610 × 610 × 149	500	850	1.0	250
5	24 × 24 × 11 1/2	610 × 610 × 292	1,000	1,700	1.0	250
6	24 × 24 × 11 1/2	610 × 610 × 292	1,250	2,125	1.3	325
7	24 × 24 × 11 1/2	610 × 610 × 292	1,500	2,550	1.3	325
8	24 × 24 × 11 1/2	610 × 610 × 292	2,000	3,400	1.3	325
9	12 × 12 × 11 1/2	305 × 305 × 292	250	424	1.3	325

[Note: AG-1 currently allows for the qualification of the largest size to apply smaller size filters, i.e., a size 5 filter fan be used to qualify a size 4 filter. It has been brought to the attention of the CONAGT that the qualification of the size 4 filter listed above may need to be independent of the size 5 qualification. Readers should check revisions to AG-1 post 2003].

3.3.5.6 Filter Weight

The weight of a filter unit is an important factor in design and maintenance. **Table 3.3** lists the weight of clean, open-faced filters and enclosed filters of rectangular design. For design purposes, the weight of a dirty filter that is ready for change-out is approximately 4 pounds heavier per 1,000 cfm of rate capacity. Because many applications employ multiple filter units in banks that are as many as 6 to 10 units in height, minimal filter weight, without loss of performance, is critical to the ease of original installation and replacement.

Table 3.3 – Weight of Unused HEPA Filters

Filter Size (inches)	*Nominal Airflow Capacity (cfm)*	*Approximate Weight (pounds) of Filters With*	
		Wood Case	*Steel Case*
Open-face			
8 × 8 × 3 1/16	25	2	3
8 × 8 × 5 7/8	50	3.6	5.8
12 × 12 × 5 7/8	125	4.8	7.3
24 × 24 × 5 7/8	500	17	22
24 × 24 × 11 1/2	1000, 1250, 15000	32	40
Enclosed	25	5	9
8 × 8 cross-section	50	7	10.5
8 × 8 cross-section	125	17	20
12 × 12 cross-section	500	64	72
24 × 24 cross-section	1000	78	95
24 × 24 cross-section			

3.3.6 HEPA Filter Performance Characteristics

3.3.6.1 Airflow Resistance

Resistance to airflow (pressure drop) of a nuclear-grade, 1,000 cfm capacity filter should not exceed 1 in.wg when tested at rated airflow (see Table 3.2 for additional filter capacities and pressure drops). The pressure drop for ULPA filters is frequently greater than for standard HEPA filters, and this feature is subject to negotiation between customer and vendor. Resistance increases with particulate loading. A new nuclear-grade filter is qualified by a wet overpressure test up to 10 in.wg for 1 hour; however, this should not be confused with normal in-service operating pressures. Normal in-service pressures should be limited to 3 to 5 in.wg above startup pressure.

3.3.6.2 Dust-Holding Capacity

The dust-holding capacity of a filter is a function of the type, shape, size, and porosity of the filter as well as the aerosol size, shape, and concentration characteristics to which the filter is exposed. As HEPA filters are designed to filter out the smallest particles, they can accommodate only extremely light particulate loadings without experiencing a rapid pressure drop increase. HEPA filters are affected particularly adversely by fibers, lint, and other materials that exhibit a large length-to-diameter ratio because they tend to bridge the air entrance gaps between the adjacent pleats of medium, thereby preventing particles from accessing the full depth of the filter. A HEPA filter can be protected by a prefilter capable of removing the bulk of large particles and fibers, thereby extending its useful lifetime. As noted earlier, a dust-holding capacity of 4 pounds per 1000 cfm of rated airflow capacity may be assumed for design purposes. This is probably a conservative figure for granular dusts, but may overestimate the filter's dust-holding capacity for metal fumes.

An increase in dust accumulation on the filter medium both improves filtration efficiency and increases resistance to airflow. One of the limitations of HEPA filters is their low-dust-holding capacity and their need for frequent replacement when exposed to high aerosol concentrations. The pressure rise curve experienced by HEPA filters also depends on the particulate composition of the atmosphere to which it is exposed. A filter installed in a moderately contaminated urban area will show as much as a six-fold increase in resistance in a year's time, whereas a unit in a clean room application may last ten years or longer before reaching a six-fold pressure increase. The use of a prefilter (described in Section 3.4) increases the service life of HEPA filters and helps make the combined filtration system cost effective.

Tests conducted at the Harvard Air Cleaning Laboratory[24] explored the pressure buildup of filter units under urban conditions. During testing, commercial deep-pleat, aluminum-corrugated separator HEPA filters and mini-pleat HEPA filters, all 24 × 24 × 11.4 inches in size, were exposed side-by-side to an urban atmosphere while being operated continuously at rated and downrated airflow without prefiltration. The downrated mini-pleat HEPA filters did not fulfill the theoretical prediction of three times the service life of a deep-pleat U.S. HEPA filter when both were operated at 1,700 m^3/hr; instead, an extended service life of about 1.6 times was achieved. This shortfall was attributed to dust and lint bridging the narrow openings between the pleats of the mini-pleat unit (the pressure rise curves of the two filter types are illustrated in Figure 3.4). Extremely high concentrations of soot and dense particular matter from fire conditions may overwhelm both the prefilters and the HEPA filters, thereby inactivating the total system. For this reason, some practical means of suppressing smoke before it reaches the filters is required. Water curtains, electrostatic precipitators, inertial separators, or other devices have been utilized for this purpose with varying success.

3.3.6.3 Shock and Blast Resistance

The resistance of HEPA filters to shock and blast is important because these filters are often the final barrier between a highly contaminated enclosure and the environment. Shock stress may occur from disruptive natural phenomena (e.g., earthquakes) or from internal and external explosions.

Early tests at the Harvard Air Cleaning Laboratory showed that filter units of 1950s vintage sustained moderate damage at 6-inch-mercury [2.95 pounds per square inch (psi)] overpressure, and complete destruction at 10-inch-mercury overpressure (4.91 psi). The U.S. Navy determined that filter units subjected to an overpressure simulating an atomic explosion (50-millisecond duration) failed at variable values depending on the face and depth dimensions. The values listed in **Table 3.4** are the maximum shocks that can be tolerated without visible damage or loss of filtration efficiency. Specific conclusions reported from the Harvard study included: (1) filters with faceguards on both faces had about a 40 percent greater resistance to shock than those without faceguards; (2) dirt-loaded filters had 15 percent less shock resistance than clean filters; (3) the smaller the filter face area, the greater the resistance to shock; (4) the greater the filter depth, the greater the resistance to shock. At overpressures exceeding those listed in Table 3.4 by 0.5 to 1.0 psi, the filter medium ruptured or experienced cuts on the downstream face. At pressures 2 psi greater than those listed in Table 3.4, extensive damage occurred. At pressures above 5 psi, the entire filter pack within the frame was dispersed. No significant differences were found between successive tests of increasing shock force on the same filter and a one-shot test of the same force—both procedures produced the same failure modes. Using the data on shock overpressure resistance versus face depth and dimensions, Burchsted[18] produced the chart shown in **Figure 3.11**. Los Alamos National Laboratory (LANL) repeated some of the Navy shock tests and arrived at similar values for loss of structural integrity. In addition, the researchers discovered that, although the break point for the units was similar in value, the specific values for rupture were highly dependent on the filter source. Tests on HEPA filters constructed with a special scrim-backed glass-fiber filter medium showed that this filter retained an efficiency in excess of 99.92 percent for the test aerosol after exposure to a differential pressure of 7.5 kPa and a temperature of 932 degrees Fahrenheit (500 degrees Celsius).

LANL also conducted tests on filter units under simulated tornado pressure loadings (represented by a slower pressure buildup, but sustained for a longer period of time). Damage levels in these tests were identical to those found for shock overpressures of the same level, but shorter duration. Filters of U.S. and European manufacture gave comparable results. LANL found separatorless filters had only two-thirds the structural strength of their separator-containing counterparts when subjected to tornado conditions, and only one-half the strength under shock overpressure exposures. However, another series of seismic simulation tests conducted by Wyle Laboratories found that separatorless filters successfully withstood seismic shocks equivalent to 12 moderate (less than 4.0 Richter scale) earthquakes when correctly mounted in well-designed housings. During these tests, the filters were operated at design flow rate of 1,700 m^3/hr, but under cumulative (multiple earthquake) worst-case conditions. The units were challenged continuously with heterogeneous test aerosol, with no demonstrated resulting loss of efficiency for the filter, housing, or fluid seal between the filter and housing. Current NRC regulations do not require seismic testing for filters, but do allow mathematical analysis of the housing, with the sole consideration being the weight of the filter(s) in the housing.

Table 3.4 – Shock Overpressure Resistance of Open-face HEPA Filters[25]

Filter Dimensions (inches)		Overpressure (psig)		
			Recommended Design Limit for Used Filters	
Face	Depth	Overpressure at Failure [a]	With Faceguards	Without Faceguards
8 × 8	3 1/16	3.7	[b]	2.0
8 × 8	5 7/8	4.5	[b]	2.5
12 × 12	5 7/8	3.6	[b]	2.0
24 × 24	5 7/8	2.2	1.7	1.2
24 × 24	11 1/2	3.2	1.7	1.8

[a] Clean filter with 4 by 4 mesh faceguards on both faces.
[b] Faceguards not available.

3.3.6.4 Heat from Fire and Explosion

Grade 1, fire-resistant filters are fabricated from a glass medium with flame-inhibited or self-extinguishing adhesive or sealant, aluminum alloy separators, and fire-retardant wood or metal frames. Nevertheless, the material that collects on the filters poses special fire and explosion hazards when it contains substantial amounts of organic or pyrophoric substances. Fires from this source can produce undiluted hot gases that attain temperatures as high as 1,830 degrees Fahrenheit. The softening point of glass fibers used in currently manufactured HEPA filter media is about 1,250 degrees Fahrenheit, and direct impingement of a

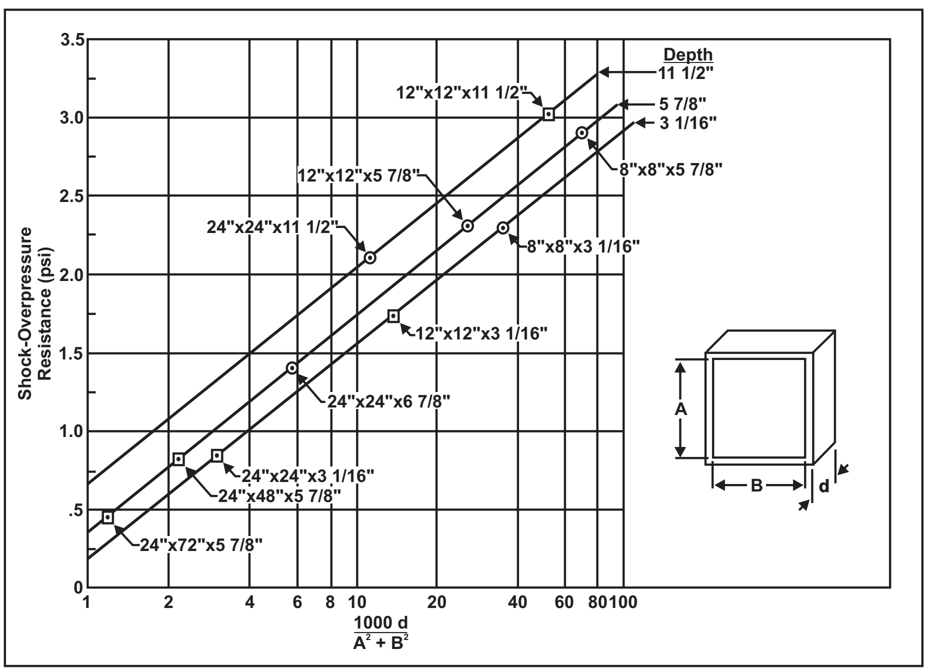

Figure 3.11 – Shock-Overpressure Resistance of Clean HEPA Filters (Separator Type) as a Function of Size

1,700 degrees Fahrenheit flame will cause immediate melting. A glowing solid particle that lands on HEPA filter media will perforate it if it continues to burn. Explosions that could destroy or seriously damage the filter from high pressure, shock waves, or an excessive temperature excursion can also occur from ignition of organic or pyrophoric dusts, vaporized organics, or combustible gas products of combustion. The spark and flame arresters installed upstream of the filters are designed to alleviate this problem. Spark arresters constructed of coarse glass fibers provide reasonable protection at low cost. Spark and flame arresters constructed of grids or heavy wire mesh that provide graduated openings are required to provide a 2-minute delay before flame penetration.

The recommended limitation for filter operating temperature is 250 degrees Fahrenheit.[19] The filter media binder is assumed to be the HEPA filter component that is most susceptible to failure resulting from elevated temperature. The binder begins burning off at 350 degrees Fahrenheit.

Commonly used sealants are also highly susceptible to elevated temperatures. **Tables 3.5 and 3.6** list continuous-service temperatures for wood- and steel-cased filters. At temperatures well below the char point of an elastomeric sealant, the sealant loses its shear strength, resulting in a reduction from approximately 6,000 kPa at room temperature to a low of 100 kPa at 300 degrees Fahrenheit. HEPA filters exposed to thermal stress will begin to release contaminates at temperatures above 300 degrees Fahrenheit.

Table 3.5 – Recommended Limited Service Temperatures for Steel-Framed Fire-Resistant HEPA Filter Units Sealed with Elastomeric Adhesives

Sealant Used	*Temperature to Which Filter was Exposed (degrees Fahrenheit)*				
	Up to 10 Min [a]	*Up to 2 Hours*	*Up to 48 Hour*	*Up to 10 Days*	*> 10 Years*
HT-30-FR [b]	750	350	325	300	260
Z-743 [c]	750	325	300	275	200
EC-2155 [d]	750	250	220	200	200
Polyurethane foam	750	325	300	275	230

[a] Some reduction in efficiency may occur after 5 minutes of exposure.
[b] Goodyear.
[c] Pittburgh Plate Glass.
[d] Minnesota Mining and Manufacturing (3M).

Table 3.6 – Recommended Limited Service Temperatures for Wood-Framed Fire-Resistant HEPA Filter Units [a]

Frame Material	*Temperature to Which Filter was Exposed (degrees Fahrenheit)*				
	Up to 10 Min	*Up to 2 Hours*	*Up to 48 Hours*	*Up to 10 Days* [b]	*> 10 Years* [b]
3/4-inch-thick plywood [a, c]	750	300	275	200	180

[a] Subject to sealant limitations given in Table 3.5.
[b] Maximum temperature of 120 degrees Fahrenheit where relative humidity is 75 percent or higher.
[c] Exterior grade, fire-retardant-treated.

3.3.6.5 Moisture and Corrosion Resistance

Moisture

Water exposure is unquestionably an important factor leading to the deterioration of HEPA filters and their degradation to 0 percent efficiency when coupled with higher pressure drop. HEPA filters become weak and plug with water. One of the most common events is when people think no detrimental effects occur as a result of repeatedly wetting the filter and drying it. Tests have shown that repeat wetting and drying of a HEPA filter will cause the loss of half its strength. There also are very strong effects of operational time on the behavior of HEPA filters under wet conditions. Tests have shown that the binder starts to get soft and dissolves at high differential pressures. One of the most serious issues dealing with HEPA filters in DOE facilities is their potential for rupture during accidental fires and the resulting release of radioactive smoke. The water spray systems in the HEPA filter housings used in nearly all DOE facilities for protection against fires were designed under the assumption that the HEPA filters would not be damaged by the water spray. The most likely scenario for filter damage in these systems involves filter plugging by the water spray, followed by fan blowing out of the medium.

Water repellency is important for units that are used in laboratory and industrial applications. Repellency is measured by the height of a water column that does not leak through the paper. A water repellency of 20 in.wg is required for filters that are operated in high-humidity conditions and stream-containing atmospheres. In the absence of adequate water repellency characteristics, liquid contaminants that collect on the filter paper can be carried through it by air pressure or capillary action and become re-entrained into the downstream air.

Humidity

Numerous German studies from the Nuclear Air Cleaning Conferences during the 1970s and 1980s showed that high humidity can result in high pressure drop and a corresponding decrease in media strength, the combination of which can lead to structural damage and a loss of filter efficiency. These tests showed the most frequent failure mode is rupture of the downstream pleat. With particle deposits, the filter would absorb water at a lower relative humidity (RH) and would rupture even with a demister installed to protect the filter. The tests further showed that filter failure under the humid air condition occurred at differential pressures that were one-third to one-fourth the comparable values for filter failure under dry conditions. The tests also showed that the tensile strength of a new filter is reduced by a factor of three due to humidity exposure.

Previous studies have shown serious problems exist with HEPA filter wetting [22, 26, 27, 28] (Bergman, Fretthold). HEPA filters exposed to wetting or high humidity must be removed from service before an accident can happen because the strength of the filter may be seriously compromised (see Appendix C).

Corrosion

For many industrial applications, a moisture- and chemical-resistant filter should be capable of withstanding attack by acids, most gas-phase alkalis, and solvent droplets and vapors. However, fine glass fibers have poor resistance to hydrogen fluoride (HF), only moderate resistance to other concentrated acids, and fair resistance to water and milder chemical corrosive agents. On occasion, corrosive chemicals in the airstream will condense on the filter medium, accelerating the attack on the finest fibers. Airstreams containing some residual HF and droplets of liquid carryover after treatment by an alkali scrubber produce a severe attack on the glass fiber filter medium.

In AEC-sponsored research to develop an HF-resistant filter medium, Johns-Manville Corporation formulated a special glass fiber for the purpose. However, the high costs associated with the finished paper, together with a high shot content, large fiber diameter, and production difficulties, resulted in only marginal benefits and precluded the glass fiber's adoption for industrial use. Media made from ceramic fibers (a combination of silicon dioxide and aluminum oxide) were found to have higher HF resistance than glass, but in this case as well, the fibers have not been produced with diameters small enough to provide the required efficiency characteristics. A U.S. filter manufacturer has developed an HF-resistant, high-efficiency glass fiber paper containing up to 7 percent of a temperature-resistant polyamide (nylon). Filter units incorporating this medium were exposed to 2 to 3 parts per million (ppm) of HF and 100 ppm of nitric acid in a humid atmosphere. The test results were considered successful, and the medium was incorporated into filters used at a nuclear energy plant. The service life of the new filters was three to four times longer than that of previously used filters that were manufactured with a glass-asbestos filter medium. The adoption of plastic-coated separators has contributed significantly to extending the life of HEPA filters under corrosive service conditions.

A wooden case is more resistant to chemical attack than is a steel case. Exterior-grade material should be specified, however, because interior-grade plywood is unsuitable for outdoor filter operation or for continuous interior operation in very humid (90 to 100 percent RH) environments at temperatures above 131 degrees Fahrenheit (55 degrees Celsius), particularly when operation and shutdown periods alternate and the environment returns to room temperature. During cooling, moisture may condense on the surfaces of the wooden case and infiltrate the structure, causing swelling of the elements and a separation between the seal and frame. Most exterior-grade wood products employ a moisture-impermeable phenolic resin bonding agent, while water-soluble urea-formaldehyde resins are used as bonding chemicals for interior-grade products. Stainless steel is recommended when a metal frame is required. Mildew growth may occur on the sealant and frame interface in high humidity while the filter is in storage, causing filter degradation.

Seepage of particles collected on HEPA filters never occurs unless the filter paper becomes thoroughly wet. For this condition, different entrainment mechanisms are involved.

3.3.6.6 Radiation Resistance

Most applications for HEPA and ULPA filters in the electronics and other industries do not involve exposure to high levels of ionizing radiation. However, post-accident cleanup by nuclear reactor containment systems and some fuel reprocessing applications of facilities can involve exposure of filters to high levels of radiation. One reactor accident scenario estimates an integrated beta-gamma dose to the engineered safety feature (ESF) filters of 3.5×10^7 rads. This radiation level can result in a significant reduction in tensile strength, an increase in penetration, and an impairment of water repellency. Tests of commercial HEPA filter media before and after radiation exposures up to a level of 4.5×10^7 rads were made at the Savannah River Site. The filter papers were tested at a face velocity of 28.2 feet per minute, which is more than five times the design service velocity and greater than any velocity anticipated under post-accident conditions. Test results showed up to 64 percent loss of strength and penetration increases of 4 to 50 percent. When samples were tested for degradation of water repellency as a function of gamma dose, half of the samples showed hydrophilic action in less than 10 seconds and the remainder in 60 to 100 seconds. The current code, ASME AG-1[2], calls for filter papers to support a 6-inch column of water after exposure to an integrated gamma dose of 6.0 to 6.5×10^7 rads. Other tests exposed small HEPA filters to a range of radiation doses, and then exposed them to a flowing steam-air mixture to determine the residual resistance to plugging and rupture. Plugging was found to be inversely proportional to radiation dose (e.g., filters exposed to 6×10^8 rads ruptured in 100 seconds) but a sample irradiated to only 1×10^8 rads withstood the steam-air mixture for 250 seconds before failure. Despite some blinding (water vapor interference with particulate capture), unirradiated samples did not rupture under the same flow regimen. These tests verified the need to provide filter systems with reliable protection from wetting wherever exposure to spray or condensing steam is possible, particularly when water exposure may be coupled with high levels of radiation.

3.3.7 HEPA Filter Performance Testing for Nuclear Service

HEPA filters for nuclear service undergo a qualification procedure and two testing regimens. The first regimen consists of a stringent visual examination and penetration tests at the place of manufacture. The second regimen is an in-place leak test performed at the place of utilization. DOE requires independent inspection and penetration tests at the designated DOE FTF prior to installation at its final destination. [For a detailed discussion of qualification procedures, see Section 8.2, "Proof of Design – HEPA Filter

Qualification for Nuclear Service."] The state of DOE testing and the test facility are discussed in DNFSB Tech-23.[29]

The manufacturer's testing regimen involves two distinct phases: (1) a quality control routine to ensure careful manufacture of the product, and (2) a series of tests to verify filter compliance with standards and performance criteria related to collection efficiency and resistance to airflow. When all factors are within the tolerance limits set by applicable specifications, the manufacturer certifies that each filter unit meets the specification acceptance criteria.[30]

In addition, DOE mandates independent inspection and penetration testing for all filters purchased. Testing is currently required for filters installed in hazard Category 1 and 2 facilities that perform a safety function, and a statistical approach for the balance.[31] The filters are tested for compliance with the requirements for physical characteristics, efficiency, and airflow resistance. This testing is conducted at the DOE-supported FTF before the filters are released to the customer's facility. Filters failing to meet the FTF specification acceptance criteria are rejected and turned over to the purchaser for disposition; typically, they are returned to the manufacturer for credit. Both DOE and the NRC do not permit repairs of HEPA filters intended for nuclear service.

3.3.7.1 Manufacturers' Filter Qualification Test Protocols

Penetration (Efficiency)

For HEPA filters, particle removal is usually expressed as collection penetration (treated air concentration ÷ untreated air concentration × 100) or as penetration (100 - efficiency). Concentration may be expressed by particle count per unit air volume (emphasizing the smallest particles present), particle weight per unit air volume (emphasizing the largest particles present), ionizing radiation intensity per unit volume of air (particle size effect indeterminate), or by light-scattering intensity per unit air volume (emphasizing small particle sizes). Sometimes filter penetration is expressed as a decontamination factor (DF), the ratio of the untreated air concentration to the treated air concentration, (e.g., a 99 percent collection efficiency is the same as a DF of 100, and is equal to a penetration of 1 percent). The DF descriptor is most frequently used when ionizing radiation is the concentration descriptor.

Airflow Resistance

The resistance of a filter to airflow, often expressed as "pressure drop" and "back pressure," is almost always measured as the height of a water column that exerts an equal pressure. This practice probably was borrowed from hydrology, where the unit has a more direct relationship, as well as the use of water-filled manometers to measure air filter resistance. The characteristic flow regime through HEPA filter media is aerodynamically described as laminar. For this reason, the airflow resistance of these filters changes in direct proportion to changes in air volume throughput (expressed as feet per unit area), even though the air approaching the filter may be turbulent. The direct proportionality of resistance to flow rate is not a characteristic of prefilters. For prefilters, resistance is a power function of airflow rate with an exponent larger than 1, but not exceeding 2.

The test protocols used to qualify HEPA filters for nuclear service are described below. Testing of all new filters intended for nuclear service in the United States is conducted with a 0.3-μm test aerosol in a rig called a Q107 penetrometer that was designed by the U.S. Army Chemical Corps during the 1950s. Construction and operation are described in MIL-STD-282, Method 102.9.[5] The complete penetrometer consists of test aerosol generator, an instrument that measures the size and uniformity of the particles formed, a clamping device to seal the filter under test into the test rig, a total scattering photometer to measure test aerosol penetration, and a manometer to measure filter resistance at rated airflow rate.

The Q107 penetrometer, used for filters of 1,700 m^3/hr rated capacity, exceeds 40 feet in length (**Figure 3.12**). The Q76 penetrometer, which tests smaller filters and is based on the same principle of operation, is considerably smaller. When testing a 1,700 m^3/hr filter, about 2,400 m^3/hr of outside air is drawn into the system and divided into 3 parallel ducts that carry approximately 170, 500, and 1,350 m^3/hr, respectively. The remainder, approximately 350 m^3/hr, is exhausted through another path. The 170 m^3/hr duct contains electric heaters that raise the temperature of the air to 374 degrees Fahrenheit (190 degrees Celsius). Other electric heaters keep the liquid test aerosol reservoir heated to approximately 392 degrees Fahrenheit (200 degrees Celsius). The test aerosol is vaporized from the reservoir into the heated airstream as it sweeps across the liquid surface and is mixed with the air in the 500 m^3/hr duct that contains both cooling units and reheaters to provide partial dilution and temperature control of the test aerosol vapor stream. The temperature of the test aerosol liquid reservoir establishes the mass concentration of the aerosol; a liquid temperature of 392 degrees Fahrenheit (200 degrees Celsius) produces 80 to 100 μg/L of test aerosol when diluted with 2,400 m^3/hr of air. The particle size of the aerosol is determined by the temperature differential between the evaporated test aerosol vapor stream and the much cooler diluting stream—the greater the temperature differential, the smaller the resulting particle size. Temperature fluctuations in both airstreams influence particle size distribution; the greater the fluctuation, the wider the size distribution. The combined flows from the 170- and 500-m^3/hr ducts are diluted further with the air in the 1,350-m^3/hr duct to produce the final aerosol concentration used for filter testing. Baffles are placed upstream and downstream to help mix the aerosol entering and leaving the filter being tested.

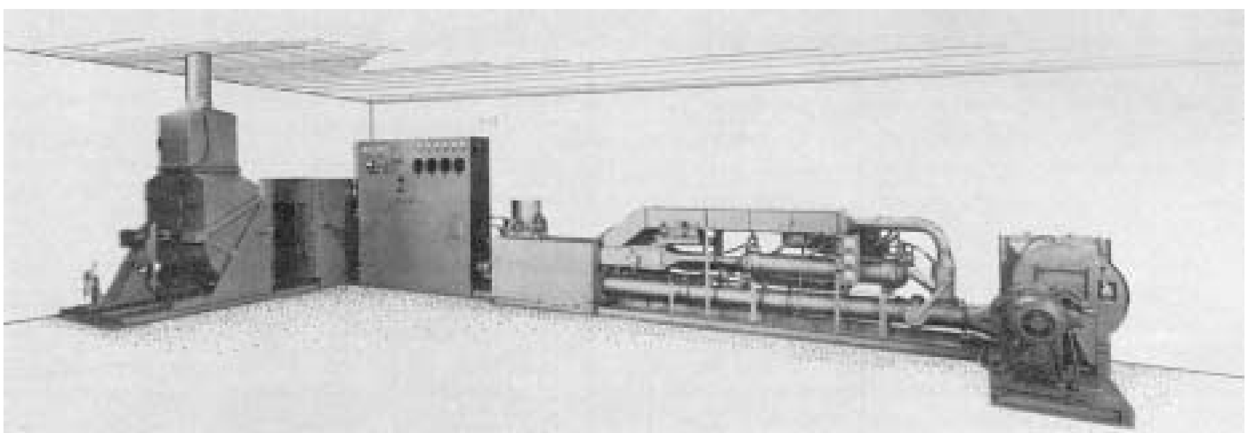

Figure 3.12 – Q107 Penetrometer

The test aerosol particle size is determined by passing a sample through an optical particle-sizing instrument called an OWL[32] and noting the degree of polarization of a light beam. A polarization angle of 29 degrees indicates a particle diameter of 0.3 μm when the aerosol is monodisperse.[33]

The optical device used to measure particle concentration is a forward-angle, light-scattering photometer capable of measuring scattering intensity over a range of at least five orders of magnitude. Current commercial instruments can give a useful signal with a concentration as low as 10 particles/cm^3 when finely tuned and used by a skilled operator. For routine testing, a downstream concentration of 10^{-4} mg/m^3 can be measured with reliability when the upstream concentration is 10 mg/m^3, indicating a filter efficiency of 99.99 percent for the test aerosol. This level of measurement is considered adequate for nuclear applications (in view of the lesser efficiency credit regularly assigned to filters by regulatory authorities), however, manufacturers of microelectronic chips have sought filters with much higher retention efficiency.

ULPA filters have an efficiency of 99.9995 percent for particles in the 0.1-μm range, which is the minimum filterable particle size for currently manufactured HEPA filters operating at their design airflow rate. This degree of efficiency is beyond the range of the Q107, but a laser spectrometer has been developed that can measure filter performance at much higher efficiencies and for smaller particle diameters. This device measures the sizes of individual particles in an aerosol and displays the particle-size distribution on a screen and a printout. When used with a polydisperse aerosol challenge, it can measure penetration values as low as 1×10^{-9} in a range of particle diameters from 0.07 to 3.0 μm. Use of duplicate instruments upstream and downstream permits the determination of a "particle size-collection efficiency" table or chart for individual filters at a modest cost and within a reasonable period of time. Laser spectrometers can also be used to determine such important filter performance parameters as maximum penetrating size, efficiency of filters in series, and the optimum formulation of filter fibers. The laser spectrometer has been used experimentally for in-place filter testing, but an inability to detect and isolate small leaks in a filter bank at low upstream aerosol concentrations is unresolved. [Note: Lasers are currently being used routinely for high-efficiency filters (HEPA and ULPA) with acceptable results. Operator training is still an important issue, as is recognition that most lasers are calibrated using polystyrene latex (PSL) rather than the test aerosol. The properties of PSL (e.g., refractive index) are not identical to the test aerosol. This can produce inaccurate results unless operators understand the differences and set up the equipment properly. Upstream concentration is also critical because lasers can be blinded by the passage of too many particles to the counter. Most successful applications use calibrated particle diluters to ensure the laser is not overwhelmed.]

An international sampling of laser use for filter efficiency testing was conducted in 1985 by the Institute of Environmental Sciences and Technology (IEST) Working Group RP7 (IEST-RP-CC007.1)[34]. Samples of 14 different high-efficiency filter media were sent to interested parties with recommended protocols for instrument calibration and test performance. Results from eight participants showed wide variation in particle size efficiency results for identical filter papers. Incorrect calibration of laser spectrometers and incomplete knowledge of laser operation were contributing factors.

Based on the 1985 IEST findings, standards-writing groups organized at DOE since 1980 have established rigid procedures for spectrometer calibration and use for filter testing. The operating policy of DOE's filter testing program, contained in DOE-STD-3022-98[9], calls for testing of all HEPA filters intended for environmental protection at a DOE-operated FTF. Delivery of filters to a test facility for quality assurance review is mandatory for all DOE facilities, and the service is also available to the public for a fee. When the filter manufacturer's test data are confirmed, the FTF test results are added to the information on the filter case. The test procedures at the FTFs call for "penetration and resistance tests…visual inspection for damage and visible defects…[and other]…visually verifiable requirements." Except for the smallest filter sizes, penetration tests are required to be conducted at 100 percent and 20 percent of rated airflow capacity, and the maximum penetration of 0.1- to 0.2-μm particles at both airflow rates is 0.03 percent, in accordance with draft DOE-STD-3025-99, *Quality Assurance Testing of HEPA Filters*.[10] Penetration tests may be conducted using a monodispersed aerosol and a total light-scattering photometer, or a polydisperse aerosol with a single particle counting and sizing instrument.[10] A quality assurance program for DOE's FTFs is contained in draft DOE-STD-3026-99,[11] and specifications for HEPA filters to be used by DOE contractors are contained in draft DOE Standard DOE-STD-3020-97.[6] The HEPA filter specifications in DOE-STD-3020-97 are the same as those in the previously cited military specifications, except that the size and size distribution of monodispersed aerosols, when measured by the OWL, must be verified by a single particle counter.[6]

3.3.7.2 Quality Control/Assurance Considerations

Systematic quality control and quality assurance testing are conducted at all stages of the product cycle from development to use. The filter medium receives the most rigorous and extensive control and evaluation, perhaps because its development and manufacture necessarily demand a degree of art as well as science. Performance of the filtration medium is determined by a thermally generated monodispersed aerosol generated by a Q127 penetrometer,[35] a smaller version of the Q107 used to test cased filters. The physical characteristics of the medium are controlled by a battery of standard test protocols developed by the TAPPI, ASTM, and ASME AG-1.[2] The use of ASME AG-1 requires an ASME NQA-1[36] program. After fabrication, in addition to measuring the efficiency and airflow resistance of the filter assembly with a Q107 or a Q76 penetrometer (depending on the rated airflow capacity and physical size of the filter), a series of physical tests described in ASME AG-1, Section FC,[2] are applied to filter prototypes for qualification. These include tests of dimension tolerances and resistance to rough handling, pressure, heated air, flame, and unfavorable environments (simulated desert, tropical, and Arctic conditions).

Filter Test Facilities were established in the early 1960's (see Chapter 1, Section 1.1.8). The last remaining FTF is at Oak Ridge, Tennessee, and continues to inspect and test HEPA filters destined for safety class or safety significant service at DOE facilities. The FTF continues to routinely find problems with HEPA filters sent by the various manufacturers. Problem HEPAs are returned to the manufacturer at no cost to DOE. Problems encountered occur in two categories: (1) flow/resistance/penetration amounting to approximately 1 to 2 percent per year, and (2) obvious defects in workmanship (which do not get flow tested) such as splinters, protruding nails, improper gaskets, etc.) amounting to an additional 2 to 3 percent per year. There have been major spikes (up to 20 percent) when a media making or packaging process was changed. The FTF serves its function well.

3.3.7.3 Other Historical Methods of Testing New HEPA Filters

Nebulized Paraffin Oil

In Germany, new HEPA filters are tested according to German Standard, DIN 24-184[37] The aerosol used is generated from a distillate oil fraction (paraffin oil) with a viscosity of 3 to 3.8×10^{-5} m^2/sec by heating the oil to 212 degrees Fahrenheit (100 degrees Celsius) and nebulizing it with compressed air. The oil mist concentration is about 10 mg/m^3, with a droplet size median diameter of 0.36 μm and a geometric standard deviation of about 2.0. A 45-degree angle, light-scattering aerosol photometer is used to measure the light-scattering concentration of the aerosol entering and leaving the filter undergoing a penetration test. The DIN 24-184[20] test method differs in details, but is very close in principle to the U.S. test method.

Nebulized Sodium Chloride

The standard test method used in Great Britain for new HEPA filters[38] utilizes a dried sodium chloride aerosol generated from solution with a compressed air nebulizer. An emission-flame photometer is used to measure the quantity of sodium chloride entering and leaving the filter being tested. The dried aerosol particles have a concentration of about 3 mg/m^3, a mass median diameter of 0.65 μm and a geometric standard deviation of 2.1. The test rig and test procedures employed do not differ significantly from those used in the United States, Germany, and a number of other countries.

Nebulized Uranine

The French standard test method, AFNOR NFX 44.011,[39] uses dried particles of uranine, a fluorescent material generated from a solution with a compressed air nebulizer. The aerosol concentration for the test is about 8×10^{-3} mg/m^3. The mass median diameter of the particles is 0.15 μm, with a geometric standard deviation of 1.55.

Aerosol samples are extracted from the test apparatus upstream and downstream of the filter being tested and are collected on filter papers. After the sampling period has expired, the filter papers are extracted in water and analyzed by fluorimetry. Filter efficiency is expressed as the percent by weight of fluorescent particles collected by the filter. Because of the need to collect samples over some averaging period (e.g., 10 minutes) and then to extract the uranine quantitatively from the filters and read the fluorescence intensity in a fluorimeter, about 30 minutes is required for an analysis. Direct readout of filter efficiency is characteristic of most other standard test procedures.

Interrelationships Between Test Methods

A number of comparative analyses have been conducted for the purpose of establishing ratios between the several standard test methods, with indifferent results. This is understandable because different test methods use different test aerosols, very different analytical processes, and are applied to filters that respond differently to aerosols that have variable fractions of large and small particles. So, it is wise to view a filter's ability to pass the formal test protocols as simple assurance that the filter is constructed of quality components and was assembled in a sufficiently careful manner to make it free of unacceptable defects. In short, passing any one of the tests establishes that the filter is satisfactory for nuclear service—nothing more.

3.3.8 The Impacts of Aging, Wetting, and Environmental Upsets on HEPA Filter Performance

Intuitively, the aging of filters in storage or in use inplace should lead to a higher probability of media or structural failure. At least five experimental studies [22, 40, 41, 42, 43] have shown that with aging, HEPA filters lose strength and water repellency but do not necessarily become less efficient. Logically, it follows that filter efficiency depends on the physical geometry of the filter media, and is not significantly affected when the organic binders and sealants become brittle or degrade with age. Filter strength prevents structural failure during events that produce high stress across filter media, e.g., when particle deposits and water accumulation cause filter plugging. Historical measures of filter strength are: (1) the tensile strength of the paper in combination with a 10-inch overpressure test on the filter, and (2) burst strength. Burst strength (the pressure required to tear open the media) quantitatively measures two-dimensional stretches as compared to the one dimension used to measure the tensile strength. The brittleness of the media, which is measured by flexing it, is a third major strength measurement, although it is not generally measured in aging studies. Several authors have noted that aged HEPA filters are very brittle.

Decreasing water repellency produces filter plugging as accumulated moisture plugs filter media and decreases tensile strength. Critical filter parameters such as media tensile strength and water repellency unfortunately vary widely by manufacturer and types of particulate deposits. These varying parameters frequently mask the effects of aging, often making it difficult to derive an age limit using the available experimental data. M.W. First[43] qualitatively described the deterioration mechanisms involved in HEPA filter aging as:

- Aging and weakening of glass fibers;
- Aeterioration of the resin binder and the organic sealant;
- Corrosion of the aluminum separators;
- Moisture damage; and
- Mechanical stresses caused by handling the filter and airflow pulses.

Johnson, et al.,[41] were unable to measure the tensile strength across the media folds for aged HEPA filters because the brittle media cracked; they also observed that the media had lost most of its water repellency.

Following issuance of the Defense Nuclear Facilities Safety Board's Technical Report 23, *HEPA Filters Used in the Department of Energy's Hazardous Facilities*,[29] DOE initiated efforts to update ERDA 76-21, *The Nuclear Air*

Cleaning Handbook,[44] to present new guidelines for root causes and factors that would dictate replacement of HEPA filters within DOE nuclear facilities. However, as publication of this revision was delayed, increasing risks identified with aging HEPA filters at many DOE sites required the development of interim criteria for replacing safety-related HEPA filters to address wetting and environmental conditions, as well as aging considerations.

Many of these issues have been reviewed throughout the DOE complex in response in part to the Defense Nuclear Facilities Safety Board (DNFSB) Recommendation 2000-2, *Configuration Management, Vital Safety Systems.*[31, 45] DOE reviewed several facilities for their conformance to regulations, Orders, and standards concerning confinement ventilation systems (CVS). These reviews identified both strengths and weaknesses in the sites' filter programs in the following areas: (1) independent quality assurance testing/inspection by the FTF; (2) receiving inspection; (3) storage of HEPA filters; (4) in-place testing; (5) system bypass testing, and (6) service life. They also identified the need for more periodic CVS reviews. These have typically been woven into ongoing periodic assessments.

3.3.8.1 Aging

Bergman[45] stated that, "a conservative interpretation of my experimental results indicates that the maximum total life (storage and in-service) of HEPA filters for consistently removing greater than 0.9997 of 0.3 micron particles from highly hazardous aerosols is 10 years from the date of manufacture for applications in dry systems, and 5 years in applications where the filter can become wet more than once for short periods of time." If a filter gets wet it should be replaced expeditiously. At Oak Ridge National Laboratory (ORNL), Lawrence Livermore National Laboratory (LLNL), Idaho National Engineering and Environmental Laboratory (INEEL), and Savannah River Site (SRS) for "dry service" at normal relative humidity, the 10-year criterion is applicable to HEPA filters for aging. The date of installation is available for most safety-related HEPA filters. Historically, the date of manufacture has not been documented in a readily accessible manner, but will be under the new Standards Based Management System (SBMS). Clearly, however, the date of manufacture may not be retrievable for currently installed filters. If this information is available (without having to remove the filter to retrieve the data on its frame), the filter service life will be determined based on the date of manufacture. If the date of manufacture is not available, the date of installation will be used. If neither is available, the filter will be assumed to be over 10 years old and subject to immediate replacement.

3.3.8.2 Wetting

In his experiments, Fretthold[42] demonstrated that "previous water exposure weakened the filter media irreversibly," and that the "burst strength of the filter media decreased significantly with each wetting and drying." The replacement criteria will be exposure to a single occurrence of filter wetting. Potential sources of filter wetting are entrained droplets from actuation of sprinklers in areas that are upstream of the airflow to the filters, rain or groundwater inleakage into the filter system, or condensation from a leak of steam or hot water.

3.3.8.3 Upset Environmental Conditions

Section 12.05 of the Lawrence Livermore National Laboratory Health and Safety Manual,[47] *High Efficiency Particulate Air (HEPA) Filter System Design Guidelines for LLNL Applications*, stated that continuous exposure to the following operational environments will permanently damage or compromise HEPA filters:

- **Moisture and Hot Air**: 95 to 100 percent RH at temperatures higher than 130 degrees Fahrenheit.
- **Fire**: Direct fire or high concentrations of particulate matter produced by fire.

- **High Pressure**: 6.0 in.wg or more, internal or differential across the filter media. Filters should be changed if the differential pressure [adjusted for rated flow] exceeds 4.0 in.wg.

- **Corrosive Mist**: Dilute moist or moderately dry concentrations of acids and caustics.

- **Shock Pressures**: More than 1.7 psig.

The following criteria were modified for conservatism and simplification for use in an SBMS.

- **Wetting:** A single occurrence of filter exposure to water including entrained droplets from actuation of sprinklers in the area upstream of the filters, rain or groundwater, or condensation from a leak of steam or hot water.

- **Moisture and Hot Air:** HEPA filters may be operated continuously at 180 degrees Fahrenheit and between 5 and 75 percent RH, or at 120 degrees Fahrenheit and between 75 and 95 percent RH. HEPA filters are not to be used for installations where there is a possibility of condensation forming on them. They will provide maximum service life when operated below 100 degrees Fahrenheit and 75 percent RH.

- **Fire:** A single occurrence of direct flame impingement. [Note: Filters subjected to smoke from fires must have an in-place leak test performed on them immediately by the responsible in-place testing group (i.e., within 24 hours) and must be replaced if the filter fails the in-place leak test.]

- **High Differential Pressure:** A single occurrence of a differential pressure across a single filter of 8.0 in.wg or more.

- **Shock Pressure:** A single exposure to more than 1.7 psig.

- **Corrosive Mist:** Prolonged exposure (more than 4 weeks) to dilute moist or moderately dry concentrations of acids and caustics.

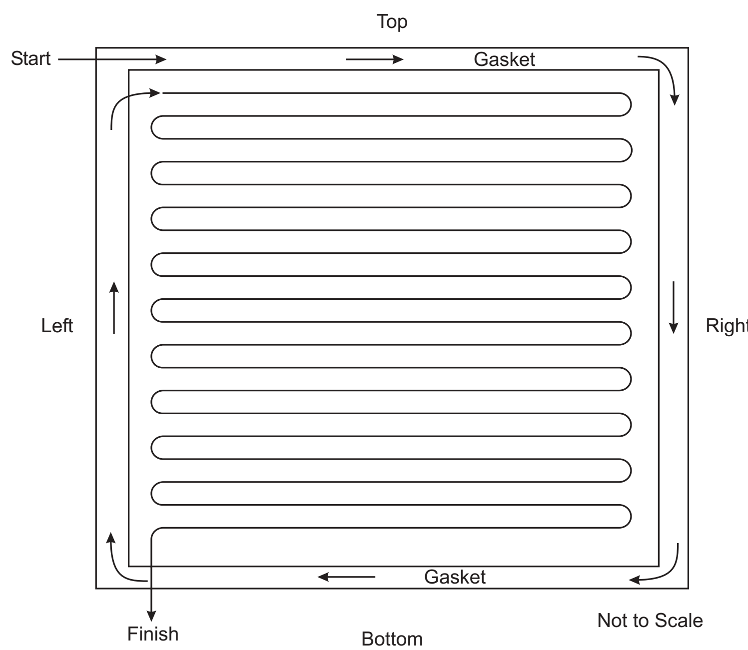

Figure 3.13 – Suggested Filter Probe Traverse Diagram

3.3.8.4 In-Place Testing of Filter Installations

An in-place leak test is done after filters are installed at a DOE nuclear facility to ensure the performance of the confinement ventilation system. The in-place leak test is used both for an acceptance and for surveillance leak testing of the installed HEPA filter bank. An in-place leak test and visual inspection of HEPA filters are performed initially upon installation to detect bypasses and damage to filters and periodically to establish current condition of a nuclear air cleaning system and its components. Specific objectives of in-place filter testing are (1) to test the aggregate performance to filters in a filter bank, (2) to evaluate the effectiveness of seals between the filter gasket and the filter housing, (3) to assess the leak-tightness of the filter housing, and (4) to determine whether bypasses exist around the filter housing. Each time repairs are made, the system must be retested until it meets the established criteria for leaktightness.[48] Detailed information on in-place filter testing is included in Chapter 8.

3.3.8.5 Packaging, Storage, and Handling of HEPA Filters

The manufacturer should have a quality program for the packaging, shipping, handling, and storage of HEPA filters (e.g., NQA-1). HEPA filters are normally packaged in corrugated cardboard cartons that conform to shipping regulations. Additional internal pieces are inserted to protect the filter faces from damage during handling and transit. Palletizing crating should be constructed for ease of disassembly (see **Figure 3.14**). For multiunit shipments, individual cartons should be crated and palletized to minimize handling, particularly at trans-shipment points when using public carriers. For very large shipments, sealed and dedicated trailers are recommended. [Note: Filters shipped in less-than-truckload amounts using common carriers are often rearranged incorrectly by the carriers, resulting in damaged filters.] Upon delivery at the destination, mechanical warehousing equipment should be used for unloading and transferring the shipment. Cartons should be placed in clean, dry, interior storage until used. They should be positioned as directed on the carton exterior, and no more than three filter cartons should be stacked atop each other.

Figure 3.14 – Filter Crating and Palletizing

When a filter is inserted in the cardboard shipping container, the pleated folds should be oriented in the vertical direction (except Type B filters), and both the filter frame and the enclosing carton should be labeled with a vertical arrow or the notation, "This Side Up" (including Type B filters). When handling a filter inside a carton, the box should be tilted on one corner, picked up, and carried by supporting it at diagonally opposing corners. Removing the filter from its shipping carton without damaging the medium is best accomplished by opening and folding back the top flaps of the carton, inverting the carton onto a clean surface, and lifting the carton off the filter. Then the filter unit can be grasped by the outer frame surfaces without the danger of personnel coming into contact with the filter pack enclosed within the frame. Additional details can be found in Appendix B.

3.4 Prefilters for HEPA Filters

3.4.1 Filter Descriptions

The service life of HEPA filters can often be extended by using less efficient filters that selectively remove the largest particles and fibers from the incoming airstream. In some cases, HEPA filter lifetimes can be increased by as much as four times with multiple prefilter changes during the interval between HEPA filter changes. It is recommended that HEPA filters be protected from: (1) particles larger than 2 μm in diameter, (2) lint, and (3) particle concentrations greater than 2.3 mg/m^3. Selection of an appropriate prefilter includes consideration of: (1) the rapidity of filter resistance buildup and associated energy costs, (2) the size and complexity of the resulting filtration system, (3) the fact that replacement filters and associated costs generally increase with increasing prefilter efficiency, and (4) the disposal costs for contaminated HEPA filters and potentially uncontaminated prefilters. It has been estimated that, with frequent prefilter replacements, savings in filter system operation could be as much as one-third the cost of operating without prefilters. Assessment of an acceptable combination of prefilters and HEPA filters depends on the dust-loading and efficiency characteristics of the different filter types available for the particular aerosol to be filtered. The clogging susceptibility of HEPA filters will vary with the dust and filtration characteristics of the prefilters.

The types of filters used as prefilters are also widely used for cleaning ventilation supply air in conventional HVAC systems. The important advantage of filtering ventilation supply air for many operations that generate radioactive particles is a reduction in the dust load that reaches the final contaminated filters. This helps extend the service life of the exhaust filters, thereby reducing overall system costs because the supply air filters can be changed without resorting to radiation protection measures—often the most costly aspect of a contaminated exhaust filter change. These filters have a wide range of efficiencies, including 5 to 10 percent for warm air residential heating systems; 35 to 45 percent for ventilation of schools, stores, and restaurants; and 85 to 95 percent for fully air-conditioned modern hotels, hospitals, and office towers.

3.4.2 Classes, Sizes, and Performance Characteristics of Prefilters

For prefilters intended to remove only the largest airborne particles, a reverse relationship between retention and re-entrainment forces occurs, causing collected particles to seep through the filter under prolonged airflow unless the filter fibers are coated with viscous liquids to wet the collected particles and increase the area of contact between them and the filter surfaces.

The most widely used test methods for ventilation air filters are published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) as Standard 52.1-92,[49] which contains two different protocols. One uses a prepared "test dust" consisting of road dust, carbon black, and cotton fibers. In this procedure, the test dust is aerosolized by compressed air and blown into the filter at a concentration many times that normally found in ambient air. The filter is rated by the weight percent of dust retained. This obsolete test method originated in the days when coal was the only fuel and has little relevance to today's air filter requirements. The second test method uses unaltered atmospheric air as the test medium and rates filter efficiency on the basis of the percent reduction in discoloration of simultaneous samples taken on white filter papers upstream and downstream of the filter being tested. Reductions in discoloration cannot be related to weight percent efficiency. In addition to dust-collecting efficiency, the first test procedure measures filter resistance increase with dust deposition and dust-holding capacity. Ventilation filters in the 35 to 95 percent efficiency range are evaluated by the atmospheric dust discoloration test.

Table 3.7 (from ASHRAE 52.2)[50] shows cross-reference and application guidelines for air cleaners with particulate contaminants. For comparison purposes, the HEPA filter is rated at 100 percent for both the stain-efficiency and artificial dust arrestance tests. Because the atmospheric dust test is based on the staining capacity of the dust that penetrates the filter, compared to the staining capacity of the entering dust, it is not a true measure of particle-removal efficiency for any one particle-size range.

Table 3.7 – Cross-reference/Application Guidelines for Air Cleaners with Particulate Contaminants

Std. 52.2 Minimum Efficiency Reporting Value (MERV)	*Approximate Std. 52.1 Results*		*Application Guidelines*		
	Duct Spot Efficiency	*Arrestance*	*Typical Controlled Contaminant*	*Typical Applications and Limitations*	*Typical Air Filter/Cleaner Type*
20 19 18 17	n/a n/a n/a n/a	n/a n/a n/a n/a	**≤0.30 µm Particle Size** Virus (unattached) Carbon dust Sea salt All combustion smoke Radon progeny	Cleanrooms Radioactive materials Pharmaceutical manufacturing Carcinogenic materials Orthopedic surgery	**HEPA/ULPA Filters** ≥99.999% efficiency on 0.1-0.2 µm particles, IEST Type F ≥99.999% efficiency on 0.3 µm particles, IEST Type D ≥99.99% efficiency on 0.3 µm particles, IEST Type C ≥99.97% efficiency on 0.3 µm particles, IEST Type A
16 15 14 13	n/a >95% 90-95% 80-90%	n/a n/a >98% >98%	**0.3-1.0 µm Particle Size** All bacteria Most tobacco smoke Droplet nuclei (sneeze) Cooking oil Most smoke Insecticide dust Copier toner Most face powder Most paint pigments	Hospital inpatient care General surgery Smoking lounges Superior commercial buildings	**Bag Filters**: Nonsupported (flexible) microfine fiberglass or synthetic media, 12 to 36 inches deep, 6 to 12 pockets **Box Filters:** Rigid style cartridge filters 6 to 12 inches deep may use lofted (air laid) or paper (wet laid) media.
12 11 10 9	70-75% 60-65% 50-55% 40-45%	>95% >95% >95% >90%	**1.0-3.0 µm Particle Size** Legionella Humidifier dust Lead dust Milled flour Coal dust Auto emissions Nebulizer drops Welding fumes	Superior residential Better commercial buildings Hospital laboratories	**Bag Filters:** Nonsupported (flexible) microfine fiberglass or synthetic media, 12 to 36 inches deep, 6 to 12 pockets. **Box Filters:** Rigid style cartridge filters 6 to 12 inches deep may use lofted (air laid) or paper (wet laid) media.
8 7 6 5	30-35% 25-30% <20% <20%	>90% >90% 85-90% 80-85%	**3.0-10.0 µm Particle Size** Mold Spores Hair spray Fabric protector Dusting aids Cement dust Pudding mix Snuff Powdered milk	Commercial buildings Better residential Industrial workplaces Paint booth inlet air	**Pleated Filters:** Disposable, extended surface, 1 to 5 in. thick with cotton-polyester blend media, cardboard frame. **Cartridge Filters:** Graded density viscous coated cube or pocket filters, synthetic media **Throwaway:** Disposable synthetic media panel filters
4 3 2 1	<20% <20% <20% <20%	75-80% 70-75% 65-70% <65%	**>10.0 µm Particle Size** Pollen Spanish moss Dust mites Sanding dust Spray paint dust Textile fibers Carpet fibers	Minimum filtration Residential Window air conditioners	**Throwaway:** Disposable fiberglass or synthetic panel filters **Washable:** Aluminum mesh, latex coated animal hair, or foam rubber panel filters **Electrostatic:** Self charging (passive) woven polycarbonate panel filter

ASHRAE Standard 52.1-92[49] tests have replaced those sanctioned formerly by the Air Filter Institute and the Dill Dust-Spot Test of the National Institute for Standards and Technology. Care must be taken in the interpretation of data from the ASHRAE tests. Arrestance test results depend highly on particles that exceed 1 μm in diameter, but the ambient atmospheric dust test results depend on the nature and concentration of aerosol particles at the testing location. The average particle size of the urban atmosphere is assumed to be 0.5 μm. The results of the various tests are not comparable, and a filter determined to be efficient by one test may be determined to be inefficient by another. Users should examine the test used to evaluate a filter's efficiency to properly understand the results. Efficiency tests are made on prototype filters, and the results are extrapolated to other units of similar design (certification of every prefilter by testing would be too costly).

Values stated in Table 3.7 for dust-holding capacity were determined with resuspended synthetic dust mixtures. Dust-holding capacity varies with the nature and composition of the particles (e.g., carbon black, cotton linters). Dust-holding capacity under service conditions cannot be predicted accurately on the basis of manufacturers' data. Air resistance is the primary factor in prefilter replacement. Although manufacturers recommend specific values of resistance for prefilter replacement, loss of adequate airflow is often a more reliable indicator of system performance and is also more cost effective. Panel filters will plug rapidly under heavy loads of lint and dust. An accumulation of surface lint may increase the efficiency of an extended-medium filter by adding "cake" filtration principles to the existing physical mechanisms. The extended-medium prefilter will plug readily in an airstream carrying profuse smoke and soot from a fire. Operation at airflows below rated capacity will extend the service lives of filters and be more cost effective by reducing the frequency of filter replacement. On the other hand, when airflow exceeds rated values, dust-loading rate and system costs begin to increase exponentially along with proportional increases in airflow. [ASHRAE also publishes Standard 52.2-99,[50] which gives methods for testing filter efficiency by particle size using optical particle counters, including lasers.]

3.4.3 Construction of Prefilters

Prefilters are classified by the American Refrigeration Institute (ARI) 850-93[51] as follows:

- Group I - Unit or panel.
- Group II - Self-cleaning, self-renewable, or any combination thereof.
- Group III - Extended surface.
- Group IV - Electronic air cleaner.
- Group V - Air filter media.

Group I panel filters (viscous impingement filters) are shallow, tray-like assemblies of coarse fibers (glass, wool, vegetable, or plastic) or metal mesh enclosed in a steel or cardboard casing. The medium is usually coated with an inhibited viscous oil or adhesive to improve trapping and retention of particles. Single-use disposable and cleanable-reusable types are available. The latter have metal mesh and generally are not used in nuclear applications for effluent or process air cleaning because of the high labor costs associated with cleaning and disposal of entrapped radioactive materials. A disposable panel filter has a fairly high dust-holding capacity, low airflow resistance, low initial and operating costs, and high removal efficiency for large particles. It is particularly effective against fibrous dust and heavy concentrations of visible particles, but is ineffective for smaller particles. For nuclear service, it is less cost-effective than the more costly Group II or III filters that provide better protection for the HEPA filter.

Group II (moderate-efficiency) and Group III (high-efficiency) filters are usually comprised of extended-medium, dry-type, single-use disposable units. The filter medium is pleated or formed into bags or socks to provide a large filter surface area with minimal face area. They are not coated with adhesive. The particle size efficiency of Group II filters is moderate to poor for submicrometer-sized particles, but often approaches 100 percent for particles greater than 5 µm. In most cases, the pressure drop of extended-media Group II filters varies directly with efficiency. Group II filters are recommended for high lint- and fiber-loading applications. The large filter area relative to face area permits duct velocities equal to or higher than those of panel filters.

Group III filters are preferred when higher efficiency for smaller particles is desired. The dust-holding capacity of Group III filters usually is lower than that of Group II filters.

3.4.4 Electrostatic and Electrified Filters

An electrostatic charge may be induced on filter fibers by triboelectrification and by sandwiching the fiber bed between a high voltage and a grounded electrode. Triboelectrification can be used to induce a high electrostatic charge on suitable high dielectric materials, but under practical-use conditions, the charge is subject to rapid dissipation due to air humidity, oily particles, fiber-binding particles, and other interference. Continuously activated electrodes can induce a more permanent charge.

A program to develop electrofibrous filters, undertaken by DOE at LLNL, has proved them effective in providing greater efficiency and longer service life for the prefilters used to protect HEPA filters. They have been used in gloveboxes and for other applications. Laboratory tests using test and sodium chloride aerosols have shown that an "electrofibrous prefilter increases in efficiency from 40 to 90 percent as 10 kV is applied to the electrode." A comparison of uncharged, triboelectrically charged, and permanently charged fibrous filters demonstrated the higher collection efficiency of the permanently charged filter design for submicrometer particles. When continuously charged electrofibrous filters were applied as prefilters for HEPA filters in exhaust air systems or gloveboxes used to burn uranium turnings, they significantly prolonged the life of the final filters.

3.4.5 Operation and Maintenance of Prefilters

All prefilter construction materials must be compatible with those of the downstream HEPA filters they are designed to protect. Therefore, they must conform to the rigorous physical properties prescribed for HEPA filters (e.g., resistance to shock, vibration, tornado, earthquake, moisture, corrosion, and fire). Survivability under the specific operational conditions and requirements must be addressed when prefilters are selected because moisture or corrosive products in the airstream may limit the choice of filter. Although many filter media will not withstand acid or caustic attack, glass fibers are corrosion-resistant except for fluorides. However, the casing and face screen materials may be less so. Aluminum may deteriorate in marine air, from caustics, or from carbon dioxide. Plastics have poor heat and hot air resistance and generally will not satisfy UL requirements. Condensation from high humidity and sensible water may plug a prefilter and result in more frequent replacement. In general, a prefilter made of construction materials identical to those in the HEPA filter will have equivalent corrosion and moisture resistance. Any increase in resistance from moisture accumulation will be greater for MERV 17-20 filters than for MERV 9-16 filters (ASHRAE 52.2 Table E-1)[50]. UL classifies ventilation air filters in two categories with respect to fire resistance.[50] When clean, UL Class 1 filters do not contribute fuel when attacked by flame and emit a negligible quantity of smoke. UL Class 2 filters are permitted to contain some small amount of combustible material, but they must not contribute significantly to a fire. The collected material on inservice UL-approved Class 1 and 2 filters may burn vigorously and create a fire that is difficult to extinguish. Therefore, use of an UL-rated prefilter should not lead to an unwarranted sense of security on the part of the user. The UL maintains a current listing of filters that meet the requirements of their standards.[21]

Most types of prefilters are suitable for continuous operation at temperatures not exceeding 149 to 248 degrees Fahrenheit (65 to 120 degrees Celsius). Other types with glass-fiber media in steel or mineral board frames may be used at temperatures as high as 392 degrees Fahrenheit (200 degrees Celsius). Users of high-temperature prefilters should take a conservative view of performance claims, particularly claims related to efficiency at operating temperature.

Because of waste disposal requirements, the preferred choice of a prefilter for nuclear applications is the single throwaway cartridge. A replaceable-medium filter offers an advantage over the throwaway because the bulk of material that needs to be discarded is smaller and handling and disposal costs are minimized. However, re-entrainment of contaminants and contamination of the peripheral area are possible because the medium is removed from the system and prepared for disposal. The replaceable-medium type is not recommended for toxic exhaust systems. The cleanable-medium filter is undesirable for nuclear systems because of the extensive downtime of the system that is required for changing and decontaminating areas in proximity to the filter installation.

3.5 Deep-Bed Filters

Deep-bed filters were designed, built, and placed in service early in the development of nuclear technology for treating offgasses from chemical processing operations. The first, a sand filter, was constructed at the Hanford, Washington, nuclear facility in 1948, and deep-bed glass fiber filters were constructed soon after. These were not considered competitive with then-current versions of the HEPA filter (the CWS-Type 6 or AEC-Type 1), but were thought to have a different function. With the thin-bed filters, the intent is usually to replace or clean the filter medium periodically. The deep-bed filter, on the other hand, usually has as its objective the installation of a unit which will have a long life, in the dust capacity sense, of say 5 to 20 years, corresponding to either the life of the process or the mechanical life of the system. Thus, when resistance starts increasing rapidly, instead of replacing or cleaning the filter medium, the entire filter installation would be abandoned and replaced with a new unit. In fact, the life span of some deep-bed filters constructed during the early 1950s has not yet been entirely expended. A partial explanation for this longevity is the original design concept that deep-bed filters would be used where the total aerosol concentration was usually on the order of or less than normal atmospheric dust concentrations. An important reason for selecting sand for the initial bed material was a need to filter large volumes of wet corrosive aerosols for which more usual filter materials would prove unsatisfactory. Deep beds of crushed coke had been used by the chemical manufacturing industry for many years to remove sulfuric acid mist from the effluent gas of sulfuric acid manufacturing plants prior to 1948. Silverman cited efficiencies as high as 99.9 percent by weight for a crushed-coke bed against a sulfuric acid mist of 0.5 to 3.0 μm in diameter.[52] Perhaps a carbon-filled bed was considered unsuitable for filtering an aerosol that might contain fissile material, and sand was selected for the first deep-bed filter for nuclear fuel processing facility ventilation air.

3.5.1 Deep-Bed Sand (DBS) Filters

Some of the following material is taken directly from ERDA 76-21[44]. Although dated, it is still relevant today. It has been updated where appropriate. Initially, sand filters were installed at the Hanford, Washington, nuclear facility and at the Savannah River nuclear plant. Following their success, more were added at Hanford and Savannah River and others were constructed at plants in Morris, Illinois, and Idaho Falls, Idaho. The Argonne National Laboratory compiled a bibliography of DBS filters. These DBS filters had collection efficiencies for particles greater than or equal to 0.5 μm that compared favorably with the HEPA filters of that era. Their advantages for the nuclear programs at these sites included large dust-holding capacity, low maintenance, chemical resistance, high heat tolerance, fire resistance, and a capability to withstand large shock and gross pressure changes without operational failures. They also had disadvantages such as high capital costs, need for large areas and volumes, inability to maintain the granular fill, and lack of a reasonable means of disposing of the contaminated fill.

DBS filters contain up to 10 feet of rock, gravel, and sand constructed in graded layers that diminish granule size by a factor of 2 as the layers go from bottom to top. Airflow direction is upward so that granules decrease in size in the direction of flow. A top layer of moderately coarse sand is generally added to prevent fluidization of the finest sand layer underneath. The rock, gravel, and sand layers are positioned and sized to provide the desired structural strength, particle collection ability, dirt-holding capacity, and long service life. Ideally, the layers of the largest granules, through which the gas stream passes first, remove all the large airborne particles, whereas the fine sand layers on top retain the finest smallest particles at high efficiency. Below the granular bed there is a layer of hollow tile that forms passages for air distribution. The total bed is enclosed in a concrete-lined pit. The superficial velocity is about 5-feet per minute, and pressure drop across the seven layers, sized 3 1/2-inch average diameter down to 50 mesh, is from 7 to 11 in.wg. Collection efficiencies as high as 99.98 percent for test aerosols have been reported. Some DBS filters have experienced premature plugging at relatively low dust loadings. Another suffered partial collapse from disintegration of grout between the tiles supporting the overhead filter structure. These failures were caused by moisture leaking through voids in the system perimeter or by chemical corrosion and erosion of system components from nitric acid fumes in the effluent air. Disposal of inoperable DBS filters, usually contaminated, is generally accomplished by sealing and abandonment. Replacement systems normally are constructed nearby to accommodate the same air intake duct system.

Currently, there is renewed interest in sand filters for ESF applications (e.g., the plutonium Pit Disassembly and Conversion Facility in Savannah River, South Carolina; emergency confinement venting for light-water reactors). The Swedish confinement venting system, known as FILTRA, features large concrete silos filled with crushed rock. It is designed to condense and filter the stream blown from the confinement and to release to the atmosphere less than 0.01 percent of the core inventory.

3.5.2 Deep-Bed Glass Fiber (DBGF) Filters

The rapidly emerging glass fiber technology of the late 1940s shifted attention to the use of very deep beds (1 or more meters thick) of graded glass fibers as a satisfactory substitute for sand filters when treating gaseous effluents from chemical operations. They proved to be more efficient, less costly, and to have a lower airflow resistance than the DBS filters they replaced. In addition, these DBGF filters employ a medium that has more controllable physical features and more assured availability than the DBS to permit a larger airflow per unit volume at lower pressure drop, lower operating costs, and potentially lower spent-filter disposal costs. DBGF filters have been used at Hanford for several decades on their Purex process effluent streams. However, the DBGF filters do not have the corrosion resistance of the DBS, particularly from HF, and are less fire-resistant. The DBGF is also less of a heat sink and has less capability to resist shock and high-pressure transients.

The intake segment of the DBGF filter system was designed with layered beds of uniform-diameter glass fibers to a total depth of 8 to 84 inches. Each layer in the direction of airflow was compressed to a higher density and enclosed in a stainless steel tray with impermeable walls and a perforated screen above and below. Capacity varied from 200 to 200,000 cfm (350 to 350,000 m^3/hr). Although the first unit constructed at Hanford was small (400 m^3/hr (235.4 cfm), many of the 25 subsequent units were much larger and experienced extensive usage from nuclear fuel processing to hot cell ventilation. The glass fiber of preference for this application was Owens-Corning's 115-K, a 29-μm-diameter, curled glass fiber that resisted clumping, settling, and matting. A system that was designed for downward airflow became inoperative from precipitation of ammonium nitrate at the filter face. Subsequent units were designed with airflowing upward and were equipped with water sprays directed from below to dissolve salt precipitation on the intake face to reduce pressure drop buildup. The design airflow velocity of a typical DBGF was 50 feet per minute, and clean pressure drop was close to 1.5-in.wg. The final pressure drop, after a total particle loading estimated at 10,500 pounds, was 8-in.wg. The final stage of a second-generation DBGF filter system employed two 12-mm blankets of 3.2-μm- and 1.2-μm-diameter glass fibers fabricated as a twin-layer bag stretched over a stainless steel framework. Airflow from the first stage passed through the filtration blankets from the outside to the inside, then was exhausted from inside the metal framework. The number of bag filters was proportional to the capacity of the intake segment of the DBGF filter. Later designs of the DBGF filter's cleanup stage substituted HEPA filters in a group of manifolded caissons (encapsulating filter holders), and a comparable increase in collection efficiency was realized. The most recent installation of a DBGF filter system required more than 100 HEPA filters downstream of a deep bed containing more than 38,000 pounds of 115-K fiber. By carefully selecting the packing density, bed depth, and airflow velocity, collection efficiencies greater than 99 percent for 0.5 μm particles were attained.

Provision for periodic backflushing will often extend the life of the total filter. Most DBGF filter systems, contained in vaults below ground, are resistant to shock and overpressure from natural phenomena. The dust-holding capacities of DBGF filters are very large, and many units have operated for years without attendance or maintenance. Pressure drop sensors can often predict evolving difficulties and indicate when it is time for backflushing, precipitate dissolution, or other preplanned remedial actions. Just as for DBS filters, decontamination and disposal is difficult for small systems and nearly impossible for the larger systems.

3.5.3 Deep-Bed Metal Filters

Deep beds of metal fibers have a number of applications in the nuclear industry, particularly where maximum resistance to fires, explosions, and overpressure shocks are essential. In offgas systems containing substantial concentrations of HF, use of stainless steel metal fibers has been studied as a substitute for glass.

In most cases, the objective when using metal fiber filters is to obtain particle collection efficiencies that duplicate those obtainable with HEPA filters. However, the unavailability of metal fibers with diameters close to or below 1 μm makes it necessary to provide great filter depth as a substitute for small fiber collection efficiencies. For sodium fire aerosols, high collection efficiency can be obtained with relatively large diameter metal fibers because the combustion products in air, sodium oxide, and carbonate rapidly form large flocs that are easily filtered. The ease of filtration results in the extremely rapid formation of a high-resistance filter cake that severely limits the amount of sodium aerosol particles that can accumulate in the filter before the limit of the fan's suction pressure is reached. Here, the requirement is for a graded-efficiency, deep-bed, metal filter with a large storage capacity in the initial layers of the filter for the fluffy sodium aerosol particles, a high efficiency for small particles in most downstream layers of the filter, and the elimination of abrupt interfaces between graded fiber layers where a filter cake might form. This is a different filtration requirement than obtaining high efficiency for low concentrations of small, nonagglomerating particles—instead, the requirement is for uniform particle storage throughout the depth of the filter. Here also, uniform diameter fibers can be used in great depths, as in the DBGF filters, to substitute for the presence of very small-diameter filter fibers.

Other types of metal filters have been constructed by sintering stainless steel powders or fine fibers into a sieve-like structure that function very much like a conventional pulse-jet-cleaned industrial cloth filter. The metal membrane has an inherent high efficiency for particles greater than a few micrometers, but depends on the formation of a filter cake to obtain high efficiency with submicrometer particles. Clean airflow resistance is high and increases rapidly as cake thickness builds up. It is cleaned periodically by backflow jets of compressed air. Efficiencies are comparable with those of HEPA filters when the sintered metal filters are precoated with filter aids. Because of their high-temperature resistance and ability to handle high concentrations of mineral dusts, these types of filters have been used in nuclear incinerator offgas cleaning systems, particularly when heat recovery from the hot filtered gases is desired. However, care must be exercised to avoid releasing tar-like combustion products to sintered filters that are operated at high temperatures because the tarry material tends to lodge in the pores and turn to cake that cannot be removed by chemical means or by elevating the temperature to the limit of the metal structure.

Another type of sintered filter construction for high-temperature applications has been prepared from a mixture of stainless steel and quartz fibers. The composite material has the same efficiency and pressure drop as HEPA filter glass paper, but has 4 times the tensile strength and can operate continuously at temperatures up to 932 degrees Fahrenheit (500 degrees Celsius). Applications of the stainless steel and quartz fiber HEPA filter medium have not proceeded beyond the laboratory stage.

3.6 Demisters

Liquid droplet entrainment separators are required in the standby air treatment systems of many water-cooled and -moderated power reactors to protect the HEPA filters and activated-charcoal adsorbers from excessive water deposition should a major high-temperature water or stream release occur as a result of an incident involving the core cooling system. Droplet entrainment separators are also used in fuel processing operations to control acid mists generated during dissolving operations and subsequent separation steps.

Entrainment separators consisting of a series of bent plates are widely used in HVAC applications for controlling water carryover from cooling coils and humidifiers; but for nuclear applications, their droplet removal efficiency is inadequate. Therefore, fiber-constraining demisters with a much greater efficiency for small droplets are standard for nuclear service. Entrainment separators utilizing fiber media remove droplets by the same mechanisms that are effective for dry fibrous filters, but they must have the additional important property of permitting the collected water to drain out of the cell before it becomes clogged. Should clogging occur and the pore spaces fill with water, the pressure drop across the separator will rise and some of the water retained in the pore spaces will be ejected from the air discharge side to create sufficient passages for air to pass through. The ejected water can become airborne again by this mechanism.

Droplets from condensing vapors originate as submicrometer-sized aerosols, but the droplets may grow rapidly to multimicrometer size by acting as condensation centers for additional cooling vapors and by coagulation when the concentration of droplets exceeds 10^6 droplets/ml. Firefighting spray nozzles, confinement sprays, and other devices that mechanically atomize liquid jets yield droplets that predominantly range from 50 to more than 1,000 μm in diameter. This range means that entrainment separators must not only be capable of removing the smallest droplets, but also must resist becoming flooded by the largest droplets and releasing the collected liquid as entrained water.

The NRC recommends the use of entrainment separators for engineered safety systems when the air may be carrying entrained liquid droplets or a cooling and condensing vapor.[8, 31, 45, 50] Although HEPA filter paper is treated for water repellency, high-water loadings rapidly saturate the paper and raise its airflow resistance to a point where gross holes can result. Hot water and steam cause paper to lose its strength and to fail even more rapidly. Therefore, the criteria for entrainment separators used for nuclear service call for: (1) at least 99.9 percent retention by weight of entrained water and condensed steam in the size range 1 to 2,000 μm diameter, at a duct velocity from 250 to 2,500 linear feet per minute, and water delivery rate of 8 gallons per minute (gpm) per 1000 cfm of installed HEPA filter capacity; (2) at least 99 percent retention by count of droplets in the 1- to 10-μm-diameter range, at a duct velocity from 250 to 2,500 linear feet per minute; (3) no flooding or water re-entrainment at a water-steam delivery rate of 8 gpm at a duct velocity of 2,500 linear feet per minute; and (4) a temperature tolerance at least to 320 degrees Fahrenheit (160 degrees Celsius) and gamma radiation exposure up to 10^6 rads integrated dose without visible deterioration or embrittlement of the materials of construction. An entrainment separator with these characteristics will provide long-term protection for a downstream HEPA filter that would be destroyed in a few minutes without it. Entrainment separators are usually constructed of deep layers of high-porosity metal and glass fibers, either packed or woven into stable batts, and arranged in graded sizes and packing density to give the desired small droplet collection capability with excellent resistance to flooding and re-entrainment.

3.7 Filter Design Selection

Nuclear-grade HEPA filter papers are distinguished from otherwise identical products by their proven resistance to deterioration by radiation. This requirement is spelled out in ASME AG-1,[2] which calls for 50 percent retention of original strength and water repellency after exposure to an integrated dose of 6.0×10^7 to 6.5×10^7 rads at a dosage rate not to exceed 2.5×10^6 rads per hour. Because all fabricated filters destined for nuclear service will contain identical or equivalent paper, selection can be based solely on the type of filter construction.

Deep-pleat filters with corrugated aluminum separators have dominated nuclear service both by numbers and years of use, and therefore have the longest and most thoroughly documented performance record. They appear to be stronger than other filter designs, although mini-pleat and separatorless filters are able to meet existing strength requirements in applicable filter standards. Mini-pleat construction has the desirable advantage of packing twice as much paper into a given volume of filter. A disadvantage of the mini-pleat design is the narrowness of the air passages between adjacent pleats, which make it susceptible to premature clogging of the openings by large particles and fibers. This may not be a difficulty when the air being filtered is exceptionally dust-free or when efficient prefilters are employed. Nuclear service experience is sparse or totally lacking for types of filter construction other than deep-pleat filters with corrugated separators, although there may be equivalent experience in nonnuclear applications.

Special nuclear filters are needed when service conditions involve exceptional physical or chemical stress. Although the usual run of filters for nuclear service must provide resistance to short-term exposure to heated air and flame, they are not designed for long-term operation at temperatures exceeding 250 degrees Fahrenheit (120 degrees Celsius). Because the organic sealant between filter pack and filter frame is the least temperature-resistant component, it is possible to increase temperature resistance by substituting a tightly compressed fine-fiber batt for the organic adhesive. In addition, substituting a metal frame for a plywood or composition board increases temperature resistance to the melting point of the glass fibers in the filter medium [932 degrees Fahrenheit (500 degrees Celsius)]. Before this temperature is reached, the organic binder and water-repellent chemicals in the paper will be lost, but this may not adversely affect filtration efficiency or airflow resistance, but does reduce the filter strength.

The chemical resistance of low-temperature nuclear filters is generally excellent for all dry gases. With high humidity, the presence of HF will cause etching and embrittlement of the glass fibers and ultimate failure of the filter. When droplets of HF or condensed water plus HF gas are present in the airstream, rapid failure of the glass filter paper may be anticipated. Rapid failure (within hrs) also occurs when hydroscopic salts from chemical processing collect on the filter surface and form a moist, slush-like cake that absorbs HF and infiltrates the pores of the filter paper. Special filter papers have been formulated with 7 percent Nomex fibers to provide extra chemical resistance for this type of service.

Aluminum separators are especially susceptible to chemical attack by many substances other than HF. United States requirements call for vinyl-epoxy coatings of 0.2 to 0.3 μm in thickness on both the sides and edges of aluminum separators when the presence of acid is predicted. Stainless steel separators are a more costly alternative.

Deep-bed filters of sand, gravel, and crushed stone do not compete directly with HEPA filters, except at a few installations involved in chemical operations associated with fuel reprocessing, but they have recently come under intense study as a means of mitigating core meltdown events by providing a filtration capacity for venting confinement vessel overpressures and for coping with a possible hydrogen burn inside the confinement. DBS filters have also been studied extensively for a potential role in mitigating loss of coolant accidents for metal-cooled reactors.

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CHAPTER 4

HOUSING DESIGN AND LAYOUT

4.1 Introduction

This chapter discusses housing design and requirements for air cleaning units in which filters and/or adsorbers are installed (see Chapter 6, "Small Air Cleaning Units," for single filter housing design information). Two basic designs are addressed in this section: man-entry and side-access (see **Figures 4.1** and **4.2**). In addition, two side-access housing types are addressed—one utilizing square filters and the other radial flow/round filters (**Figure 4.3**). Both side-access designs are for housings with two or more filters and for system capacities greater than 2,000 cubic feet per minute (cfm). Single-filter inline housings, man-entry housings larger than 30 high-efficiency particulate air (HEPA) filters, and masonry/concrete housings are not considered here.

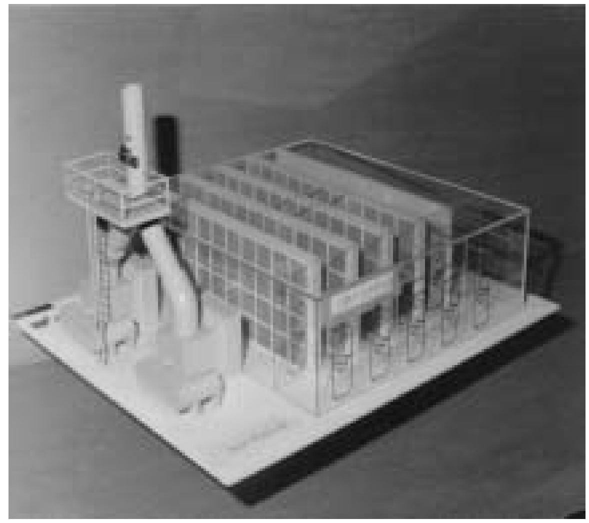

Figure 4.1 – Model of a Man-entry Plenum

4.2 Housing System Design

Large-volume air supply and exhaust requirements may be met by a number of side-access or man-entry filter housing installations operating in parallel, or in a single central system. Parallel housings have the advantages of: (1) greater flexibility for system modification; (2) minimum interference with operations during filter replacement because individual units can be shut down without affecting the remaining systems; (3) good overall ventilation control in the event of malfunction, fire, or accident to one or a few individual units; and (4) easy system testing and balancing.

4.2.1 Man-entry Housing System Design

The man-entry filter housing consists of a fabricated steel confinement room with one or more walls seal-welded in place. The walls have holes and hardware to mount HEPA filters or absorbers. The room has access doors providing entry at each side of the walls. Air is ducted into one end of the room; passed through the filters/absorbers mounted on the wall; and exits from the other end of the room. A wall with filters/absorbers mounted on it is considered a "stage" or "bank." The man-entry design is best used for housings with stages of 15 filters (5 across, 3 high) or more. As the number of filters/absorbers increases, consideration must be given to the ability to test the filters/absorbers and to the distribution of airflow. For larger systems (over 30 filters per stage), the designer should consider segmenting the system into two or more parts of equal airflow capacity, with each part in a separate, parallel housing. Isolation valves on each housing are desirable for convenient system control,

Figure 4.2 – Side-access Design (Square Filter)

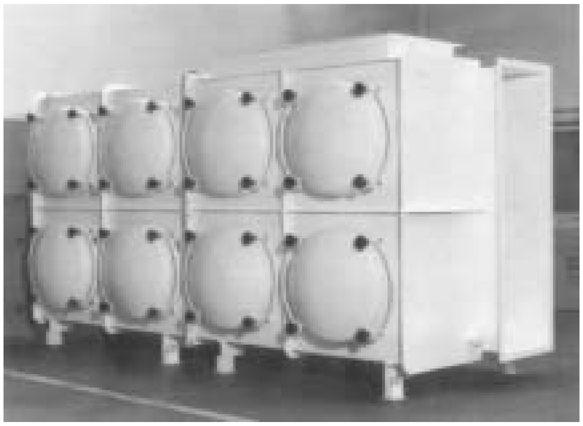

Figure 4.3 – Side-access Design Cylindrical (Radial Flow Filters)

isolation of individual units during an emergency, and maintenance or testing activities.

4.2.2 Arrangement and Location

Maintainability is a major consideration when laying out filter housings. Although some systems may have only a single bank of HEPA filters, most will have at least one additional bank of prefilters, and many will have multiple banks of HEPA filters. Those systems in which contaminated gaseous releases must be controlled will also require one or more banks of adsorbers. Often a bank of demisters is required, resulting in as many as six or more banks of components in a single housing. There must be sufficient clear corridor space adjacent to the housing for handling filters during filter changes, as well as an adequate number of corridors to and from the housing. Dollies are often used to transport filters to and from the housing area. This practice results in safer operations that reduce the risk of both injury to personnel and spread of contamination from dropped filters. When dollies are used, space is required to move the dollies in and out, and for loading and unloading. Additional space is desirable for stacking new filters adjacent to the work area during the filter change-out process. Recommended clearances for housings and adjacent aisles or airlocks are given in **Figure 4.4**.

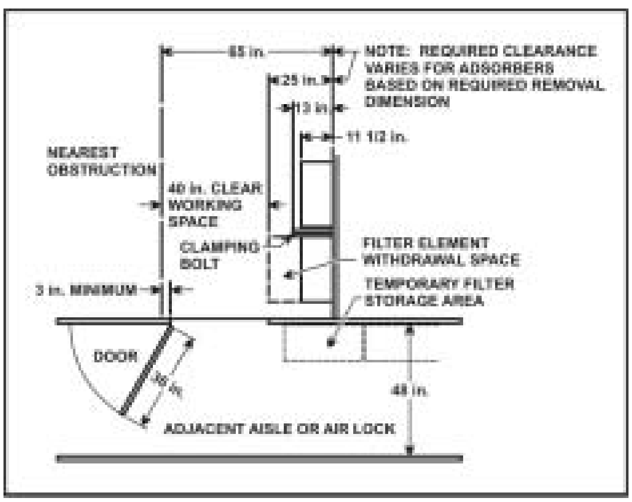

Figure 4.4 – Recommended Clearances for Man-entry HEPA Filter Banks

Proper access to the filter housing is sometimes overlooked. Too frequently, housings are situated among machinery, equipment, and ductwork where workmen are required to climb between, over, or under obstructions to get to the housing door, where they still have inadequate workspace. In some installations, it is necessary to carry filters one at a time over ductwork and then rely on rope slings to transfer them up to the floor above where the air cleaning system is located. It is essential to preplan the route for getting filters and adsorbers to and from the housing, and to provide elevators or cranes where they have to be hoisted to an upper level. Gallery stairways are also recommended in lieu of ladders. See **Figures 4.5 through 4.10**.

High-risk operations often require segmented systems with two or more housings ducted in parallel that exhaust from the same area and vent to the same stack. Each housing must have inlet and outlet isolation dampers to permit one to be held in standby or, when both are normally operated simultaneously, to allow one housing to be shut down for maintenance, testing, and emergencies.

Another important consideration in housing layout is uniformity of airflow through the installed components. This is especially important for adsorbers, since flow through those components must achieve the gas residence time required for efficient adsorption of gaseous contaminants. For large, multiple-filter housings that must operate in parallel, equalizing screens may be required in each filter unit to ensure uniform flow in housings. Long transitions are difficult, particularly in large housings. Nevertheless, every effort should be made to locate and design inlets and outlets to avoid stratification and to enhance the uniformity of airflow through components.

Special care must be taken in designing side-access housings to ensure uniform flow through all filter elements. It is recommended that manufacturers performance-test prototype side-access filter units in accordance with American Society of Mechanical Engineers (ASME) AG-1, Section TA,[1] to document uniformity of flow through side-access filter units before fabrication of production units. When high-activity alpha-emitters such as plutonium or transuranic elements are handled, it may also be desirable to compartmentalize the system, both in series, with separate housings for prefilters and HEPA filters, and in parallel for extra safety.

Figure 4.5 – Airlock Entry for Man-entry Plenum (Filters Above Doors are to Allow Pressure Equalization)

4.3 Component Installation

4.3.1 General

Proper installation of HEPA filters, adsorber cells, and demisters is critical to the reliable operation of a high-efficiency air cleaning system. HEPA filter and adsorber frames should be designed in accordance with the requirements of ASME AG-1, Section FG.[1]

4.3.2 Considerations

The following factors must be considered in designing HEPA filter and adsorber frames:

- Structural rigidity of mounting frames;
- Rigid and positive clamping of components to the mounting frame;
- Careful specification of and strict adherence to close tolerances on alignment, flatness, and the surface condition of component seating surfaces;
- Welded-frame construction and the welded seal between the mounting frame and housing;
- Ability to inspect the interface between components and the mounting frame during installation (man-entry);
- Adequate spacing between components in the bank (man-entry); and
- Adequate spacing in the housing for men to work (man-entry).

Figure 4.6 – Man-entry Two-Level Plenum (lower level) (Looking at Mist Eliminator Upstream Side of First HEPA Filter Stage)

Figure 4.7 – Man-entry Two-Level Plenum (Upper Level Looking at Upstream Side of First HEPA Filter Stage)

Figure 4.8 – Man-entry Plenum (Looking at a Ship Door Between HEPA Filter Stages)

4.3.3 Housing Construction

The components and mounting frame should form a continuous barrier between the contaminated and clean zones of the system. Any hole, crack, or defect in the mounting frame or in the seal between components and the frame that permits bypassing will result in leakage of contaminated air into the clean zone and reduced system effectiveness. A mounting frame that is not sufficiently rigid can flex so much during operation, particularly under abnormal conditions, that leaks may develop in the HEPA filters clamped to the frame (due to differential flexing of the filter case relative to the mounting frame). Cracks may also open between the filters and the frame, between frame members (due to weld cracking or fatigue), or between the frame and the housing. Insufficient attention to maintenance provisions in the original design can increase operating costs and reduce reliability of the system. Once the system is installed, defects are difficult to locate, costly to repair, and may even require rebuilding the system.

Mounting frames for HEPA filters and other critical components should be all-welded structures of carbon or stainless steel structural shapes. Carbon steel frames should be painted or coated for corrosion resistance. Galvanized steel is not recommended because of welding difficulties and because the zinc coating does not give adequate protection in the environments that may be encountered in a contaminated exhaust system. Aluminum is not recommended because of the high cost of surface preparation. Stainless steel is often the best and most economic choice for radiochemical plant applications. Suitable housing and mounting frame materials include the following (source references are listed at the end of this chapter as noted below):

- Stainless steel shapes, American Society for Testing and Materials (ASTM) A479, alloy UNS S30403, class C, annealed and pickled[2];
- Stainless steel plate, ASTM A240, alloy UNS S30403, hot-rolled, annealed, and pickled[3];
- Stainless steel sheet, ASTM A240, alloy UNS S30403, annealed and pickled, 2D or 2B finish[3];
- Carbon steel shapes and plate, ASTM A36,[4] A499[5];
- Carbon steel structural tubing, ASTM A500[6], and
- Carbon steel sheet, ASTM A1011-03.[7]

Information relating to fabrication includes:

- "Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings," *Manual of Steel Construction Allowable Stress Design*, American Institute of Steel Construction, New York, NY, 1989. [8]
- *Cold Formed Steel Design Manual and Specification for the Design of Cold-Formed Steel Structural Members,* American Iron and Steel Institute, 4th Edition, New York, NY, 1996. [9]
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Figure 4.9 – Common Aisle Between Two Man-entry Plenums

4.3.4 Potential Housing Leakage

Contaminated filter housings must be leaktight to prevent contamination of adjacent service and operating areas. (Leak-testing of filter housings is covered in Chapter 8). The design of nuclear air cleaning system housings must consider the potential for leakage. By locating the filter unit in an appropriate plant location and locating the fan relative to the filter housing, leakage amounts (especially leakage of contaminated air) can be minimized.

A once-through contaminated exhaust filter housing may be designed with the exhaust fan located after the filter housing and the housing located in a space that is "cleaner" than the air entering the housing. The benefit of this system configuration is that the air cleaning system up to the fan is under a negative pressure. Leakage is into the housing, thereby minimizing the potential impact of contaminated leakage on plant personnel during system operation. This system configuration does not mean leakage should not be considered. It means that the leakage potential can be reduced by component location and that further reductions in personnel dose to levels as low as reasonably achievable (ALARA) are possible via housing construction.

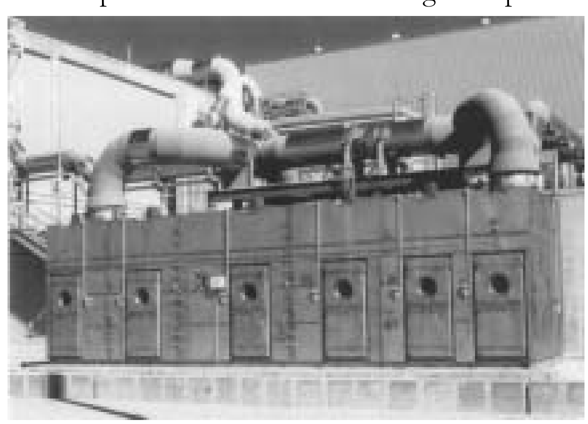

Figure 4.10 – Man-entry Housing Located Outside Building

If the space where an air cleaning system housing is located is more contaminated than the air entering the housing, it would be better to locate the fan on the inlet side of the housing. This arrangement would eliminate in-leakage of more contaminated air downstream of the filters.

For a habitability system where the housing is located within a protected space, the fan should be located downstream of the filter unit to ensure any potential in-leakage is "cleaner" air. If the housing in a habitability system is located in an area outside the protected space, then the fan should be located upstream of the filter unit to ensure potentially contaminated air does not bypass the filter unit.

The first step in determining housing leaktightness is to assess the relative contamination potential between the air entering the housing and the space where the housing is situated. Locate the fan accordingly, then determine the allowable leak rate to maintain: (1) the personnel dose within the requirements of 10 CFR 20[12] for inplant personnel, (2) the offsite dose per 10 CFR 100,[13] and (3) the ability of the system to maintain performance [e.g., direction of airflow, required pressure differential, air exchange (dilution) rates]. The latter item depends on the system design and margin. ASME N509-89[14] and ASME AG-1,[1] Section HA, "Housings," provide guidance on determining allowable leakage.

The allowable leakage should be considered when determining construction requirements. However, for filter housings, the structural design requirements for pressure and dynamic forces dictate that the housing fabricated of heavy platework (10-gauge to 3/16-inch-thick) can be seal-welded to join the transverse and longitudinal joints, instead of using bolts, without significantly increasing cost. This will result in a low-leakage installation.

4.3.5 Paints and Protective Coatings

Coatings and paint requirements must be consistent with the corrosion expected in a particular application and the size of the duct. Corrosion and radiation-resistant paints and coatings should, at a minimum, meet the requirements of ASTM D5144[15], *Standard Guide for Use of Protective Coatings in Nuclear Power Plants*. Unless special spray heads are used, spray coating the interior of ducts with an effective minimum diameter of 12 inches is often unreliable because it is difficult to obtain a satisfactory coating and inspection for defects and voids. The interior of ducts 8 inches and smaller cannot be satisfactory brush painted. Dip coating is recommended instead. Ducts to be brush painted should not exceed a length of 5 or 6 feet to ensure proper coverage.

Carbon steel housing interiors and mounting frames must be painted to protect against corrosion and to facilitate cleaning and decontamination. Surfaces must be properly prepared, and primer and topcoats must be applied in strict accordance with the coating manufacturer's instructions in order to obtain the necessary wet-film and dry-film thicknesses. Film thicknesses should be tested during and after application. Surfaces to be coated should be abrasive blasted to a profile of 1 to 2 mils in accordance with the Society of Protective Coating (SPC) SSPC-SP-5/NACE No. 1, *Near White Metal Blast Cleaning.*[16] The prime coat must be applied within 2 to 3 hours, but in no case more than 8 hours, after surface preparation.

For exterior carbon steel surfaces, either hand or power tool cleaning (SSPC-SP-2[17] or SSPC-SP-3[18]) is usually sufficient. For certain conditions, such as highly humid atmospheres, exterior carbon steel surfaces should be prepared in accordance with SSPC-SP-5/NACE No. 1 instead. Both ambient and metal surface temperatures should be 10 to 20 degrees Fahrenheit (6.6 to 12.2 degrees Celsius) above the dew point before starting to paint and there must be adequate drying time (recommended by the coating manufacturer) between coats.

Quality assurance for nuclear grade coatings is discussed in ASTM AG-1, Section AA[1] and ASTM D3843[19], *Practice for Quality Assurance for Protective Coatings Applied to Nuclear Facilities*. Other standards applicable to painting of nuclear facilities include ASTM D3911,[20] *Standard Test Method for Evaluating Coatings Used in Light Water Nuclear Power Plants at Simulated Design Basis Accident (DBA) Conditions* and ASTM D3912-95,[21] *Standard Test Method for Chemical Resistance of Coatings Used in Light Water Nuclear Power Plants.*

Because the difficulty in applying nuclear grade coatings to carbon steel surfaces often results in unsatisfactory performance of the coatings in service, designers should seriously consider use of stainless steel for mounting frames and housings in corrosive environments or where frequent decontamination is required. While there are some special handling and fabrication rules associated in working with stainless steel, (particularly the highly polished surface finishes that must be protected from scratches during fabrication) the overall costs of painted carbon steel versus stainless are similar.

4.4 Man Entry Housing

4.4.1 General

Steel man-entry housings may be shop built or field fabricated. The trend is increasingly toward shop-built steel housings. Stainless steel is the most common material of construction; however, carbon steel also may be used. Aluminum and galvanized steel are not suitable.

4.4.2 Structural

The mounting frame is a statically indeterminate lattice that generally consists of a set of full-length members spanning the height or width of the bank (whichever is shorter), connected by cross members that are slightly shorter than the width of individual filter (adsorber) units. For design purposes, the frame may be considered as an array of simply supported, uniformly loaded beams. Experience has shown that, to obtain adequate frame rigidity, these beams (frame members) should deflect no more than 0.1 percent of their length under a loading equivalent to 1.5 times the maximum dirty filter pressure drop across the bank. This loading is determined from the following equation.

$$W = 0.036(1.5)\Delta pS \qquad (4.1)$$

Where

0.036 = conversion factor, inches water gauge (in.wg) to pounds per square inch (psi)
W = uniform beam loading, lb/in.

Δ p = pressure drop across bank, in.wg.

S = center to center spacing of filters on bank, inches

Assuming a center-to-center spacing of 26 inches for 24- x 24-inches filters, equation (4.1) reduces to:

$$W = 1.404\Delta p \qquad (4.2)$$

The value determined from equation (4.2) can be used in standard beam equations[8] to determine the minimum moment of inertia required. Knowing the minimum moment of inertia required for the member, the size and shape can be selected directly from the tables of structural shape properties given in the American Institute of Steel Construction (AISC) *Manual of Steel Construction*.[8] It can also be determined by calculating the moment of inertia of a built-up or cold-formed section. For ASTM A36 steel, the standard beam equation reduces to the following equations.[4]

Major frame members, $I = \dfrac{\Delta pL^3}{1.59x10^6}$ (4.3)

Cross members, $I = \dfrac{\Delta p}{149}$ (4.4)

Where

I = minimum moment of inertia[4] required, inches
Δp = maximum dirty – filter pressure drop across bank, in.wg.
L = length of member, inches (cross members assumed to be 22 inches long)

In addition to flexural strength, the frame for an exhaust or air cleanup filter system should also be capable of withstanding a shock loading of at least 3 psi across the bank without exceeding the elastic limit of the frame material. In most cases, members calculated using equations (4.3) and (4.4) will meet this requirement; nevertheless, they should be checked. The section moduli (S values) given in Part I of the AISC *Manual of Steel Construction*[8] then should be compared with the minimum values obtained from the following equations.

Major frame members, $$S = \frac{13L^2}{f_a} \qquad (4.5)$$

Cross $$S = \frac{6290}{f_a} \qquad (4.6)$$

Where

S = section modulus, in.^{3}
F_a = maximum allowable fiber stress, psi
L = length of member, inches (cross members assumed to be 22 inches long)

For ASTM A36 steel, these equations reduce to

Major frame members, $S = 0.00361L^2$ *(4.7)*
Cross members, S = 0.175 *(4.8)*

For built-up and cold-formed members, the minimum *S* value calculated from these expressions is compared with the value for the member calculated from the formula.

$$S = \frac{I}{c} \qquad (4.9)$$

Where

S = section modulus, in.^{3}
I = moment of inertia[8] of the section, inches
c = distance from neutral axis of member to extreme fiber, inches

If the *S* values obtained from the AISC manual or calculated by using equation (4.9) are greater than the values calculated from equations (4.5) through (4.8) (as applicable), the members selected are satisfactory.

Note: The above equations are for illustrational purposes only. The designer is responsible for verifying this information.

4.4.3 Structural Design

Structural design of housings for both Engineered Safeguard Feature (ESF) air cleaning units and non-ESF units must consider the service conditions the housing may experience during normal, abnormal, and accident plant conditions. The design requirements for determining housing plate thickness, stiffness, spacing, and size are presented in the ASME ASME AG-1, Section AA.[1]

Housing design should consider the following load criteria.

- Additional dynamic loads,
- Constraint of free end displacement loads,
- Dead weight,

- Design pressure differential,
- Design wind,
- External loads,
- Fluid momentum loads,
- Live load,
- Normal loads,
- Normal operating pressure differential,
- Seismic load, and
- System operational pressure transient.

Stress criteria limits are given in ASME AG-1, Section AA.[1] The maximum deflection for panels, flanges, and stiffeners for the load combination should be the lesser of the two values derived as shown below.[14]

4.4.3.1 Criterion 1

- Plate or sheet: 1/8 inch per foot of the maximum unsupported panel span in direction of airflow, but not more than 3/4 inch
- Stiffeners and flange connections: not to exceed 1/8 inch per foot of span, but not more than 3/4 inch
- Flange connection to dampers and fans: $1/360^{th}$ of the span, but not to exceed 1/8 inch

4.4.3.2 Criterion 2

Deflections shall be limited to values that will not cause:

- Distortion of the airflow path cross-section, resulting in unacceptable increase in system pressure;
- Damage to safety-related items such as instrumentation or other safety-related equipment or accessories;
- Impingement of deflected elements on adjacent services such as equipment, pipe, cables, tubing, etc.;
- Loss of leaktightness (in excess of leakage limit);
- Buckling (refer to ASME AG-1, Section AA-4000)[1]; or
- Functional failure of components attached to ductwork (e.g., instrument lines, etc.).

4.4.4 Mounting Frame Configuration

The basic type of mounting frame construction is face-sealed (i.e., the filter seals to the outermost surfaces of the frame members by means of gaskets glued to the front surface or to the flange around the face of the filter unit) as shown in **Figure 4.11**. The face-sealed configuration is generally recommended for conventional-design HEPA filters and Type I adsorber cells.[22]

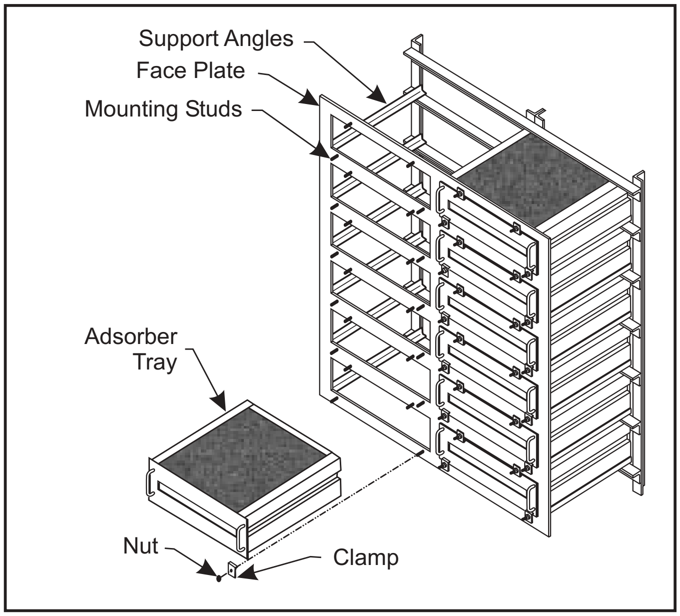

Figure 4.11 – Adsorber Gasket Seals Against Mounting Frame Face Plate

A minimum face width of 4 inches is recommended for major and cross members of face-sealed HEPA filter frames. This allows 1-inch-wide filter-seating surfaces to compensate for any misalignment of the filter during installation and a 2-inch space between filters, horizontally and vertically. It also provides adequate room for handling (personnel replacing contaminated filters will probably have to wear double gloves), using power tools or torque wrenches during filter change, and manipulating a test probe between units.

Face widths of frame members for installing Type I (pleated-bed) adsorber cells are the same as those for HEPA filters. Face widths of frame members for installing Type II (tray-type) adsorber cells may be narrower, since handles are provided on the front of the trays to facilitate installation. To provide interchangeability for cells of different manufacture, Institute of Environmental Sciences and Technology (IEST) CS-8[22] recommends the following mounting frame dimensions for the installation of Type II cells (see IEST CS-8[22] for standard cell dimensions):

- Openings: 6.37 by 24.188 inches (+0.063 inches, -0 inches),
- Space between openings: vertical, 2.5 inches minimum; horizontal, 2 inches minimum.

Figures 4.12 and 4.13 show a built-up all-welded Type II adsorber cell mounting frame made from rectangular structural tubing; note that a structure is required behind the frame openings to support the weight of the cells (approximately 100 pounds each). Because the length of Type II cells may be different for each manufacturer, the support structure should be deep enough to take a cell up to 32 inches long to permit interchangeability of cells of different manufacture.

Figure 4.12 – Adsorber Tray Mounting Frame ("X" Cross Units Are for Test Gas Injection)

Satisfactory mounting frames may be made from rolled structural shapes or rectangular structural tubing. **Figure 4.14** shows a HEPA filter frame made from 4- × 4-inch structural tubing that meets all structural requirements. Rolled structural shapes for building mounting frames are given in **Table 4.1**. Square structural tubing frames for HEPA filters should be made from rectangular tubing with a face width of at least 4 inches; structural tubing frames for Type II adsorber cells may have narrower face widths.

4.4.5 Frame Fabrication – Gasket-Type Filter and Adsorber

Filter mounting frames should be shop-fabricated if practicable because it is nearly impossible to avoid misalignment, warping, and distortion in field fabrication. Shop fabrication is less costly than field fabrication and permits better control over assembly, welding, and dimensional tolerances. Care must be taken to avoid twisting or bending the completed frame during handling, shipping, and field installation. For proper performance and maintenance of installed filters, dimensional and surface-finish tolerances must be tight and rigidly enforced. **Table 4.2** gives minimum tolerances for the installed frame. Welds on the filter-seating side of the frame must be ground flat, smooth, and flush.

Only welders qualified in accordance with the American Welding Society (AWS) D1.1, *Structural Welding Code-Steel* [10] or Section IX of the ASME *Boiler and Pressure Vessel Code* [23] should be permitted to make welds on HEPA filter and adsorber mounting frames. Both seal and strength welds should be visually inspected by a qualified inspector under a light level of at least 100 foot candles on the surface being inspected. In addition, liquid penetrant (ASTM E165)[24] or magnetic particle inspection (whichever is applicable for the base material being inspected) of the seal welds between frame members is recommended.

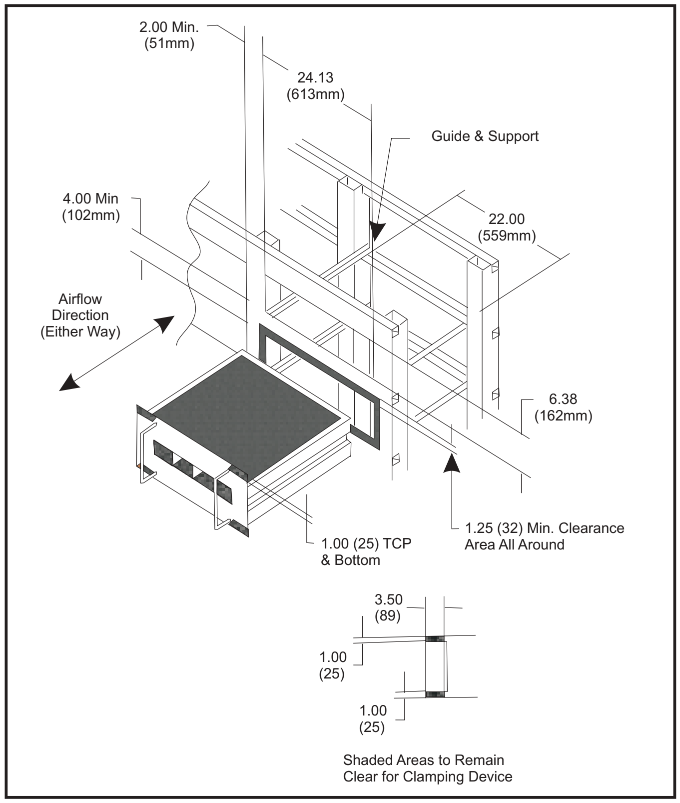

Figure 4.13 – Adsorber Mounting Frame with Carbon Trays

Figure 4.14 – Filter Mount

Table 4.1 – Minimum-Cost Structural Members for 24-by-24 HEPA Filter and Type I Adsorber Mounting Frames (maximum pressure drop to 12 in.wg)

Number of 1,000 cfm Units High	Principal Member[a] I-beam			Cross Member Channel (span = 22 in.)	
	Span[b]	Size (in.)	lb./ft.	Size (in.)	lb./ft.
2	4 ft. 8 in.	4 × 4 M	13	4 × 1¾	5.4
3	6 ft. 10 in.	4 × 4 M	13	4 × 1¾	5.4
4	9 ft. 0 in.	4 × 4 M	13	4 × 1¾	5.4
6	13 ft. 4 in.	6 × 4 B	16	4 × 1¾	5.4
8	17 ft. 8 in.	8 × 4 B	10	4 × 1¾	5.4
10	22 ft. 0 in.	10 × 4 5/8	25.4	4 × 1¾	5.4

[a] Principal members should span the shortest dimension of the bank.
[b] Span = [(number of filters) (26) = 4] inches
Note: This table is intended to provide information only. The designer is responsible for verifying this information.

Table 4.2 – Recommended Tolerances for HEPA Filter and Adsorber Mounting Frames

Alignment	Perpendicularity: maximum offset of adjoining members 1/64 inch/foot or 1/16 inch, which ever is greater. Planarity of adjoining members: 1/64 inch maximum offset at any point on the joint.
Flatness	Each filter surface shall be plane within 1/16 inch total allowance. Entire mounting fixture shall be plane within 1/2 inch total allowance in any 8-by 8-foot area.
Dimensions	Length and spacing of members shall be true within +0, -1/16 inch.
Surface-finish	Filter seating surfaces are 125 microinch (μin.) AA maximum, in accordance with USA Standard B46.1; pits, roll scratches, weld spatter, and other surface defects shall be ground smooth after welding, and ground areas shall merge smoothly with the surrounding base metal; waviness not exceeding 1/32 inch in 6 inch is permissible, as long as the overall flatness tolerance is not exceeded.

Note: This table is intended to provide information only. The designer is responsible for verifying this information.

4.4.6 Filter Clamping and Sealing

HEPA filters and adsorber cells must be carefully sealed to the mounting frame (**Figures 4.15 and 4.16**) to achieve the required low penetration leakage rates and to allow easy replacement. Except for the fluid-seal design described at the end of this section, sealants are not a satisfactory substitute for gaskets. Experience in clean rooms and contaminated exhaust and air cleanup applications has shown that flat, closed-cell, neoprene gaskets, ASTM D1056[25] grade 2C3, give the most satisfactory seal for high-efficiency filters, adsorbers, and demisters. There is no advantage in using shaped (molded) gaskets; not only are they more expensive, but research has shown that they are prone to leaks.[26, 27] Gaskets that are too soft (i.e., are less than grade 2C3) take an excessive compression set that may permit leakage when there is relaxation of the clamping bolts. Gaskets that are too hard (i.e., harder than grade 2C4) require such high clamping loads to effect proper scaling that the filter itself can be distorted or damaged.

As little as 20 percent gasket compression is needed to effect a reliable seal when the thickness of the gasket is uniform to within ±0.01 inches and the seating surface of the mounting frame is plane to within ±0.01 inches[16] However, these tolerances are much too restrictive for economical construction, and experience has shown that it is usually necessary to compress a 2C3 gasket at least 80 percent to effect a reliable seal over long periods. Eighty-percent compression requires a loading of approximately 20 pounds per square inch of gasket area, or a total clamping load of about 1,400 pounds for a 24- by 24-inch filter unit. The recommended procedure for installing filters under nonhazardous conditions is to initially torque the clamping bolts to produce 50 percent gasket compression and then retorque them 1 or 2 weeks later to a total compression of about 80 percent. In a radioactively contaminated filter system, replacement can be a hazard to personnel and to the filters and/or adsorbers installed in the system. Under such conditions, one entry is advised. One option is to manually compress the filter gasket to an estimated 50 to 80 percent. A spring-loaded hold-down (**Figure 4.17**) is another option used at some U.S. Department of Energy (DOE) sites. Torsion bar clamps designed to exert the proper clamping forces are a third option.

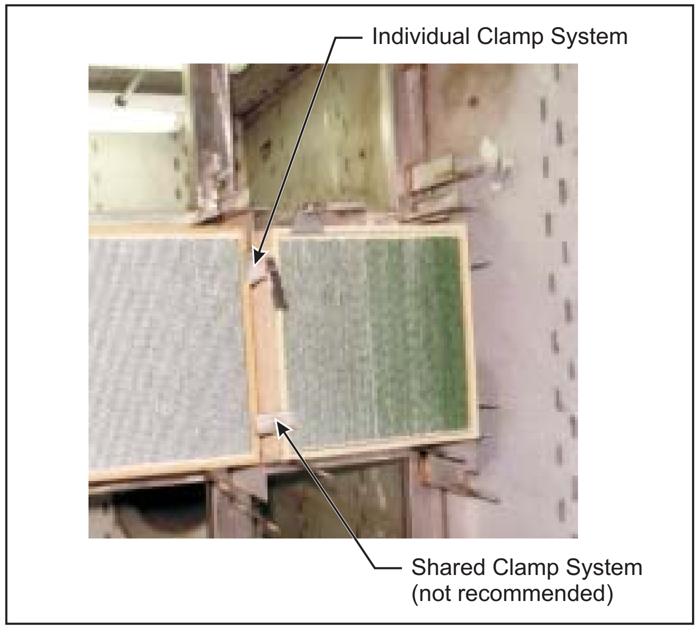

Figure 4.15 – HEPA Filter Mounting Frame (Showing Two Clamp Designs)

Gaskets that are too thin may not give a reliable seal using the recommended frame tolerances given in Table 4.2, whereas those that are too thick may be unstable and tend to roll or pull off the flange of the filter case as they are compressed, perhaps to the extent that sections may be extruded between the case and mounting frame and produce a serious air leak. Recommended gasket sizes are 1/4 to 3/8 inch thick by 3/4 inch wide and 1/4 to 3/8 inch thick by 5/8 inch wide. Gaskets must be glued to the filter element rather than to the mounting frame because they must be replaced with each filter change. A sealant such as silicone could be applied lightly to the filter gasket. Residue must be removed before installing new filters as the sealant may be contaminated, making disposal more difficult. Gaskets should have cut surfaces on both faces because the "natural skin" produced by molding sometimes tends to bridge discontinuities or defects in the seating surface, and because the silicone mold-release compounds used in the manufacture of sheet neoprene prevent proper adhesion of the gasket to the filter case.

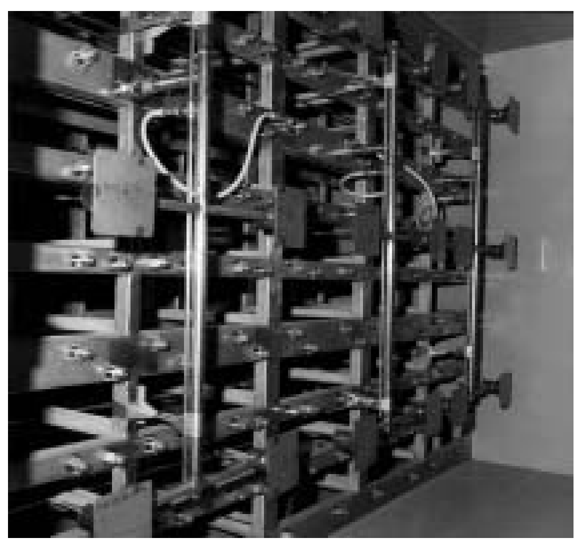

Figure 4.16 – Absorber Mounting Frame with Test Section Manifold

Filter units and adsorber cells must be clamped to the mounting frame with enough pressure to enable the gasket to maintain a reliable seal when subjected to vibration, thermal expansion, frame flexure, shock, overpressure, and widely varying conditions of temperature and humidity that can be expected in service. Clamping devices must function easily and reliably after long exposure to hostile environments. In addition, they must be capable of easy operation by personnel dressed in bulky protective clothing, gloves, and respirators (or full-face gas masks) while working in close quarters. Experience has shown that a simple nut-and-bolt system (Figure 4.17) gives satisfactory service under these conditions. Nut-and-bolt clamping, however, entails removal and handling of a large number of nuts, and this procedure can be a problem during a filter change in a highly radioactive system. However, clamping systems that provide the required torque and gasket compression without loose parts are highly recommended. Any system that achieves the desired clamping torque is acceptable. Examples of Type II adsorbent filter clamping systems are shown in **Figure 4.18**. Eccentric, cam-operated, over-center, or spring-loaded latches, and other quick-opening latches, such as the

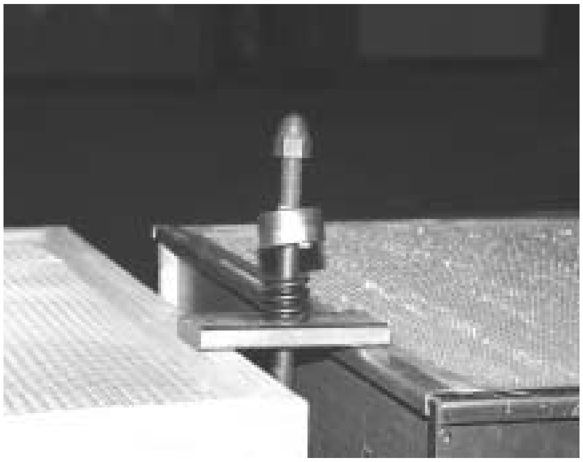

Figure 4.17 – Filter Hold-down-torque Spring Design

window latch design, are not recommended for clamping high-integrity components such as HEPA filters and adsorber cells.

Magnitude and uniformity are major requirements for filter and adsorber clamping systems. At least four, and preferably eight, pressure points are required for HEPA filters and demisters. Individual clamping of each filter unit is preferred. Shared clamping, in which holding clips (or bolts) bear on two or more adjacent filters or adsorber cells, has been widely used because it is less expensive than individual clamping and requires manipulation of fewer loose items within the confines of the housing during a filter change. However, shared clamping limits the ability to adjust or replace individual filters in the bank without upsetting the seals of adjacent units. In the improved system shown in Figure 4.18, no clip bears on more than two filter units, and the seals of only four surrounding filters are upset when replacing a filter unit. This common hold-down design is not recommended. The clamping systems shown in Figures 4.16 and 4.17 have the advantage that clips and nuts do not have to be removed to replace filters, since the clips can be rotated out of the way after the nuts have been loosened. A pressure distribution frame is shown in **Figure 4.19**. Although this type of clamping system has been used with good success in nuclear and nonnuclear applications, many inplace test personnel object to it because of the extensive leak-chasing often required before a satisfactory inplace test can be achieved. Leak-chasing also occurs in multi-filter common clamping when, on adjusting or replacing one filter, the seals of surrounding filters are disturbed, resulting in new leaks that have to be corrected. This process is time-consuming, costly, and, when conducted in a contaminated housing, can result in lengthy exposure of personnel.

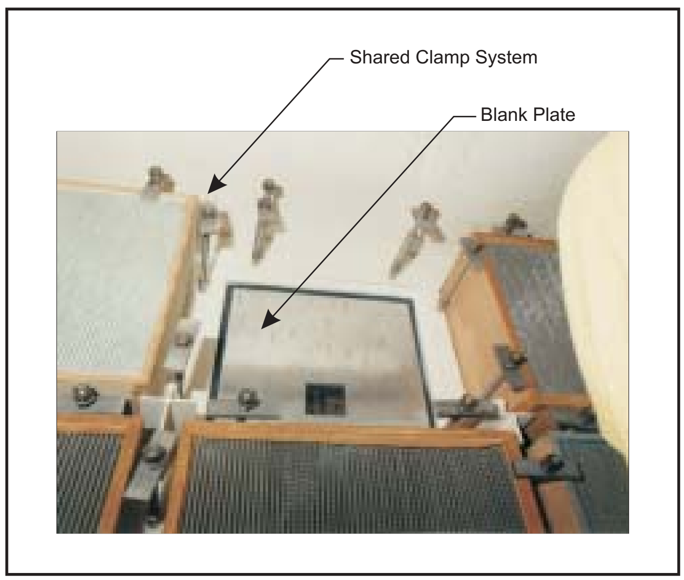

Figure 4.18 – HEPA Filters Mounting Frame with Blanking Plate Installed for Filter Change

Because of their weight, eight pressure points are desirable for clamping Type I (pleated-bed) adsorber cells. For clamping Type II (tray-type) cells, two pressure points on the top and two on the bottom edges of the front plate are needed for proper sealing, with individual clamping, as shown in Figure 4.15. Clamping on the short sides only is not adequate. As Figure 4.18 shows, captive nuts reduce the number of loose items that must be manipulated within the confines of the filter housing during filter or adsorber replacement, but they must be prevented from rotation when positioned for withdrawal of the filter.

The minimum bolt size recommended for individually clamped filters is 3/8-16-UNC, but 1/2-11-UNC or 5/8-11-UNC bolts are less prone to damage. For Type I adsorbers, 5/8-11-UNC bolts are necessary. The nuts and bolts of the clamping system must be made of dissimilar materials to prevent galling and seizing. Bolting materials and clips must be corrosion resistant. Stainless steel (300 series) bolts with brass nuts are frequently used. Springs, if used, should also be made from a PPH grade of stainless steel if they are to resist corrosion and relaxation over a period of service.

The design knife-edge type of framing and sealing (**Figure 4.20**),[28] employs a special cross-section-extruded- framing member which presents a knife-edge-sealing surface to the filter element. The filters have a channel filled with a nonflowing, nonvulcanizing, silicone polymer around the sealing edge that fits into the knife edge of the mounting frame to form a positive seal between filter and frame. Rigidity of the mounting frame is not a consideration, since frame flexure cannot affect the seal or the filter. The clamping pressure needs to be sufficient only to hold the filter unit in place. If the filters are installed on the downstream side of the frame, clamping must be sufficient to resist displacement of the filter under normal operating filter resistance and the pressures produced by shock loadings in the system.

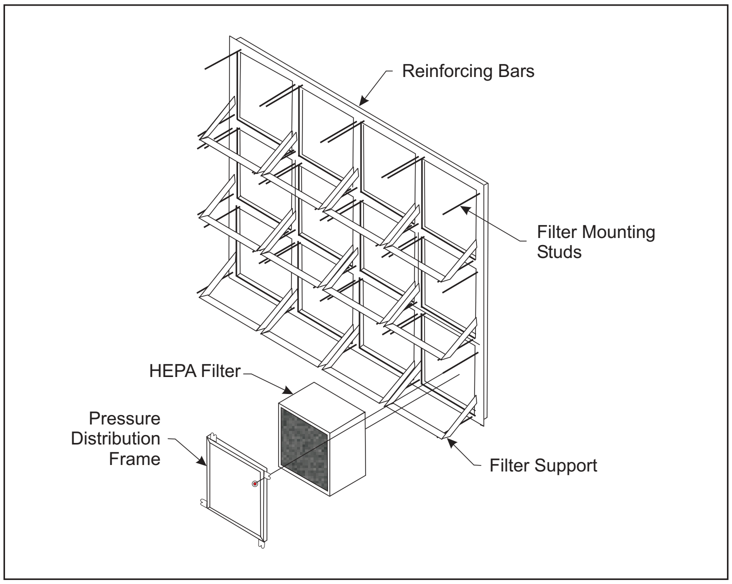

Figure 4.19 – HEPA Filter Mounting Using Pressure Distribution Frame Design Filter Hold Down

4.4.7 Filter Support

A cradle or other support for the filter element as it is moved into position on the frame is a desirable feature from a maintenance standpoint. The cradle should not obscure any more of the filter-to-frame interface than necessary to avoid interference with inspection as the filter is installed. The support shown in Figure 4.19 is better because it obscures less of the gasket-frame interface. In some installations, filters have been supported on the bottom clamping bolts, a practice that risks damage to the threads of the clamping bolts and is not recommended.

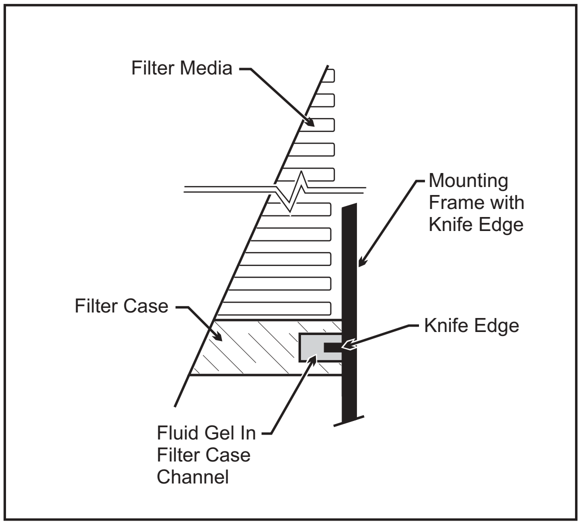

Figure 4.20 – Fluid Seal

4.4.8 Size and Arrangement of Filter and Adsorber Banks

The size (nominal airflow capacity) and orientation of filter banks (vertical or horizontal), the location of filters on the bank (upstream or downstream side), and the floor plan and height of the bank all affect the reliability, performance, maintainability, and testability of the air cleaning system. Savings gained by designing for minimum space and materials can be wiped out many times over by the higher operational, maintenance, and testing costs that will result from higher pressure drop and cramped working space in the filter housing.

4.4.9 Vertical Filter Banks

Vertical banks with horizontal airflow are preferred in contaminated exhaust systems because the filters are more favorably oriented with respect to ease of handling, mechanical strength of the filters, and collection of condensate. On the other hand, the pleats of Type I adsorber cells and the beds of Type II cells must be installed horizontally to avoid adsorbent settling in the cells. Before designing a horizontal filter bank with vertical airflow, filter/adsorber components should be validated for performance in this application/design. In addition, the design should include provisions for filter installation and removal.

4.4.10 Location of Filters on Mounting Frame

No clear-cut preference can be justified for mounting filters on either the upstream or the downstream side of the mounting frame. Both methods have been used successfully and the advantages and disadvantages of each are listed below.

4.4.10.1 Upstream Mounting of Filters

Advantages:

The filters are withdrawn into and handled within the contaminated side of the system during a filter change. No contaminated materials are brought into the clean side of the system, so there is more complete separation of the clean and dirty sides of the system.

Disadvantages:

- Personnel have to work within a potentially contaminated zone during a filter change.
- It is possible that contamination can be tracked or carried out of the contaminated zone by workmen, unless the filter change is carefully planned and executed.
- The filter clamping devices are located in the dirty side of the system where they are most exposed to corrosion and dirt.
- Contaminated material may accumulate on the horizontal surfaces of the filter case and may dislodge during removal.

4.4.10.2 Downstream Mounting of Filters

Advantages:

- Filters are withdrawn into and handled within the clean side of the system, thereby reducing the likelihood of tracking or carrying contamination into the building during a filter change.
- Filter clamping devices are located on the clean side of the system where they are less subject to corrosion.
- Leak-scanning of installed filters is more sensitive. If there are gasket or casing leaks, the driving force of air entering the filter forces the test aerosol through the leak, and they are readily detected. With upstream mounting, on the other hand, any test aerosol that goes through a leak in a gasket or filter case mixes with the air and test aerosol passing through the opening in the mounting frame, thus obscuring

the leaks. Although the existence of a leak may be disclosed by a test, the location of the leak cannot be easily determined by probing.

- Only the upstream face of the filter is contaminated during operation. The outer surfaces of the filter case and the downstream face of the filter pack are not usually contaminated.

Disadvantages:

- The contaminated filters must be withdrawn into the clean side of the system in a filter change. This disadvantage can be offset by "fixing" (locking down) the contaminated dust by spraying the upstream side of the filter pack with paint or acrylic spray or by taping cardboard over the upstream face of the filter. However, this procedure requires personnel to enter the contaminated chamber of the housing, and the possibility still exists of dislodging contaminated dust into the clean side of the system, either from the filter itself or from the edges of the frame opening (which is exposed to contaminated air during operation).

- Filters have been mounted on both sides of a mounting frame in some installations. This is not recommended. A cardinal rule in contaminated exhaust systems is that no credit is granted for untested and untestable filters. Such mounting precludes testing of both filters. Therefore, although double mounting may provide two sets of filters, the operator cannot take credit for two-stage filtration or series redundancy. This design has been shown to fail in a fire. The upstream filter blows out when plugged with smoke particles and impacts the filter downstream, causing it to blow out also.

4.4.11 Size of Banks

A nominal system capacity of 30,000 cfm has been recommended by DOE and the U.S. Nuclear Regulatory Commission (NRC) for any filter or adsorber bank. For larger systems, this limit requires the system to be segmented into two or more smaller subsystems, each contained in an individual housing and having an installed capacity of 30,000 cfm or less. The purpose of this requirement was to facilitate maintenance and inplace testing, to improve control in the event of a system upset, and to enhance the reliability of the total system. A 30,000-cfm bank was considered the largest that can be tested inplace conveniently. By breaking the system into two or more air cleaning units, testing and filter replacement can be conducted in one unit while the other unit remains online. NRC Regulatory Guide 1.52 recommends such redundancy for ESF air cleaning systems in reactors.[29] The designer may also choose to segment a system into units of substantially less than 30,000 cfm when redundancy is desired to achieve advantages of control, maintainability, and testability. The development of higher-flow aerosol generators and manifold inplace test systems has allowed larger filter banks than the recommended 30 filters. The use of 1,500-cfm filters allows higher-capacity systems without increasing the physical size of the bank. Inplace testing and maintenance is the determining factor.

4.4.12 Arrangement of Banks

Arrangement of filters on a mounting frame influences operating performance and maintenance. Where possible, banks should be laid out in an array of three filters high or nine Type II adsorber cells high. When floor space is at a premium, the bank may be arranged with one 3-high array above another, with a service gallery between, as shown in Figures 4.6 and 4.7. Thus, an 18,000-cfm bank might be arranged in an array 6-wide by 3-high or 3-wide by 6-high, with a service gallery between the third and fourth tiers. The arrangement of a 24,000-cfm bank in a 6-wide by 4-high array would be undesirable. A better arrangement is an array 8-wide by 3-high or, if floor space is at a premium, two 4-wide by 3-high arrays, one above the other, separated by a service gallery. In no case should filter changing require the use of temporary ladders or scaffolding. To require a workman dressed in bulky protective clothing (with sight obscured by a respirator or gas mask and sense of feel dulled by double gloves) to manipulate a ladder or scaffold within the confines of a filter house is an open invitation to personnel injury and filter damage (see Figure 8.9, which shows HEPA filters testing). Based on the 95th-percentile man, the maximum height at which a man can operate hand tools effectively is 78 inches, and the maximum load he can handle at a height of 5 feet or more is 40 pounds, which is the approximate weight of a clean HEPA filter. Therefore, provision for access to the higher tiers of filters is necessary. In fact, ASME AG-1, Subsection HA,[1] requires that a permanent platform be installed to access filters to access filters above 6 feet.

Filter banks should be rectangular. The use of odd-shaped banks to limit installed filter capacity to calculated system airflow requirements increases construction costs significantly. By filling out the rectangle, construction costs will be less. In addition, if all nine spaces are filled with filters, operating costs may also be reduced because the additional filters permit operation at a lower flow rate per unit resulting in longer filter life and reduced filter-change frequency, as discussed in Chapter 2. For the purposes of laying out adsorber banks, three Type II (tray) adsorbers will fit vertically into the space occupied by one 24- by 24-inch HEPA filter.

4.4.13 Floor Plan of Filter Banks

The plenum floor plan of a vertical filter bank varies with the application of the system. The location of filters and/or adsorbers is shown in **Figures 4.21 through 4.28**. Judicious configuration of banks can often reduce pressure losses in the system and bring about more uniform dust loading of filters, thereby equalizing the utilization of the filters installed in the banks.

The procedures required for construction and operational maintenance must be considered early in the planning stages. Adequate clearances for access must be maintained at turning points and between the bank and the nearest obstruction. Passageways both between the banks and between the banks and the housing wall must be wide enough for welders to operate effectively and for workmen, dressed in bulky clothing, to get in to change filters (see **Figures 4.29 and 4.30**). Both welders and workmen will have to kneel or stoop to get to the bottom tier. A 95th-percentile man in a kneeling position requires a minimum clearance of 36 inches from the face of the filters to the nearest obstruction, excluding withdrawal space for the filter unit itself. A minimum clearance of 40 inches is therefore recommended between the face of one bank and the nearest obstruction.

4.4.14 Steel Housings

Design practices used for conventional air conditioning and ventilation system ductwork and equipment casings are not adequate for high-reliability, high-efficiency contaminated exhaust and air cleanup systems. Experience has shown that, under system upset and shutdown conditions, housing leaks can result in the escape of contamination to clean areas. Even with fans operating, reverse leakage of particles from the low-pressure side of a system (i.e., the interior of the housing or duct) to the high-pressure side (i.e., the occupied area of the building) can sometimes occur because of dynamic and aspiration effects. Out-leakage may also occur when the system is shut down. Filter housings for contaminated exhaust service must be able to withstand negative pressures without damage or permanent deformation at least up to fan cutoff, which may be equal to 20 in.wg. in many systems. A pressure differential of 2 in.wg. between the inside and outside of a housing produces a load of more than 1,000 pounds over every 10 square feet of the housing wall. If the filters are operated to economical pressure drops, the housing may have to withstand 10 or more times this load without appreciable deflection. Pulsation and vibration may aggravate the condition. In addition, the housing should be able to withstand design shock loads without damage.

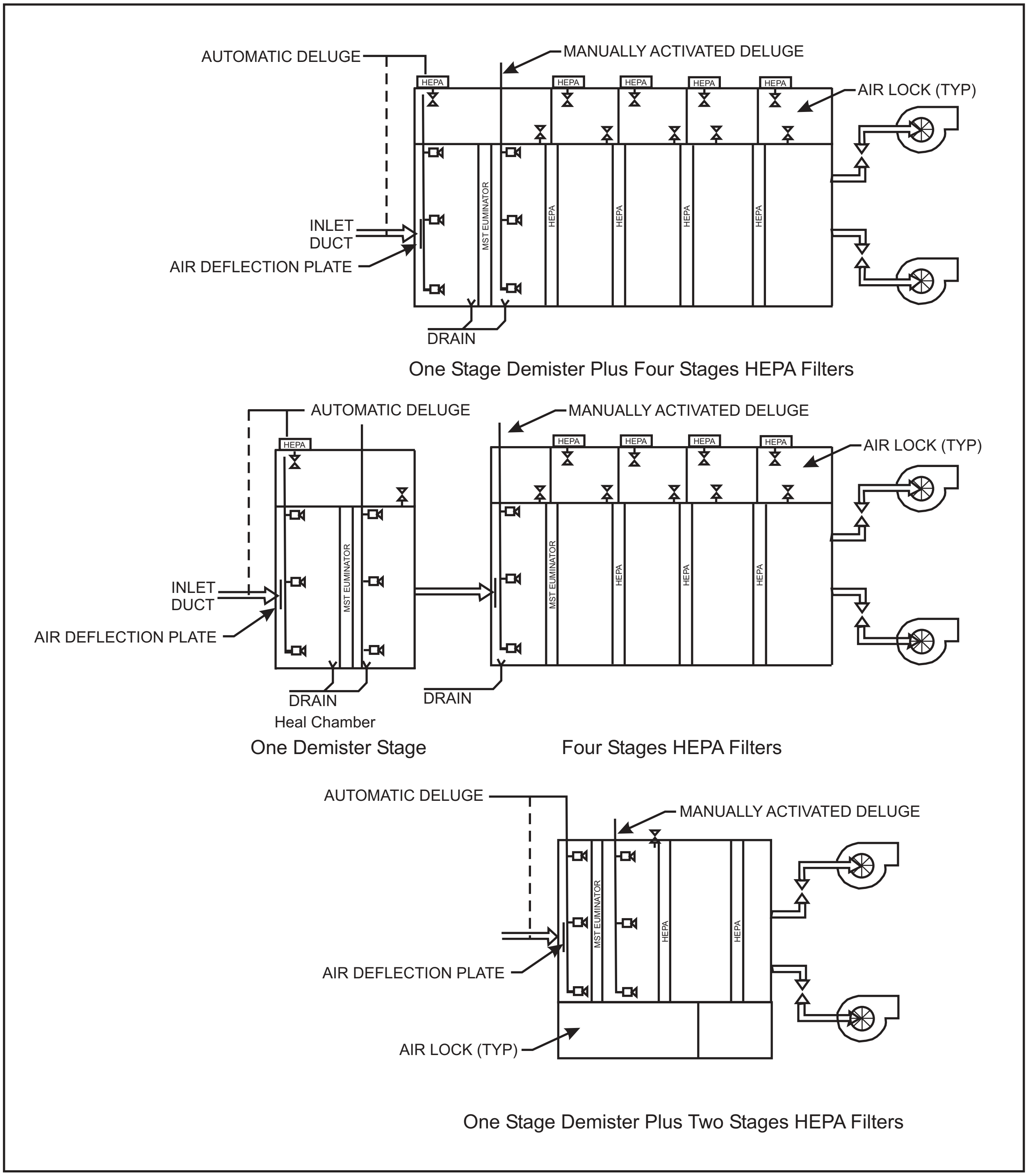

Figure 4.21 – Typical Filter and Demister Layouts

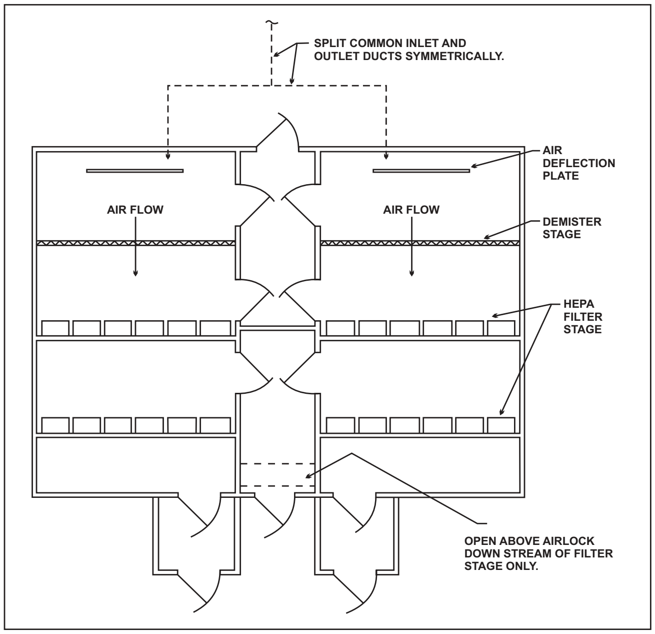

Figure 4.22 – Plan Section of "Double" Plenum

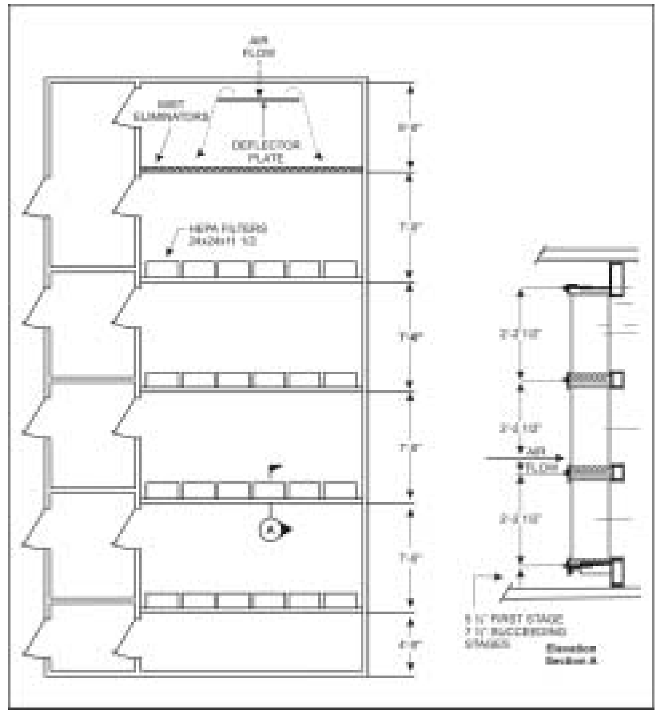

Figure 4.23 – Plan Section of "Single" Plenum

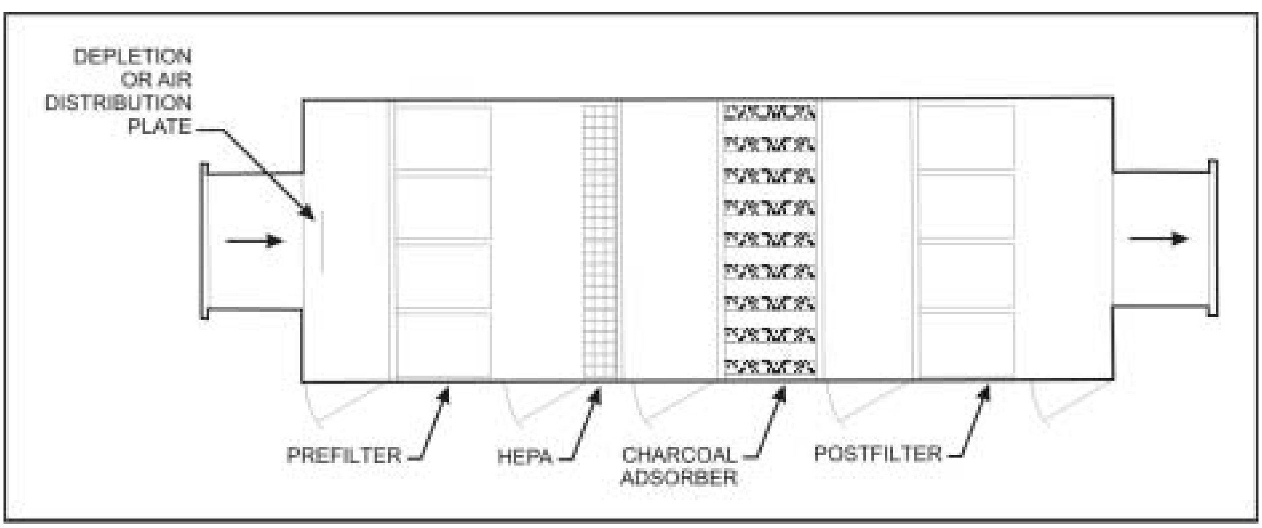

Figure 4.24 – Common Configurations Requiring Test Manifolds (Plan A)

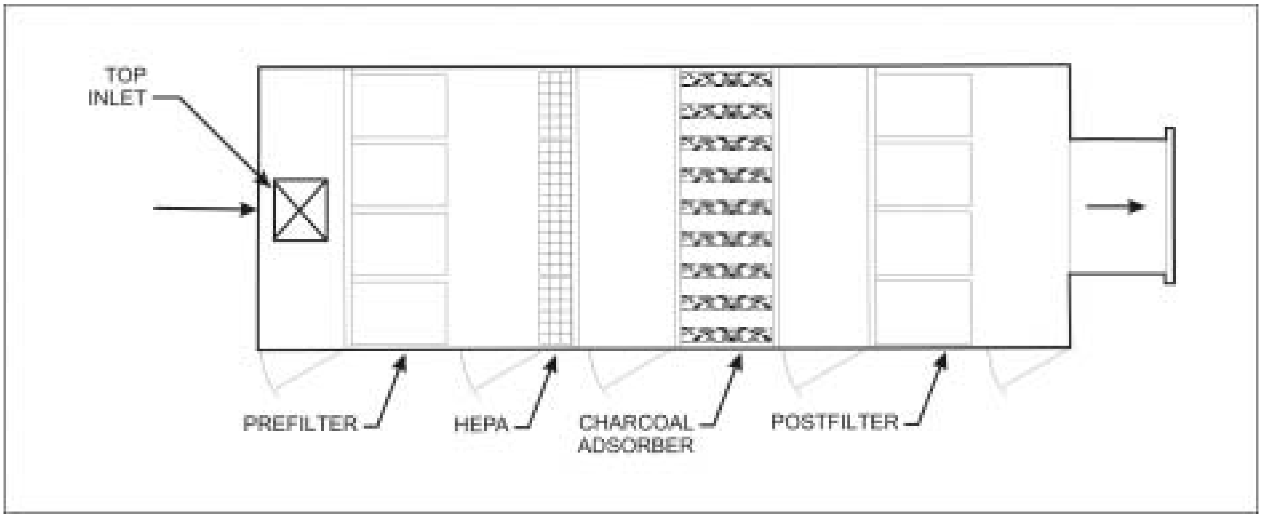

Figure 4.25 – Common Configurations Requiring Test Manifolds (Plan B)

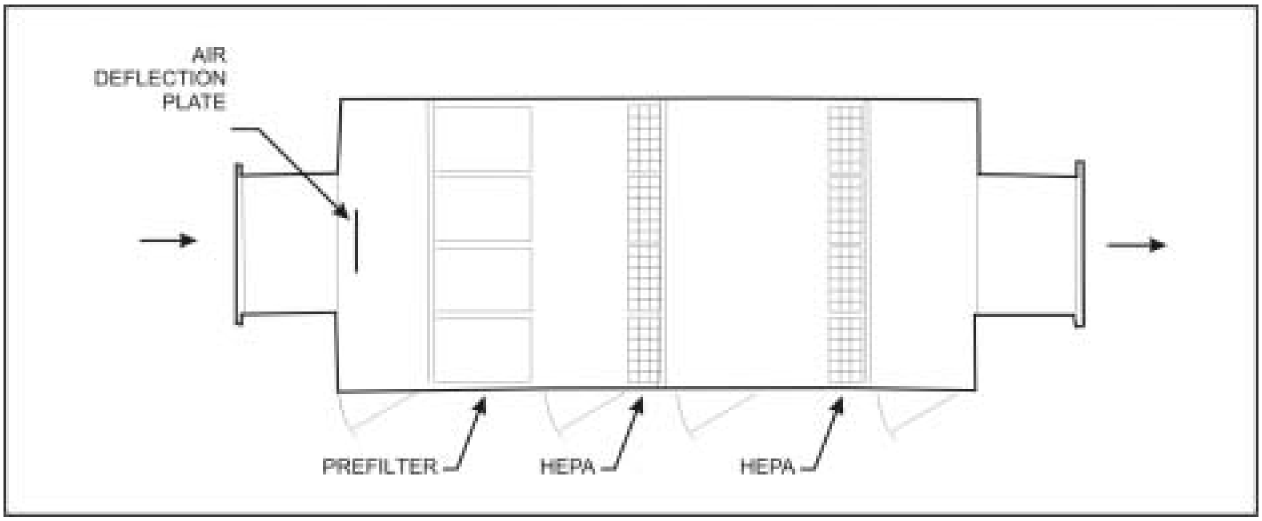

Figure 4.26 – Common Configurations Requiring Test Manifolds (Plan C)

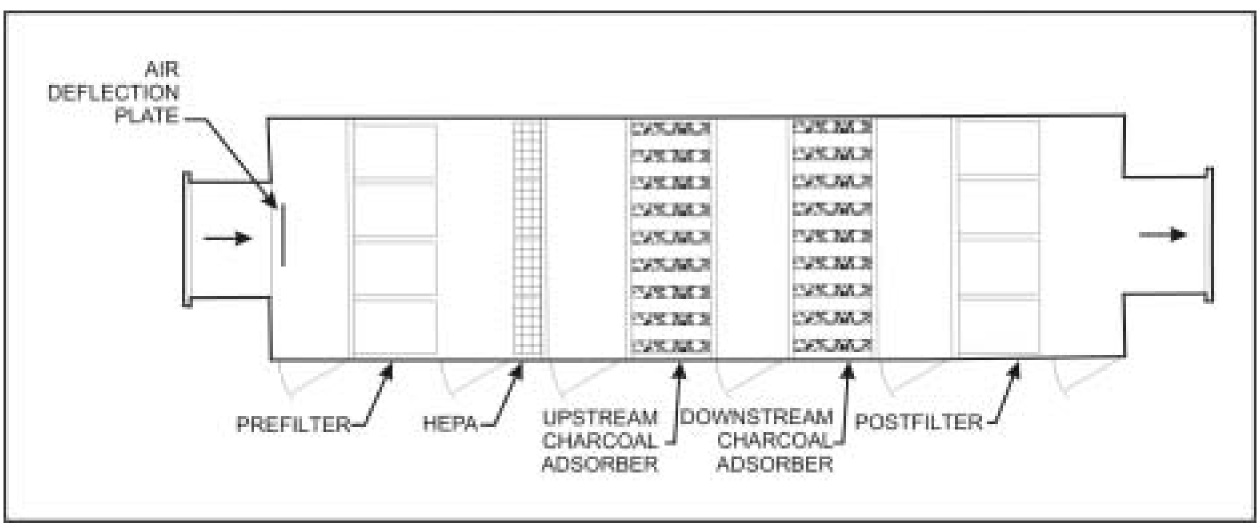

Figure 4.27 – Common Configurations Requiring Test Manifolds (Plan D)

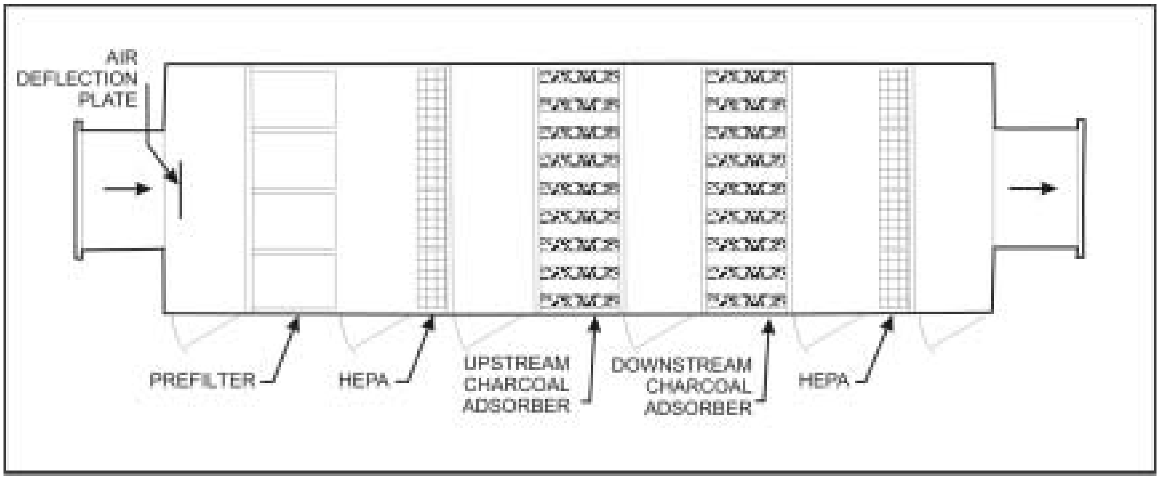

Figure 4.28 – Common Configurations

Figure 4.29 – HEPA Filter Mounted on Upstream Side of Mounting Frame Filter Replacement

Figure 4.30 – Blanking Plate Being Installed On Downstream Side of Mounting Frame

The references cited in Section 4.4.5 for the design, fabrication, and welding of mounting frames are also applicable to steel housings. Housings should be of all-welded construction, with bolted flange or welded inlet and outlet connections to the ducts and fans. **Table 4.3** gives minimum sheet metal thicknesses for sheet steel housings, and **Table 4.4** gives minimum moments of inertia for steel reinforcing members. Sheet metal thicknesses in Table 4.4 are based on a maximum deflection of 1/4 inch per linear foot at a pressure differential between the interior of the housing and atmosphere equivalent to 1.5 times the maximum pressure at fan cutoff. The moments of inertia for reinforcing members listed in Table 4.4 were selected to avoid exceeding the allowable stress of the steel. Members up to 20 inches long were considered to be uniformly loaded beams with fixed ends, whereas members longer than 20 inches were considered to be uniformly loaded beams with simply supported ends. The sheet-metal thicknesses in Table 4.3 are given in U.S. gauge numbers for sheet and fractional inches for plate.

Table 4.3 – Minimum Sheet-Metal Thicknesses [a] for Welded Steel [b] Filter Housings under Negative Pressure

Dimensions of Largest Unsupported Panel (in.)		Thickness [c] (U.S. gauge for sheet, fractional in. for plate) for negative pressure (relative to outside)					
Long Side [d]	**Short Side**	**4 in.wg.**	**8 in.wg.**	**12 in.wg.**	**20 in.wg.**	**1 psi**	**2 psi**
54 (2)	12	18	18	14	16	14	11
	24	18	14	11	12	8	1/4
	36	16	12	8	11	1/4	3/8
	48	14	12	6	8	1/4	3/8
80 (3)	12	18	16	14	16	14	11
	24	18	14	11	12	8	1/4
	36	16	12	6	11	1/4	3/8
	48	14	12	6	8	1/4	3/8
106 (4)	12	18	16	16	14	14	11
	24	18	14	12	11	8	1/4
	36	16	12	8	6	1/4	3/8
	48	16	10	6	1/4	3/8	

[a] Based on flat plate edges held but not fixed (*Roark's Formulas for Stress and Strain*),[30] and maximum deflection of 0.25 inch per foot between reinforcements.
[b] 30,000 to 38,000 psi yield strength.
[c] Metal thickness less than No. 18 U.S. gauge are not recommended because of welding problems.
[d] Length based on 2-inch spacing between 24- × 24-inch filter units; the numbers within parentheses denote number of filter units. The metal thicknesses are adequate for panel lengths within ±10 inches of the length shown.
Note: This table is intended to provide information only. The designer is responsible for verifying this information.

Housings installed inside a reactor confinement may experience a pressure lag during rapid pressurization of the confinement following a major accident. Unless the housings are equipped with pressure-relief dampers, this lag could result in a pressure differential between the housing and confinement substantial enough to collapse the housing.

Reinforcing members should be spaced to minimize vibration and audible drumming of the housing walls, which can be transmitted through the system. Reinforcements should be installed on the outside of the housing, when possible, to eliminate interior ledges and projections that collect dust and constitute hazards to personnel working in the housing (**Figure 4.31**). All sharp corners, welds, weld spatter, and projections inside the housing should be ground smooth. The housing design must minimize cracks and crevices that are difficult to clean and that may collect moisture that can cause corrosion.

Mastics and caulking compounds, including silicone-based, room-temperature vulcanizing (RTV) sealants, deteriorate in service and should not be used for sealing between panels and sections of a contaminated exhaust housing. Lock seams, rivets, and bolts used in conventional construction for joining panels do not produce leaktight joints. When bolted flange joints are used between the housing and ducts, 1.5- × 1.5- × 0.25-inch-angle flanges with ASTM D1056, grade 2C5 or 30-40 Shore-A durometer neoprene gaskets are minimum requirements.[25] A maximum bolt spacing of 4 inches is recommended for flanges.

Shop fabrication of housings is recommended over field fabrication because of the superior workmanship and control possible under shop conditions. These housings are built in sections and assembled in the field. Field joints for such housings should be seal welded, since mastic and gasket-sealed joints cannot be considered reliable for permanent installations.

Table 4.4 – Recommended Minimum Moments of Inertia for Selecting Reinforcing Members for Steel Filter Housings under Negative Pressure [a, b]

Reinforcement		Moment of inertia ($in.^4$) [c] for negative pressure (relative to outside)					
Length [d] (in.)	Spacing (in.)	4 in.wg.	8 in.wg.	12 in.wg.	20 in.wg.	1 psi	2 psi
54 (2)	12	0.04	0.04	0.04	0.04	0.04	0.08
	24	0.04	0.04	0.04	0.06	0.08	0.16
	36	0.04	0.04	0.05	0.09	0.12	0.24
	48	0.04	0.05	0.07	0.12	0.16	0.32
80 (3)	12	0.04	0.04	0.05	0.08	0.11	0.21
	24	0.04	0.06	0.09	0.16	0.21	0.43
	36	0.05	0.10	0.14	0.24	0.32	0.63
	48	0.06	0.13	0.19	0.32	0.42	0.86
106 (4)	12	0.04	0.09	0.13	0.22	0.30	0.60
	24	0.09	0.18	0.26	0.44	0.60	1.19
	36	0.13	0.27	0.39	0.66	0.90	1.79
	48	0.18	0.36	0.52	0.88	1.19	2.38
132 (5)	12	0.09	0.17	0.26	0.51	0.69	1.39
	24	0.18	0.34	0.52	1.02	1.39	2.78
	36	0.27	0.51	0.78	1.53	2.08	4.17
	48	0.36	0.68	1.04	2.04	2.76	5.55
158 (6)	12	0.15	0.29	0.44	0.73	1.0	2.0
	24	0.29	0.59	0.88	1.46	2.0	4.0
	36	0.44	0.87	1.32	2.19	3.0	6.0
	48	0.58	1.16	1.76	2.19	4.0	8.0

[a] Based on permissible deflection of 1/8 inch per foot.
[b] Uniformly loaded beam, 50 percent simply supported and 50 percent fixed end assumed.
[c] Structural angles can be chosen from the tables given in the AISC *Manual of Steel Construction*.[8]
[d] Length based on 2-inch spacing between 24- x 24-inch filter units; the numbers within parentheses denote number of filter units. The metal thicknesses are adequate for panel lengths within ±10 inches of the length shown.
Note: This table is intended to provide information only. The designer is responsible for verifying this information.

4.4.15 Masonry and Concrete Housings

Filter housings for low-gamma-activity systems and vaults for high- (or potentially high-) gamma-activity systems sometimes have been built as an integral part of the building structure utilizing the same concrete building walls for HEPA housing walls. This construction is not recommended.

4.4.16 Housing Floor

Steel housings should have steel floors welded continuously to the walls of the housing. In no case should the housing be installed on a wood floor or on a floor having less than a 3-hour fire rating. A steel curb, welded to the floor, is recommended to raise the filter-mounting frame off the floor. The section of flooring between two banks of components must be considered a separate floor to be drained independently. Floors should be free of obstructions or raised items that could be hazardous to workmen.

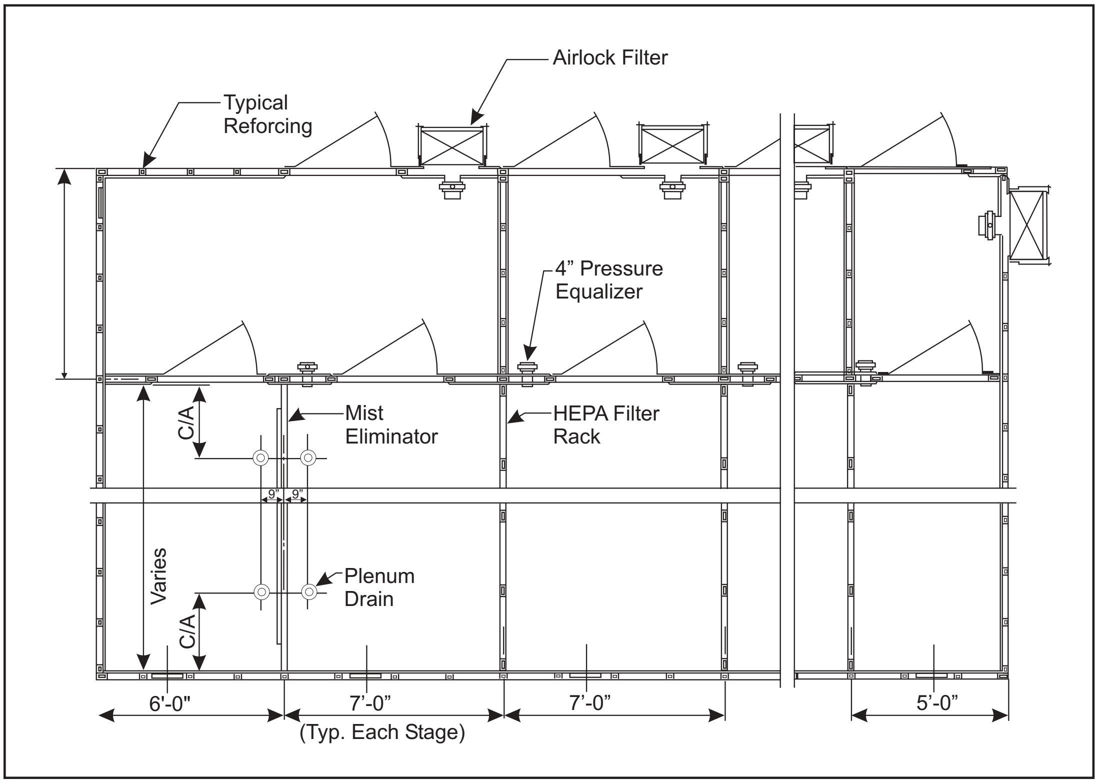

Figure 4.31 – Filter Plenum Floor Plan

4.4.17 Housing Doors

Easily opened doors are essential on large housings, and more than one door is generally needed. A door should be provided to each compartment (space between banks) where maintenance, testing, or inspection may take place. The use of bolted-on removable panels for access to filter compartments should be avoided for even the smallest filter housings when human entry is required. Sliding doors should never be used for filter housings, because they cannot be sealed and because they jam after any distortion of the housing.

Sturdy double-pin-hinged doors with rigid, close-fitting casings and positive latches, such as the marine bulkhead-type shown in **Figure 4.32**, should be provided on man-entry housings, particularly those for ESF and other high-hazard service. Doors and gaskets must be designed to maintain a hermetic seal under positive and negative pressures equal to at least the fan cut-off pressure. Doors of negative pressure systems must open outward and, since they may have to be opened against the negative pressure, a means for breaking the vacuum or for mechanically assisted opening is desirable. Doors should have heavy-duty hinges and positive-latching devices that are operable from inside and outside. Means for locking, preferably a padlock, should be provided to prevent unauthorized entry. Door stiffness is important because flexible doors can be sprung when opened against negative pressure or allowed to slam shut under load. An airlock at the entry to the housing will eliminate problems with opening doors against negative pressure and slamming, and, if large enough, will provide an intermediate work area for personnel during a filter change.

Housing doors of the type shown in **Figure 4.33** require a minimum of two latching dogs on each side. Lighter-construction doors require additional latches to achieve a satisfactory seal. Latching dogs should be operable from inside and outside the housing, and shafts must be fitted with O-rings, glands, or stuffing boxes to prevent leakage. Door hinges should be of the double-pin, loose-pin, or other type that will permit the full plane of the door to move perpendicular to the plane of the doorframe during the last fraction of an

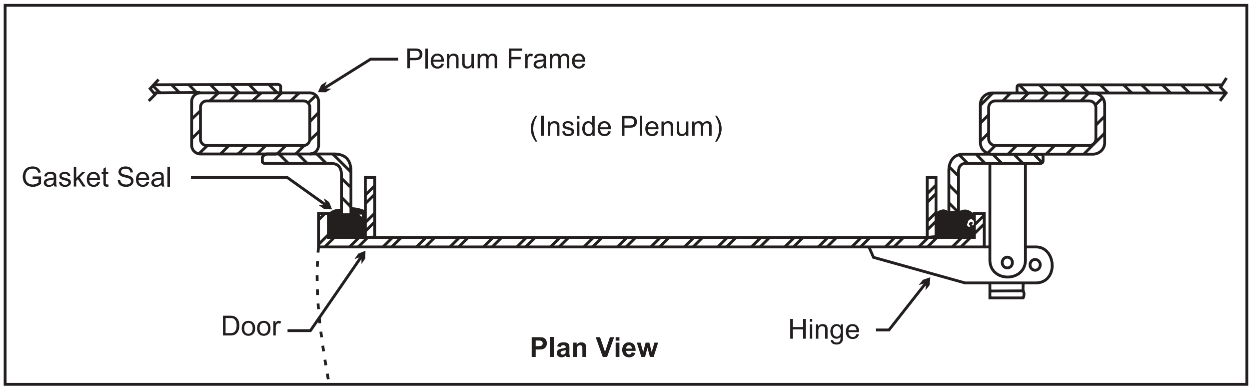

Figure 4.32 – Marine Bulkhead-Type Door

Figure 4.33 – Filter Plenum Entry Door (No Airlock Type-Test Manifold with Valves Shown)

inch of closure. Single-pin hinges, which result in angular motion throughout the door closing arc, do not permit the door to seal properly and may cause the gasket to be rolled out of its groove after a period of use, thus resulting in the loss of housing leaktightness. If door gaskets are too hard they will be incompressible, and the door cannot be sealed properly even with lever-and-wedge latching dogs. If too soft, the gasket will rapidly take a compression set and lose its ability to seal. Solid neoprene or silicone rubber of about 30 to 40 Shore-A durometer is recommended.

A compromise may have to be made in sizing doors for man-entry housings. On the one hand, the door must be large enough for easy access to personnel dressed in bulky protective clothing, wearing gas masks or respirators, and perhaps carrying 24- × 24- × 11 1/2-inch filters weighing up to 40 pounds, or 26- × 6- × 30-inch adsorber cells weighing up to 130 pounds (dimensions of the door through which a 95th-percentile man can pass erect carrying such loads are shown in **Figures 4.34 through 4.38**). On the other hand, the larger the door, the more difficult it is to seal and the more likely that it or its frame can be damaged if allowed to slam under load. The door should be as large as possible for easy access, but in no event should it be any less than 26 inches wide × 48 inches high. A coaming (2-inch-high minimum to 6-inch-high maximum) should be provided at all doors to prevent the outflow of contaminated water should the housing become flooded.

Figure 4.34 – Filter Plenum (Inside Looking at Entry Door)

Figure 4.35 – Filter Plenum (Looking from Outside through the Airlock into the Plenum)

Figure 4.36 – Filter Plenum (Looking from Outside into the Airlock at the Final Stage Upstream and Downstream Doors)

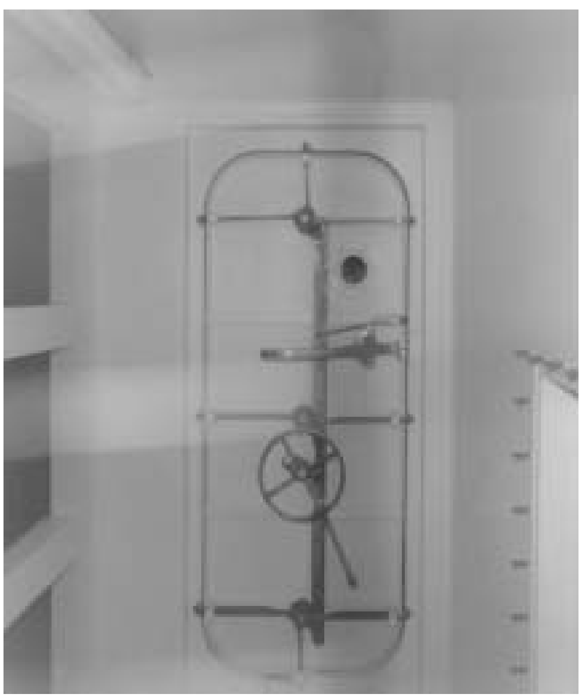

Figure 4.37 – Filter Plenum (Door-Wheel Style)

Figure 4.38 – Filter Plenum (Door Bar Style Showing Difficult Access)

4.4.18 Housing Drains

Floor drains are essential in contaminated-exhaust filter housings, particularly when sprinkler protection is provided. Even if moisture or condensation is not expected under normal conditions, occasional wash-down may be required for decontamination and water will be needed in the event of a fire. When the housing is above grade, the minimum provision for drainage is a Chicago half-coupling that is sealed with a bronze pipe plug using tetrafluorethylene (Teflon®) plastic "ribbon dope" so the plug can be easily removed when needed. [Note: Use of Teflon in radiation areas needs to be specifically considered for radiolytic decomposition on a case-by-case basis]. When the filter is at or below grade, drains should be piped to an underground contaminated waste system during initial construction, since later drainage system installation is likely to be costly. Drains from contaminated systems should be piped to the radioactive waste system. In cold climates, water seats, traps, and drain lines must be protected against freezing if they are above the frost line. In hot climates, water seats/seals may dry out. When fire sprinklers are installed in the filter house, the drains must be sized to carry away the maximum sprinkler flow without water backup in the housing.

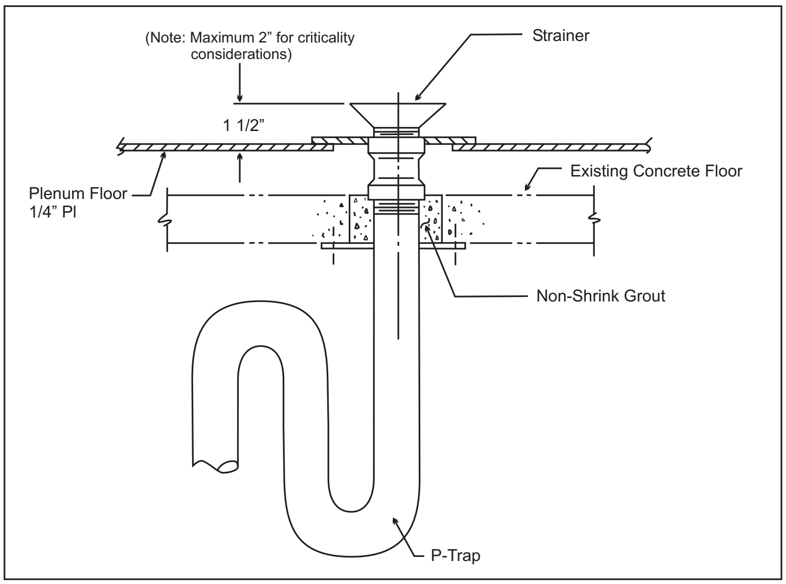

Figure 4.39 – Plenum Drain Detail

If a separate drain is needed for each chamber of the filter house, then each drain must have its own water/loop seal or trap (**Figure 4.39**). The raised drain (shown) takes into consideration criticality concerns while minimizing wastewater. The spaces between two banks of components in series are considered separate chambers. When piped to a common drain system, drain lines from the individual chambers of the housing must have a valve or be sealed, or otherwise protected to prevent bypassing of contaminated air around filters or adsorbers through the drain system. The drain system must be tested for leakage as part of the housing leak test, as well as part of system bypass testing of the HEPA and adsorbent filters.

Provision must be made for those seals or traps to ensure they are filled with water during the plant life (**Figure 4.40**). Water seals must be periodically checked to ensure they do not dry out. A manual or automatic fill system may be utilized to ensure water seals do not evaporate for systems that do not experience moisture conditions continuously. **Figure 4.41** shows alternate methods of drain connection. The design of housing drain systems is often overlooked until the time of filter housing installation or testing when it is usually very difficult and expensive to resolve.

Figure 4.40 – Filter Plenum Drain P-Trap Fill Tube

4.4.19 Demister/Moisture Separator Mounting Frame

The frame must be fabricated from corrosion-resistant, non-perforated steel sheet and must be formed and assembled in a manner that allows no bypassing of the separator pad (**Figures 4.42 through 4.46**). Drain holes must be provided in the bottom of the frame. The design must include provisions to ensure the pad is maintained in its operating position and does not settle, pack down, or pull away from the top or sides of the frame when installed. Seals must be provided as necessary to prevent bypass of entrained liquid droplets.

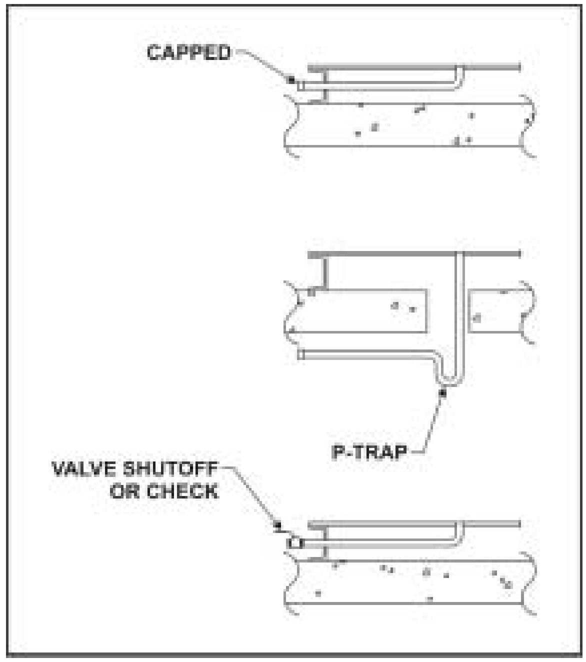

Figure 4.41 – Plenum Drain Designs

Figure 4.42 – Moisture Separator Mounting Frame

Figure 4.43 – Moisture Separator and Mounting Frame

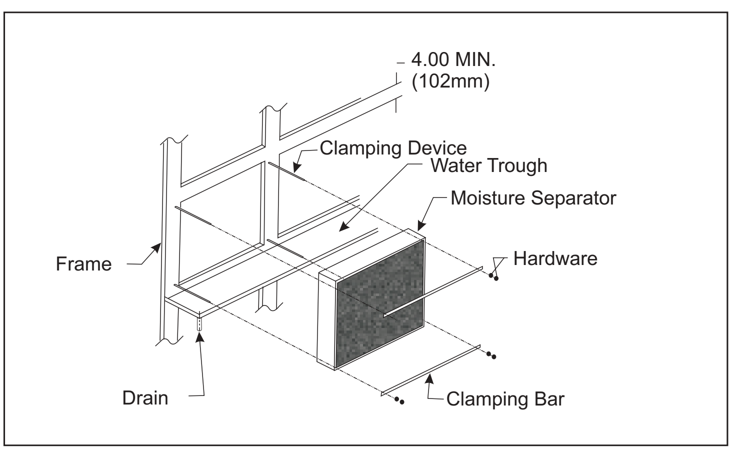

Figure 4.44 – Typical Moisture Separator and Mounting Frame

Figure 4.45 – Moisture Separators with Heat Sensor (Upstream Side)

Figure 4.46 – Moisture Separator (Downstream Side)

4.4.20 Other Housing Requirements

Figures 4.47 and 4.48 illustrate a number of features that are desirable in an air cleaning housing. The housing is all-welded construction. This housing consists of the moisture separator, prefilter, HEPA filter, carbon adsorber, and downstream HEPA filter. The housing is a 9,000-cfm capacity system and includes the following features.

- Shop fabrication,
- Wired-glass viewports on each side of the filter bank for visual inspection without entering the housing (**Figure 4.49**),
- Permanently installed lights in vapor-tight globes that are replaceable from outside of the housing,
- Wiring installed on the outside of the housing (penetrations for wiring are a common source of leakage),
- Shock-mounted instruments with a pressure-drop manometer across each bank of filters and inlet and outlet temperature indicators (**Figures 4.50 and 4.51**),
- A large marine bulkhead door that is operable from both inside and outside the housing (**Figure 4.52**),

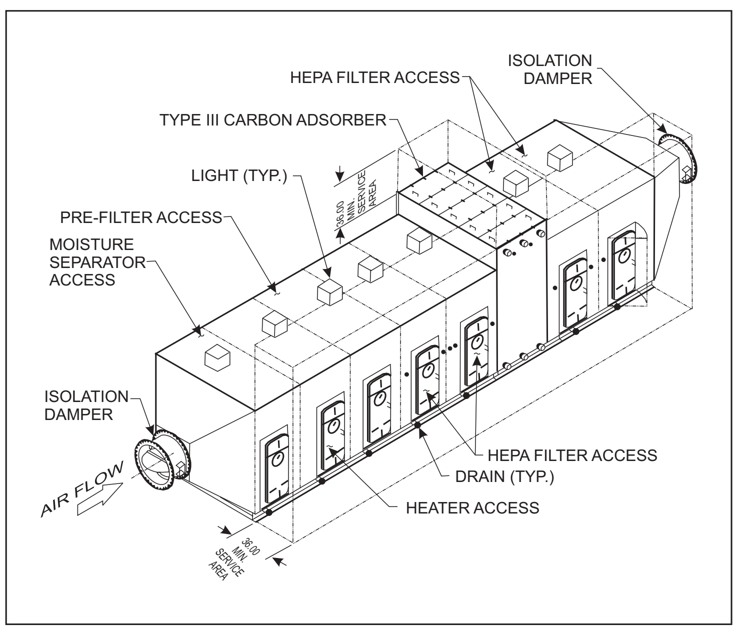

Figure 4.47 – Desirable Air Cleaning Housing Features

- Ample space (approximately 4 × 7 feet) inside the housing to allow personnel to work during a filter change,
- All reinforcements located on the outside of the housing,
- A housing opening on the aisle that can be controlled and that serves as a workspace during filter change-out,
- All-welded construction to eliminate leaks to occupied areas,
- All penetrations sealed by either continuous seal welding or adjustable compression-gland-type seals rated and qualified for the environmental conditions, and

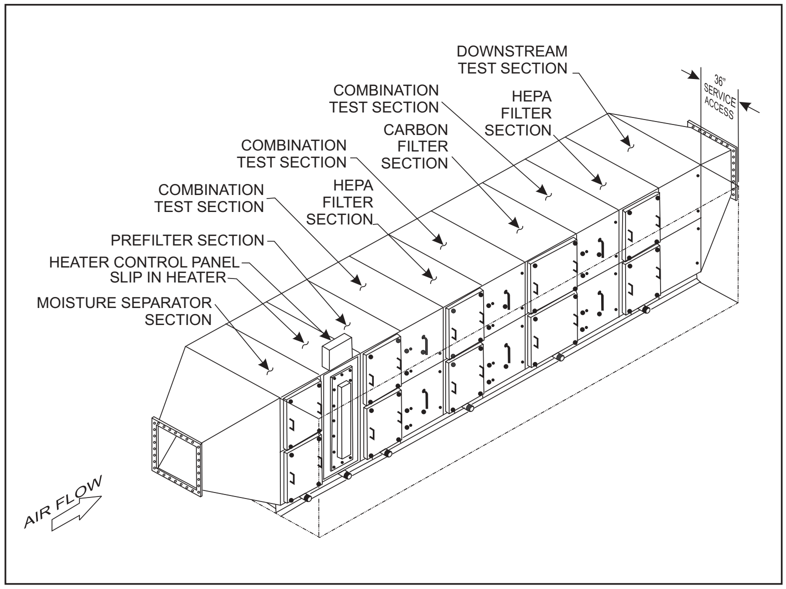

Figure 4.48 – Desirable Air Cleaning Housing Features

- Housing drains located in each compartment. Permanently installed test aerosol and Freon injection and sample ports are highly recommended.

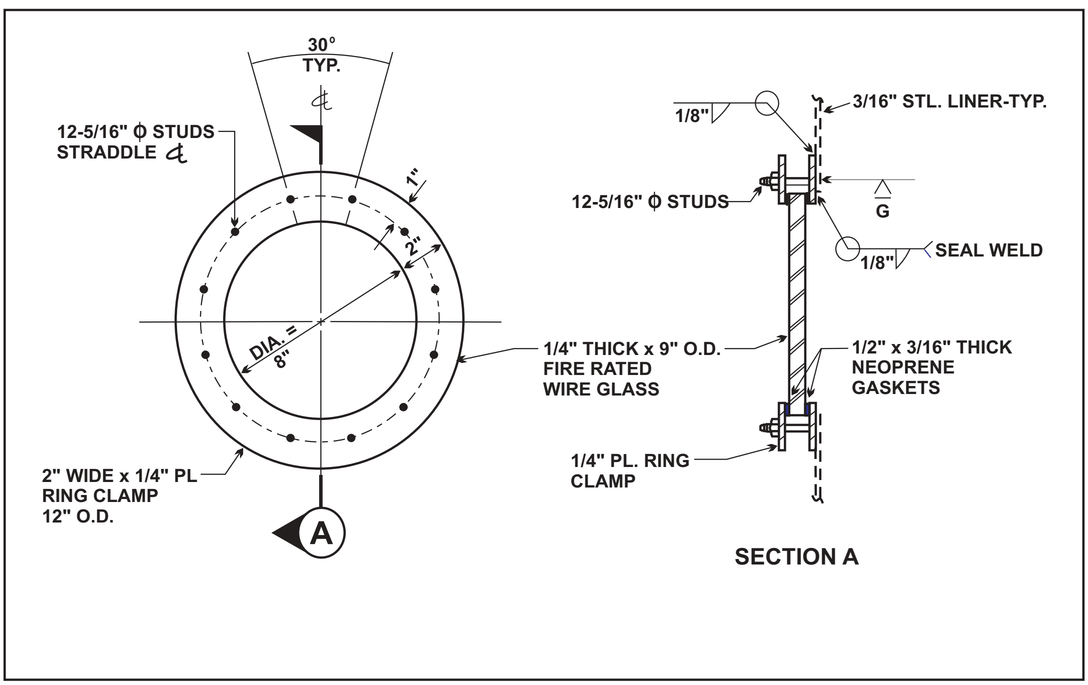

Figure 4.49 – Viewport

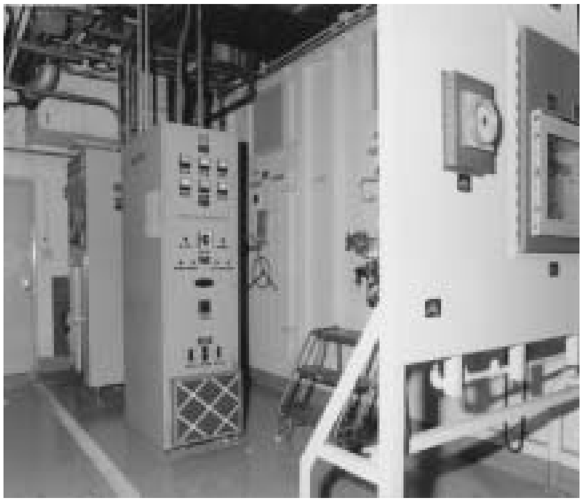

Figure 4.50 – Manual Control and Instrument Panel

Figure 4.51 – Air Monitor in Exhaust Duct from Plenum

4.5 Side-Access Housings

4.5.1 Guidance for Design of Side-Access Housings

The recommended capacity range for side-access housings is 2 filters (24 × 24 × 11 1/2 inches) per stage to 12 filters per stage (4 across × 3 high). Single filter units are also avaliable. Units may be stacked 3 high or higher if platforms are provided.

Housings may be provided with or without bag-in/bag-out features (**Figures 4.53 through 4.67**). Bag-in/bag-out side-access housings feature a ribbed bagging ring inside the side-access door. A specially designed polyvinyl chloride change-out bag is secured around the bagging ring after initial filter loading. All subsequent filter changes are accomplished through change-out bags. Contaminants are isolated to the inside of the bag to protect site personnel and permit safe handling and disposal of spent filters. A self-adjusting filter seal mechanism prevents filter bypass and maintains a positive seal during normal system operation. The housing can also be utilized without the use of change-out bags, which may be specified where future hazardous contaminants are unknown.

Figure 4.52 – Plenum Door (Wheel-Type Inside Plenum Access)

4.5.2 Recommended Design Features

4.5.2.1 Housing Material

The following is a list of recommended housing design features.

- Standard 14-gauge stainless steel.

4.5.2.2 Unit Construction

- All pressure boundary joints and seams seal welded,
- Surfaces free of burrs and sharp edges, and
- Reinforced to withstand up to 30 in.wg.

Figure 4.53 – Bag-In/Bag-Out Filter Housing

4.5.2.3 Access Panel

- Completely hand-removable,
- Handles retained in access panel after removal, and
- Protected panel gasket seal covers entire inner panel surface.

4.5.2.4 Bagging Ring

- Two continuous ribs for optimum bag seal,
- Ring depth designed to contain bag during operations, and
- Smooth outer surface and hammed outer edge.

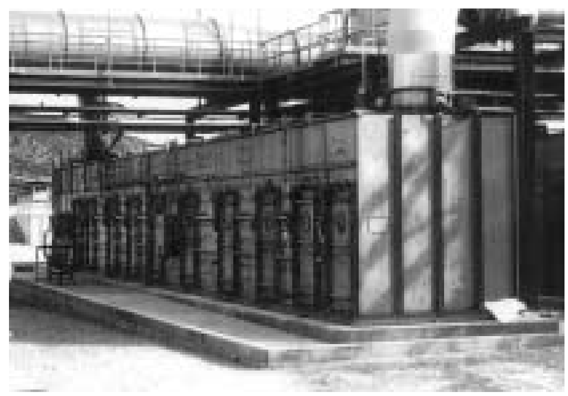

Figure 4.54 – Incinerator Exhaust Filter

4.5.2.5 Filter Clamping Mechanism

- Spring-loaded pressure bars exert uniform clamping force on filed frame;
- Spring loading compensated for any loss of filter gasket memory;
- Positive displacement screw-drive clamping mechanism;
- Leaktight connection for clamping mechanism on outside of housing;
- Stainless steel clamping mechanism; and
- Over 1/2-inch travel to prevent filter binding.

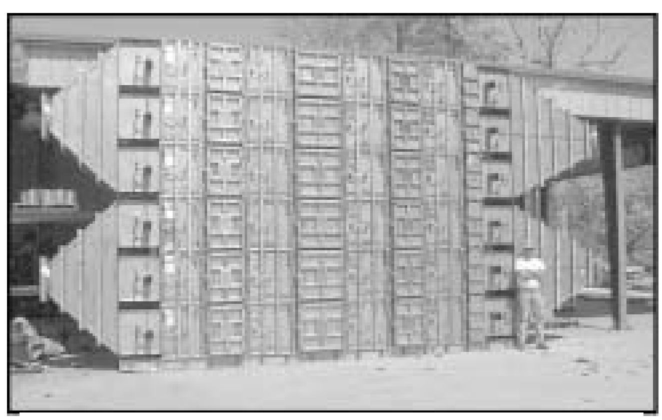

Figure 4.55 – Side Access Housing with Combination of Filter and Adsorber Sections

Figure 4.56 – Two Single Housings with Common Exhaust Fan (Dual Entry Shown)

Figure 4.57 – Side-Access Housing

Figure 4.58 – Side-Access Housing with Fan

Figure 4.59 – Side-Access Housing with Single Air Entry

Figure 4.60 – Side-Access Housing

Figure 4.61 – Side-Access Housing

Figure 4.62 – Side-Access Housing

Figure 4.63 – Side-Access Housing with Multiple Inlet Valves

Figure 4.64 – Side-Access Housing

Figure 4.65 – Side Access-Housing with Bag-In/Bag-Out Covers

Figure 4.66 – Side-Access Housing with Moisture Separator

Figure 4.67 – Side-Access Housing with Test Manifold

4.5.2.6 Filter-to-Housing Seal

- Standard full perimeter flat mounting frame mates to filter gasket; and
- Full seal weld around filter frame.

4.5.2.7 Filter Removal Rod

- Standard mechanical assist on all multiple wide housings; and
- Operated through bagging ring.

4.5.2.8 Pressure Taps

- Welded in housing, upstream and downstream of filter,
- 1/2-inch National Pipe Thread half-coupling with plug.

Seals and gaskets should be installed on panels, and a "knife-edge" gasket sealing surface should be provided. The gasket should be installed in as few pieces as possible to minimize the number of joints and designed to prevent leakage due to miss fitting butt joints. Side-access, bag-out access panels often use gaskets that accommodate the panel to the housing seals. Latches or bolts must be of sufficient quantity and strength to compress the gasket and ensure that the housing leakage criteria are met. Panels must allow access for testing and component inspection. The drawings for each type and size panel should be submitted to the owner for review before fabrication. Panel drawings should show the location and details concerning the hinges, latching lugs, and gaskets.

The number of normally open drains should be kept to a minimum. Drain lines must be valved, sealed, trapped, or otherwise protected to prevent an adverse condition where: (1) air bypass can occur around filtration components, and (2) cooling/heating coil capacity is negatively impacted.

Traps or loop seals, when used, should be designed for the maximum operating (static) pressure the housing may experience during system startup, normal operation system transients, or system shutdown. Provision should be made for manual or automatic fill systems to ensure the water loop seals do not evaporate. If manual filling is utilized, a periodic inspection or filling procedure should be implemented. Use of a sight glass should be considered to aid inspection. The same applies if a local sump is included in the design.

The drain system should be designed so that liquids do not back up into the housing. Hydraulic calculations should be prepared by the manufacturer to document this drain system feature to treat maximum coincident flow rate. Initial testing of the drain system should be performed by the owner onsite after installation to demonstrate operability. When shutoff valves or check valves are utilized, they should be initially tested for operability and leakage onsite, after installation, and periodically thereafter.

4.5.2.9 Basic Differences Between Nuclear Filtration Systems and Commercial/Industrial Filtration Systems

- The standard design pressure for nuclear systems is 10 to 15 in.wg. compared to 3 in.wg. or less for commercial/industrial systems. In addition, confinement systems can be built to higher pressures, such as 30 to 40 in.wg. without significant cost increases.

- Nuclear systems are designed, manufactured, and tested to a higher level of quality assurance, such as ASME NQA-1.[31] This includes certified welders, in-process inspections, and material traceability. Several factory tests are standard, such as filter fit, operability of filter locking mechanisms, flatness of filter sealing surfaces or alignment of knife edges and leak testing of each filter sealing surface and overall pressure boundary of each housing and/or system. Test reports are available to the customer for their files.

- Nuclear systems are designed and built with all-weld construction. All pressure-boundary welds are continuously welded. These systems are built for long life, and RTV sealants are not trusted over long periods of time.

- Over the last 2 decades, stainless steel has become a standard material of construction for confinement systems versus galvanized construction for commercial/industrial systems.

- Most nuclear systems incorporate the bag-in/bag-out feature which allows the user to protect their maintenance personnel and the surrounding environment during filter change-out. Some applications do not require the bag-in/bag-out feature, but still require all the other features of confinement.

- Nuclear filter housings incorporate filter locking mechanisms that are designed to achieve a filter-to-frame seal that will last throughout the life of the filter, not just when the filter gasket is new.

- Nuclear systems are designed so that each tier of filters has its own access door. This is absolutely necessary when the bag-in/bag-out feature is required, but it is a desirable feature even without the bag-in/bag-out feature.

- Nuclear systems offer optional inplace test sections.

- Nuclear systems offer optional separate access panels for prefilters, which allows the seal of the HEPA filters to be on the upstream side.

- Most nuclear filter housings have "filter removal rods" to assist in pulling the second or third filter to the change-out position.

- Nuclear systems now incorporate isolation dampers in many cases. These dampers are now readily available in both "bubble-tight" and "low-leakage" designs. These dampers are designed, manufactured, and tested in the same manner as the filter housings.

4.5.2.10 Advantages of Stainless Steel over Heavy Carbon Steel Construction

- Nuclear filtration systems are usually constructed of 14- and 11-gauge stainless steel reinforced externally. The cost of this design is very nearly the same as manufacturing from heavy steel plates and priming/painting for corrosion protection.

- Stainless steel offers much better corrosion protection during installation and use than painted steel.

- Decontamination and cleaning of systems is much easier with stainless steel.

- Modification of systems in the field is much easier with stainless steel. Changes, including welding, can be made without ruining the corrosion protection of the system.

- Stainless steel systems typically weigh less than carbon steel systems.

4.5.3 Side-Access Housings for Radial Flow Cylindrical HEPA Filters

Recently, radial flow cylindrical filters have been applied to DOE nuclear applications. Side-access housings for radial flow cylindrical filters have been designed for the installation of up to 12 plug-in, 2000-cfm filters, for a total of 24000 cfm. Larger installations are possible (**Figures 4.68 through 4.70**). Operational experience is still being gathered for these units.

Figure 4.68 – Side-Access Housing (Cylindrical Radial Flow HEPA Design)

HEPA filters must maintain: (1) their gasket integrity in both manual and remote handling situations; (2) a reliable seal after installation; and (3) correct orientation and fastening must be obtained. Radial flow cylindrical HEPA filter manufacturers maintain that the use of an internal seal offers the highest performance with the least force required. It is integral to the design and is extremely effective in negating alignment problems because it eliminates the remote handling restrictions of the square filters.

Manufacturers claim the following for radial flow cylindrical HEPA filters.

- Clamping is not required.
- The gasket is less likely to be damaged in normal handling.
- Positioning and orientation are not required.
- The filter is free of sharp edges and the sealing face integrity is reliable.
- The filter is normally used in-to-out so that the collected contaminant is on the inside.
- The outside surfaces are "clean," thereby easing handling.
- Radial flow filters permit higher airflow designs with lower pressure drops compared with conventional square section filtration systems.
- Plug-in filters are easy to install; they simply slide into the canister along guide rails and locate on a spigot at the rear of the canister. A ring is provided around the filter access to facilitate fitting of the change bag (**Figure 4.71**). An access cover is positioned over the filter. A locator fitted in the cover ensures correct positioning of the filter in the module.

Figure 4.69 – Side Access Housing Cylindrical Radial Flow HEPA Design

4.5.4 Inplace Leak Test

This is a test to determine if there is leakage through the filter frame/filter gasket surface or from damage to the HEPA filter. Inplace leak testing is performed at the user facility, not at the DOE FTF, because for this test, the HEPA filter must be installed in a filter housing. The FTF performs quality assurance efficiency testing on each individual filter prior to installation in a HEPA filter housing. HEPA filter housings must be supplied with test sections on the upstream and downstream sides of the filter bank. Each test section must be isolated from the other to permit individual leak testing of each HEPA filter and its supporting framework in parallel and/or in series in compliance with ASME AG-1.[1]

Figure 4.70 – Side-Access Housing (Cylindrical Radial Flow HEPA Design)

All leak testing must be conducted from a location outside the system using apparatus and devices that are supplied as an integral part of the test sections, including mixing devices and sample ports. The upstream and downstream test chambers contain mixing devices to mix and disperse a uniform challenge air/aerosol ahead of the filter and the effluent from the filter being tested. Challenge aerosol inlet ports and upstream and downstream sample ports must be provided for each HEPA filter. All mixing devices in the airstream must be designed to swing aside when testing has been completed.

The manufacturer must submit evidence that he has proof-tested his in-place test method according to the requirements of ASME AG-1[26] for systems containing two filters in series and two filters in parallel, with one leaking filter in each bank.

Figure 4. 71 – Radial Flow Filter Bag-Out

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CHAPTER 5

EXTERNAL COMPONENTS

5.1 Introduction

External components of an air cleaning system include fans, ductwork, dampers, louvers, stacks, instruments, and other miscellaneous accessories that are associated with the movement, control, conveying, and monitoring of the air or gas flow.

This chapter contains information on the design, fabrication, materials, and codes and standards requirements/considerations for air cleaning system external components for nuclear facilities. Additional information can be found in Chapters 2 and 4, as well as ASME Code AG-1.[1] Use of AG-1 requirements is mandatory for Safety Class and Safety Significant Systems and can be used as guidance for lower systems.

5.2 Ductwork

This section will address the functional design, mechanical design, materials, coatings, supports, acoustic considerations, leakage, vibration considerations, and applicable codes and standards for ductwork for nuclear facilities.

5.2.1 Functional Design

The sizing and layout of ductwork to provide desired air distribution, ventilation rates, transport velocities, and other functional requirements of the ventilation system are covered by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) handbook,[2, 3] the American Conference of Governmental Industrial Hygienists (ACGIH) *Industrial Ventilation*,[4] and American National Standards Institute (ANSI) Z9.2.[5] The purpose of this section is to review the physical aspects of the duct system in relation to nuclear air cleaning and treatment. The least expensive first-cost duct layout may not be the most economical when the total annual cost of operating the system is considered. Short-radius elbows and other shortcuts in ductwork may seriously increase system resistance, which could require, for example, the use of a larger fan and/or fan motor with resulting higher operating costs, or conversely, they could make it impossible for the system, as installed, to operate at the desired level of performance. The physical layout of ductwork in a building is often compromised to conform to the confines of a building structure or design. This may be unavoidable when installing new ducts in an existing building. In new construction, consideration should be given to providing adequate space and optimizing the duct layout configuration in the earliest phases of building layout, i.e., long before the building design has been finalized. Adequate access (as described in Chapter 4) to filter housings, fans, dampers, and other components is vital to maintainability and testability. Allowance of adequate space for well-designed elbows, transitions, and fan inlets and outlets is vital to proper operation.

5.2.2 Mechanical Design

Duct cost is influenced by the size and quantities of ductwork, construction materials, coatings used for protection against corrosion, construction methods (seams, joints, etc.), air-tightness requirements, erection sequence (including consideration of space limitations, post-erection cleaning requirements, etc.), and the number and type of field connections and supports (hangers, anchors, etc.) required. Consideration should be given to future modification, dismantling, and disposal of contaminated ductwork, particularly in the design of systems for U.S. Department of Energy (DOE) facilities, nuclear power plants, laboratories, experimental facilities, and other operations where change-out of the ductwork or removal for maintenance can be expected. Provision for adding on or changing ductwork is a consideration that is often overlooked in initial design.

Where space permits, a round duct is generally preferred to a rectangular duct because it is stronger (particularly under negative or collapsing pressure); is more economical for the high-pressure construction often required for nuclear applications; provides more uniform airflow; and is easier to join and seal than a rectangular duct. The principal disadvantages of round duct are that it makes less efficient use of building space and it is sometimes difficult to make satisfactory branch connections. Any duct system that carries radioactive material, or that could carry radioactive material, should be considered as a safety-related system. Specific requirements for the performance, design, structural load combinations, construction, inspection, and shop and field fabrication acceptance testing for ductwork, ductwork accessories, and ductwork supports can be found in American Association of Mechanical Engineers (ASME) AG-1, Sections SA and TA.[1]

The level of radioactivity will largely determine the quality of duct construction required. Although it is sometimes assumed that all leakage in negative pressure ductwork will be in-leakage, this is not necessarily true. In the event of fire or explosion in a contained space (room, enclosure, hot cell, glovebox, or confinement structure) served by the system, ductwork can become positively pressured, resulting in out-leakage. Out-leakage can also be caused by a rapidly closing damper or by dynamic effects (in a poorly laid-out system) under normal operating conditions. Under system shutdown conditions or during maintenance, the possibility of out-leakage from normally negative-pressure ductwork also exists. The engineer must consider these possibilities in the design and specification of permissible leak rates for negative-pressure portions of systems. Ducts should be sized for the transport velocities needed to convey all particulate contaminants without settling. Recommended transport velocities are given in Section 5 of *Industrial Ventilation.*[4] Ducts for most nuclear exhaust and post-accident air cleanup systems should be sized for a minimum duct velocity of 2,500 feet per minute (fpm).

ASME AG-1, Section SA,[1] contains recommendations for ductwork construction standards. This paragraph recommends the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA)[6] ductwork construction standards. Note that these standards do not incorporate structural design requirements. These standards must be evaluated for structural capability and adjusted as necessary to meet the requirements of ASME AG-1,[1] and any other facility-specific requirements.

Tables 5.1 through 5.4 list a suggested methodology for sheet-metal gauges and reinforcements for negative pressure ducts operating at pressures below 2 in.wg negative. Suggested gauges and reinforcements for positive-pressure ducts are given in SMACNA standards.[7]

Table 5.1 – Recommended Sheet-Metal Thicknesses for Round Duct Under Negative Pressure

Negative Pressure in Duct	***Reinforcement Spacing***	***Sheet-Metal Thickness (U.S. gauge No.)*** [a] ***for Duct Diameter of***								
		4 in.	***8 in.***	***12 in.***	***16 in.***	***20 in.***	***24 in.***	***36 in.***	***48 in.***	***60 in.***
4 in.wg	∞ [b]	24	24	20	18	16	14	10	8	4
	96	24	24	24	22	20	18	16	14	14
	48	24	24	24	24	24	22	20	18	16
	24	24	24	24	24	24	24	22	20	18
8 in.wg	∞	24	22	18	16	14	12	8	4	
	96	24	22	22	18	18	18	14	12	12
	48	24	24	24	22	20	20	16	14	14
	24	24	24	24	24	22	22	18	16	16

Negative Pressure in Duct	Reinforcement Spacing	Sheet-Metal Thickness (U.S. gauge No.)[a] for Duct Diameter of								
		4 in.	8 in.	12 in.	16 in.	20 in.	24 in.	36 in.	48 in.	60 in.
12 in.wg	∞	25	20	16	14	12	12	6	2	
	96	24	22	18	18	16	16	12	11	11
	48	24	22	22	20	18	18	14	14	12
	24	24	24	24	22	22	22	16	16	16
20 in.wg	∞	24	18	14	12	11	8	4		
	96	24	20	16	16	14	14	11	11	8
	48	24	22	20	18	16	16	14	12	11
	24	24	24	22	20	18	18	16	14	12
	12								20	16
1 psi	∞	20	14	12	10	8	6			
	96	24	18	16	14	12	12	10	8	6
	48	24	20	18	18	16	16	12	11	11
	24	24	24	22	20	18	18	14	12	12
	12								16	14
2 psi	∞	18	12	11	8	4	2			
	96	22	16	14	12	12	11	6	6	4
	48	24	18	16	14	14	12	10	8	6
	24	24	20	18	18	16	16	11	11	11
	12							14	12	12

Note: Factor of safety = 3 over code based on ultimate strength for ducts with diameters up to 24 inches and 5 over code for ducts with diameters over 24 inches based on paragraph UG-28 in Section VII of the ASME *Boiler and Pressure Vessel Code*.[8]

[a] Minimum sheet-metal thickness for shop-weld duct is No. 18 U.S. gauge. Minimum sheet-metal thickness for field-welded duct is No. 16 U.S. gauge.

[b] Where ∞ is shown, no reinforcement is required.

Table 5.2 – Recommended ASTM 36 Angles Reinforcement for Round Duct Under Negative Pressure

Negative Pressure in Duct	Angle Size[a] for Duct Diameter of								
	4 in.	8 in.	12 in.	16 in.	20 in.	24 in.	36 in.	48 in.	60 in.
4 in.wg	A	A	A	B	B	B	B	C	C
8 in.wg	A	A	A	B	B	B	B	C	C
12 in.wg	A	A	A	B	B	B	B	C	C
20 in.wg	A	A	A	B	B	B	B	C	C
1 psi	A	A	A	B	B	C	C	C	C
2 psi	A	A	A	B	B	C	C	D	D
4 psi	A	A	A	B	B	C	C	D	D

[a] Symbol for angle size (inches): A = 1 x 3/16; B = 1 1/2 x 1 1/2 x 1/4; C = 2 x 2 x 1/4; D = 2 1/2 x 2 1/2 x 1/4.

Source: Based on R. J. Roark, *Formulas for Stress and Strain*, 7th Edition, McGraw-Hill, 1989, Formula 12, Table XV.[9]

Table 5.3 – Recommended Sheet-Metal Thicknesses for Rectangular Welded Duct Under Negative Pressure

Negative Pressure in Duct (in.wg)	Reinforced Spacing (in.)	Sheet-Metal Thickness [a] (U.S. gauge No.) [b] for Longest Side of Length				
		12 in.	14 in.	36 in.	48 in.	60 in.
4	48	18	18	16	14	
4	24	18	18	18	16	16
4	12	18	18	18	18	16
8	48	18	14	12	12	
8	24	18	16	16	14	14
8	12	18	18	18	18	18
12	48	18	12	8	11	
12	24	18	16	12	12	12
12	12	18	18	18	18	18
20	48	14	11	6	6	
20	24	14	14	11	11	11
20	12	18	14	14	14	14
1 psi	48	12	10			
	24	16	12	11	10	
	12	18	14	12	11	
2 psi	48	12	10			
	24	14	11	10	8	
	12	16	12	11	10	

[a] For maximum deflection of 1/16 inch per foot in the long dimension.
[b] Minimum sheet-metal thickness for filed-welded duct is No. 16 U.S. gauge.
Source: Based on R. J. Roark, Flat plate formula for edges held but not fixed, *Formulas for Stress and Strain*, 7th Edition, McGraw-Hill, 1989, p. 246.[9]

Table 5.4 – Recommended ASTM A 36 Angle Reinforcement for Rectangular Ducts Under Negative Pressure

Negative Pressure in Duct (in.wg)	Angle Size [a] of Ducts with a Maximum Panel Size of											
	12 in. by				24 in. by				48 in. by			
	12 in.	24 in.	36 in.	48 in.	60 in.	24 in.	36 in.	48 in.	60 in.	36 in.	48 in.	60 in.
4	E	E	E	F	F	E	G	G	G	H	H	H
8	E	E	E	F	F	E	G	G	G	H	H	H
12	E	E	E	F	F	E	G	G	G	H	H	H
20	E	F	H	H		G	H	J				
1 psi	F	G	H	J		H	J	K				
2 psi	G	H	J	L		J	K	L				

Note: Based on uniformly loaded beam with 50 percent simple support, 50 percent fixed ends, and deflection of 1/8 inch per foot.
[a] Symbol for angle size (inches): E = 1 x 1 x 1 3/16; F = 1 1/4 x 1 1/4 x 3/16; G = 1 1/2 x 1 1/2 x 3/16; H = 2 x 2 x 3/16; J = 2 1/2 x 2 1/2 x 1/4; K = 3 x 2 1/2 x 1/4; L = 4 x 3 x 3/8.

Table 5.5 – Guide for Selecting Recommended Duct Construction Levels for Various Applications in Nuclear Facilities [a]

Contamination Level and/or Function [b]	Operating Mode [c]	System Type, Duct Location Outside Contained Space, All Systems, Duct Located in– Zone IV	Zone III	Zone II	Zone I	HVAC,[d] Supply,[e] Recirculating Portion within Contained Space
None, supply, HVAC	A	1	1	2	2	2
	B	1	1	1	1	1
Low (class 4)	A	3	2	2	2	2
	B	1	1	2	2	1
Moderate (class 3)	A	4	3	2	2	2
	B	4	2	2	2	1
High (class 2)	A	4	4	4	4	2
	B	4	4	4	4	2
Very high (class 1)	A	4	4	4	4	2
	B	4	4	4	4	2
Process off-gas	A	5	5	5	4	2
	B	5	5	4	4	2
Controlled atmosphere [f]	A	5	5	5	5	5
	B	5	5	5	5	5

[a] Duct construction level: 1, SMACNA low velocity; 2, SMACNA, high velocity; 3, SMACNA high velocity; 4, welded; 5, pipe or welded duct, zero leak.
[b] Contamination levels from Tables 2.3 for classes 2, 3, and 4.
[c] Operating mode: (A) system to operate following upset or accident; (B) system shutdown in event of upset or accident.
[d] HVAC, building enclosure zones from Section 2.2.9.
[e] Contained space: The building area or enclosure served by the system.
[f] Inert gas, desiccated air, or other controlled medium.

Table 5.6 – Recommended Maximum Permissible Duct Leak Rates[a] at 2 in.wg Negative (by methods of ASME N510)[10]

Duct Class	Maximum Permissible Leak Rate
Level 1	5 percent of system airflow per minute
Level 2	1 percent of system airflow per minute
Level 3	0.2 percent of volume per minute [b]
Level 4	0.1 percent of volume per minute [b]
Level 5	Zero detectable leak at any test pressure up to 20 in.wg
Recirculating	Leak test not required if totally within contained space served by air cleaning system

[a] Maximum permissible leak rate at pressure greater than 2 in.wg is found from the equation.

$$L_p \times L_2 \sqrt{P'/2}$$

where

L_p = permissible leak at higher pressure,
L_2 = permissible leak at 2 in.wg from table,
P' = higher pressure.

[b] Based on volume of portion of system under test.

For ducts that are fabricated by welding, a minimum of No. 16 U.S. gauge sheet metal is recommended because of the difficulty of making reliable welds in thinner material. Section 5.10 of the ANSI N509 recognizes several levels or grades of duct construction but does not define them (in terms of specific requirements) or distinguish clearly between them. Because a nuclear facility may contain spaces of widely differing potential hazard levels (see confinement zoning discussion, Section 2.2.9), the type of duct construction required may vary from one part of the plant to another. The following questions, as a minimum, must be answered to establish the type of duct construction needed for a particular application.

- Is the system nuclear-safety-related?
- If the system is nuclear-safety-related, is the level of radiation that exists in the duct, or the level that could exist in the duct in the event of a system upset, low, intermediate, or high?
- Must the air cleaning system remain operable in the event of a system upset (power outage, accident, malfunction) or can it be shut down?
- Where will the ductwork be located in relation to: (1) the contained space served by the system, and (2) the occupied spaces of the building? [Building spaces that are not normally occupied, but are occasionally entered for repair or service of equipment, are considered "occupied."]
- Is the system once-through or recirculating?
- Is it a safety-related feature system that is intended to mitigate the consequences of an accident?
- What are the environmental considerations (e.g., pressure, temperature, corrosion, etc.)?

Depending on the answers to these questions, the duct should be constructed to conform to one of the several grades outlined in **Table 5.5** and the leaktightness recommendations of ASME AG-1, Section SA.[1] Recommended construction requirements are categorized as described below.

Level 1. In accordance with SMACNA's "HVAC – Systems-Duct Design," (with the exceptions that button-punch and snap-lock seam and joint construction are not permitted), these constructions are considered unsuitable even for low-pressure construction.[7] Companion-angle or bolted (or screwed) standing-seam transverse joints are recommended. Standing edges of seams or joints and reinforcement should be on the outside of the duct (**Figure 5.1**).[7] [Note: Use of Level 1 ductwork is limited to systems serving administrative areas and other non-safety-related applications in which maximum static pressure does not exceed 2 in.wg.] See Figure 5.1.

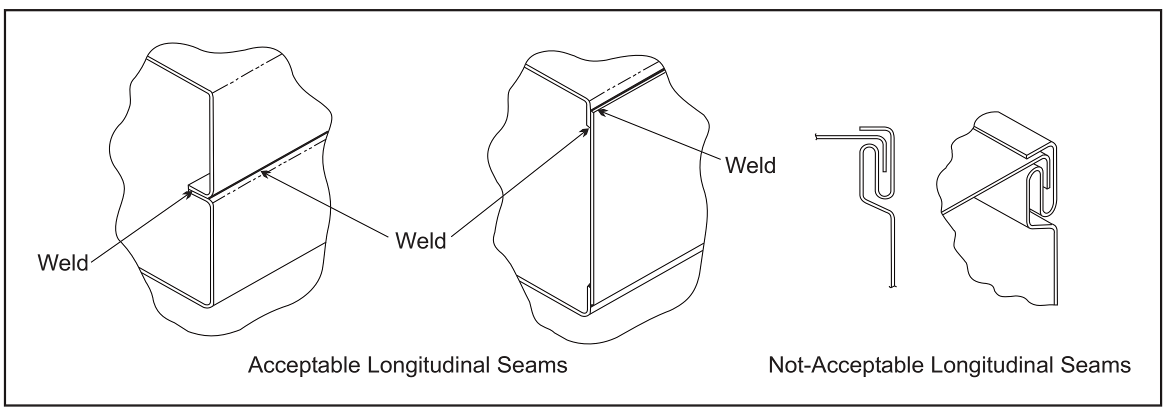


Figure 5.1 – Leakage Class 1 Duct Seams

Level 2. In accordance with SMACNA's "HVAC Systems-Duct Design,"[7] the use of Level 2 ductwork is limited to systems serving administrative areas, as well as Secondary and Tertiary Confinement Zones in which the radiotoxicity of materials that are handled or could be released to the ductwork does not exceed hazard class 2 (see Tables 2.3 through 2.5), and in which negative pressure does not exceed 10 in.wg. The following exceptions apply: (1) button-punch and snap-lock construction are not permitted; (2) only bolted flanged joints, companion-angle flanged joints, welded-flanged joints, or welded joints are permitted for transverse connections; (3) tie rods and cross-braking are not permitted on negative-pressure ducts; (4) standing edges and reinforcement of seams and joints should be on the outside of ducts only; (5) sheet-metal thickness and reinforcement of negative-pressure ducts should be in accordance with ASME AG-1, Section SA-4000,[1] and (6) radiation-resistant sealants (e.g., silicone room-temperature vulcanizing) are used as required in the makeup of nonwelded seams and in penetrations of safety-related ductwork.

Level 3. This is the same as Level 2, with the exception that: (1) transverse joints must have a full-flanged face width and use 1/4-in.-thick gaskets made of American Society of Testing and Materials (ASTM) D1056[11] grade 2C2 or 2C3 cellular neoprene; grade 2C3 or 2C4, 30 to 40 durometer, Shore-A, solid neoprene; or an equivalent silicone elastomer with interlocking notched corners; and (2) nonwelded longitudinal seams, transverse joints, or the entire exterior may have hard-cast treatment (polyvinyl acetate and gypsum tape system) or comparable fire-resistant, corrosion-resistant, radiation-resistant, nonpeeling, leaktight treatment.

Level 4. This level requires all-welded construction with sufficient mechanical transverse joints to facilitate coating (painting), erection, and future modification and/or dismantling. Mechanical transverse joints must conform to **Figure 5.2**. For sheet-metal thickness and reinforcement, see ASME AG-1, Section SA.[1] Specific guidance is provided in nonmandatory Appendix SA-C, Section C-1300.[1]

Level 5. Level 5 ductwork meets requirements for leaktightness as determined in ASME AG-1, Section SA, Nonmandatory Appendix SA-B[1] or the requirements of the *American National Standard for Pressure Piping*, ASME B31.1,[6] or the ASME *Boiler and Pressure Vessel Code.*[8]

See **Figures 5.2** through **5.4** for examples of seams, joints, gaskets, and sealing of companion angle joint corners.

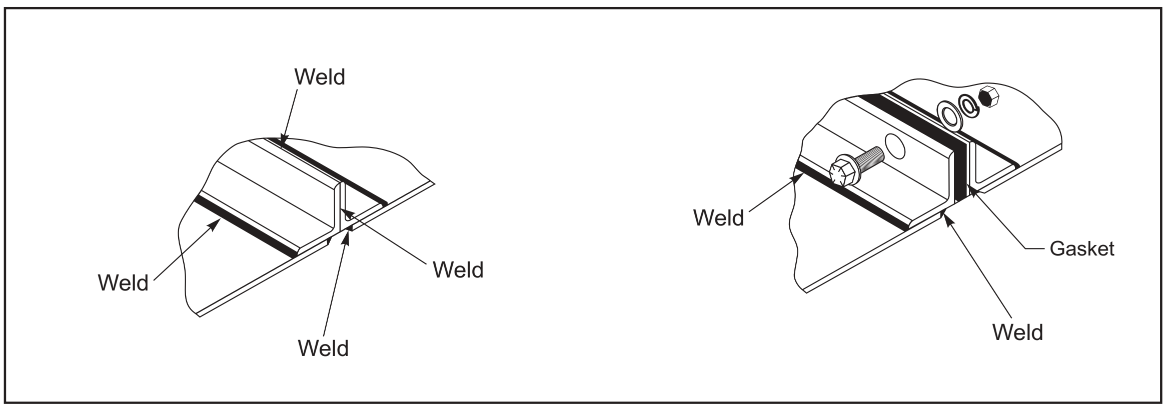


Figure 5.2 – Acceptable Transverse Joints

5.2.3 Engineering Analysis

When sheet-metal thickness and reinforcements are established from engineering analysis rather than from Tables 5.1 to 5.7, a design pressure of at least 1.25 times the normal operating pressure is necessary for level 1, 2, and 3 construction. A design pressure of 1.5 times the maximum negative pressure that can exist in the particular run of duct, under the most adverse conditions to which it can be subjected under any conceivable

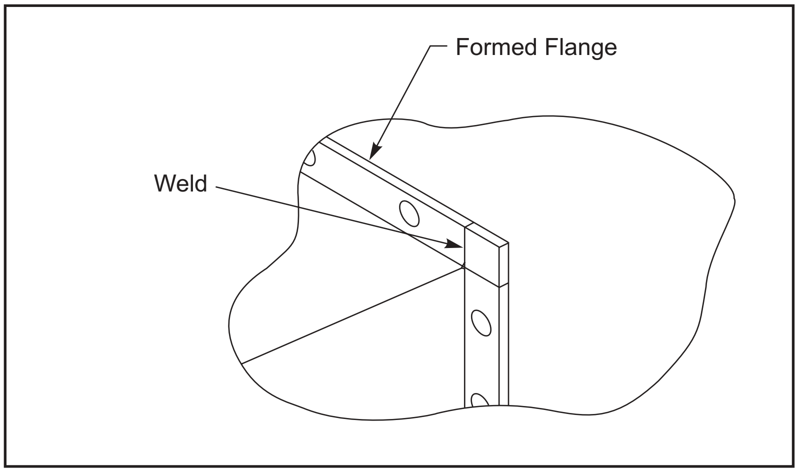


Figure 5.3 – Acceptable Formed Flange

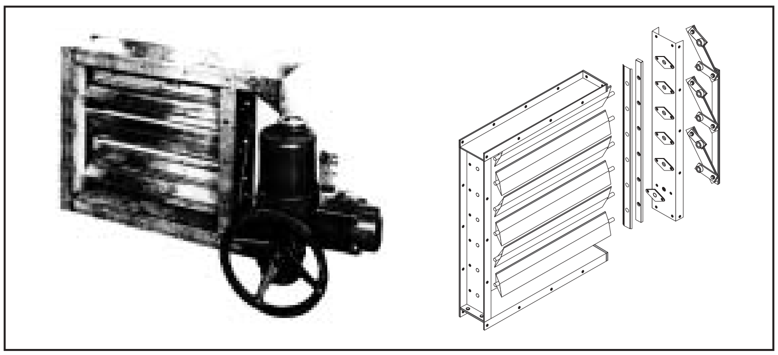


Figure 5.4 – Control Dampers

conditions, including the Design Basis Accident (DBA) and safe shutdown earthquake, is recommended. The maximum negative pressure is generally the fan shutoff pressure. In the engineering analysis, the following loadings should be considered as applicable to the particular system under consideration:

1. Differential pressure across the duct wall, as affected by maximum internal and external pressures that could prevail during testing and under normal and abnormal operating conditions, and any increase or decrease in the pressure due to inadvertent closure of a damper or plugging of an internal component. For ductwork located within the containment vessel of a reactor, the external pressure under DBA conditions, due to the lag of pressure rise within the ductwork during the pressure transient in the containment vessel, must also be considered (such overpressures may be alleviated through the use of pressure-relief dampers that discharge to the containment space).

2. Effects of natural phenomena, including tornado and earthquake, for safety class-ductwork.

3. Thermal expansion.

4. Weight of the ductwork, including all attachments.

5. Weight of personnel walking on large ductwork only. Where this situation is likely to occur, duct sections with exposed top surfaces should be capable of supporting a 250-pound weight concentrated midway between the hangers or reinforcement, without permanent deformation. The out-of-roundness produced by such loading could lead to a sudden collapse of round duct when operating under negative pressure.

   A maximum allowable stress of 0.7 times the elastic limit is recommended for the design of ductwork maximum deflections under normal operating conditions and should be:

   Rectangular duct: 0.125 inch per foot of maximum unsupported panel span in the direction of airflow, but not greater than 0.75 inches. Defection of reinforcement -0.125 inch per foot of span, but not more than 0.75 inches across total span.

   Round duct: 0.025 inch per foot of diameter, but not more than 0.5 inch at any point.

5.2.3 Engineered Ductwork

When sheet metal or piping thicknesses and reinforcement are established from analysis other than as required by ASME AG-1,[1] SMACNA standards,[7] or other referenced documents, the design should be in accordance with the criterion found in ASME AG-1, Sections AA and SA.[1] In the engineering analysis, the following are examples of loads that should be considered potentially applicable to the system under consideration:

- **Additional Dynamic Loads.** These loads result from system excitation caused by structural motion such as relief valve actuation and hydrodynamic loads due to design basis accidents (DBAs).
- **Constraint of Free End Displacement Loads.** These loads are caused by the constraint of free-end displacement and are caused by thermal or other displacements.
- **Dead Weight.** These loads are the weight of equipment and ductwork, including supports, stiffeners, insulation, internally mounted components, externally mounted components and accessories, and any contained fluids.
- **Design Pressure Differential.** These loads are dynamic pressures caused by the DBAs, and intermediate or small break accidents.
- **Design Wind.** These loads are produced by design hurricanes, tornadoes, or other abnormal, infrequently occurring meteorological conditions.
- **External Loads.** These are applied loads caused by piping, accessories, or other equipment.
- **Fluid Momentum Loads.** These are loads other than those previously listed, such as the momentum and pressure loads caused by fluid flow.
  - **Live Load (L).** Such loads occur during construction and maintenance and other loads due to snow, ponded water, and ice.
  - **Normal Loads (N).** These loads include normal operating pressure differential, system operating pressure transients, dead weight, external loads, and inertia loads.
  - **Normal Operating Pressure Differential (NOPD).** This is the maximum positive or negative pressure differential that may occur during normal system operation, including startup and testing. These include the pressures resulting from normal airflow and damper or valve closure.
  - **Seismic Load.** These loads result from the operating basis earthquake (OBE) or the safe shutdown earthquake (SSE). These seismic forces are applied in the direction that produces the worst-case stresses and deflections.
  - **System Operating Pressure Transient.** These overpressure transient loads are caused by events such as rapid damper or valve closure, rapid plenum or housing door closure, or other loads of this type that result in a short duration pressure differential (spike).

Additional information concerning the structural design and supports for ductwork and supports can be found in ASME AG-1, Section AA.[1]

5.2.4 Applicable Codes, Standards, and References

There are many codes, standards, and other references that are applicable to ductwork design. A complete, detailed listing is available in ASME AG-1, Sections AA and SA.[1]

5.2.5 Materials of Construction

Ductwork may be constructed from painted or coated carbon steel, galvanized steel, aluminum, stainless steel, or any combination of these materials as required to resist corrosion in the service environment. Glass-fiber-reinforced plastic (GFRP) and epoxy ducts have been used in corrosive environments where fire and safety requirements permit, and may be less expensive than stainless steel, lined carbon steel, or epoxy- or vinyl-coated carbon steel. Although the GFRP duct has been approved by the National Fire Protection Association and Underwriters Laboratories (UL) for commercial and industrial use, even high-temperature resins will soften under brief exposure to temperatures of 350 to 450 degrees Fahrenheit. Softening of the GFRP duct can lead to rapid collapse or distortion, followed by loss of air cleaning function. GFRP and other plastic ductwork should not be used for Level 3, 4, or 5 construction and should be used with caution for Levels 1 and 2.

5.2.6 Paints and Protective Coatings

Coating and paint requirements must be consistent with the corrosion that can be expected in the particular application and with the size of the duct. Corrosion- and radiation-resistant paints and coatings should, as a minimum, meet the requirements of ASME AG-1,[1] and ASTM D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*.[12] Unless special spray heads are used, spray coating of the interior of ducts smaller than 12 inches in diameter is often unreliable because it is difficult to obtain satisfactory coating and to inspect for defects. The interior of a duct sized 8 inches and smaller cannot be satisfactorily brush-painted; therefore, dip coating is recommended. Ducts to be brush-painted should be no longer than 5 or 6 feet to ensure proper coverage. When special coatings such as high-build vinyls and epoxies are specified, the designer must keep in mind that difficulties in surface preparation, application, and inspection may increase the cost of coated carbon steel to the point that stainless or galvanized steel may be more economical. In addition, stainless or galvanized steel may provide better protection. Note that high-build coatings and paints can be damaged during handling and shipping (as well as during construction, maintenance, repair, and testing/surveillance). Corrosion can begin under such damaged areas without the user's knowledge. Painted and coated ductwork must be inspected carefully during the painting (coating) operation, as well as on receipt. Galvanized coatings and plates should also be carefully inspected, particularly on sheared edges and welds.

5.2.7 Supports

Nonsafety class ductwork can be hung, supported, and anchored in accordance with the recommendations of Chapter 5 of the SMACNA *HVAC—Duct Design*,[7] with the following exception: anchors and attachments which rely on an interference-fit between, or deformation of, the base material (concrete roof deck, beam, etc.) and the attachment device (as is the case for power-actuated drive bolts and studs and for concrete anchors) should not be used for safety-related ductwork. Support requirements for safety class ducts and other ductwork that must remain in place in the event of an earthquake or major accident must be established by modeling or engineering analysis. Such analysis must be based on the inputs (forces, accelerations) to the building element to which the duct is fastened or from which it is hung (i.e., floor, wall, roof deck, etc.) that will be produced by the DBA or SSE, or both. Non-Engineered Safeguard Feature (ESF) ductwork located above or adjacent to other safety class equipment of the facility, which could damage such equipment if it fell, is also subject to this restriction.

5.2.8 Thermal Insulation and Acoustic Considerations

Acoustic linings and silencers are not permitted in safety-related ducts or ducts which carry, or may carry, moisture. Acoustic treatment, if required, must be attached to the exterior of the duct.

Thermal insulation, acoustic linings, and duct silencers are not permitted in ducts that carry or may carry moisture, corrosive fumes, or radioactive air or gas. Thermal insulation and acoustic treatment, if required, must be attached to the exterior of the duct and secured in such a manner that it cannot fall off during applicable DBAs.

5.2.9 Ductwork Leakage

The leaktightness of ductwork is extremely important, particularly in systems that carry or could potentially carry radioactive material. Duct leakage wastes power and thermal energy (the energy required to heat, cool, or dehumidify air), causes noise, prevents correct airflow to outlets from inlets, makes system balancing and temperature and humidity control difficult, and produces dirt collections and radioactive contamination at leakage sites.

Even one percent is excessive for systems that carry or could potentially carry intermediate- to high-level radioactivity. Leak rates based on the percentage of airflow are meaningless and are subject to misinterpretation. Duct tightness is generally tested by sealing off sections of the system and individually testing them by either the direct-measurement or pressure decay method of ASME N510.[10] With such procedures, a leakage criterion based simply on percentage of airflow can produce anomalous results. By such a criterion, two duct systems build to the same construction standards and having the same volume and surface area but different airflow rates could have widely differing permissible leakages. Conversely, if the airflow rates are the same but the volumes differ, they could have widely differing permissible leakages. For this reason, a permissible leakage based on duct volume or a permissible leakage based on the surface area of the pressure boundary of the section under test is recommended. Table 5.6 gives permissible leak rates for the various levels of construction, including the values that have been recommended over the years for nuclear grade ductwork. The values for levels 3, 4, and 5 ductwork are more stringent than those recommended for ductwork in nuclear power plants by ASME N509.[13]

In tests conducted at a DOE facility, sections of level 2 ductwork tested alternately at 2.5 in.wg positive and 2.5 in.wg negative by the pressure-decay method showed no pressure loss in 15 minutes under positive pressure, but a loss of 2 in.wg in 15 minutes under negative pressure. This tendency for the same ductwork to leak substantially more under negative pressure than under positive pressure is confirmed by SMACNA.[7] It is recommended that leak tests be made under negative pressure if possible and at the normal discharge pressure or suction pressure of the fan insofar as is practicable. These leak rates are predicated on the potential for outleakage of contamination to occupied areas of the facility should be ductwork or filter housing become pressurized under system upset conditions. Leak testing should be performed in accordance with the methods provided in ASME N509[13] and N510,[10] with additional requirements for safety-related systems contained in ASME AG-1, Section SA-5300, and Section TA.[1]

Vibration and Flexible Connections

Vibration and pulsation can be produced in an air or gas cleaning installation by turbulence generated in poorly designed ducts, transitions, dampers, and fan inlets, and by improperly installed or balanced fans and motors. Apart from discomfort to personnel, excessive vibration or pulsation can result in eventual mechanical damage to system components when vibrational forces become high or when acceleration forces (e.g., from an earthquake or tornado) coincide with the resonant frequencies of those components. Weld cracks in ducts, fan housings, and component mounting frames may be produced by even low-level local vibration if sustained, and vibrations or pulsations that produce no apparent short-term effects may cause serious damage after long duration.

Vibration produces noise that can range from unpleasant to intolerable. An important factor in preventing excessive vibration and noise is planning at the stage of initial building layout and space allocation to ensure adequate space is provided for good aerodynamic design of ductwork and fan connections. Spatial conflicts with the process and with piping, electrical, and architectural requirements should also be resolved during early design so that the compromises that are so often made during construction, which often lead to poor duct layout and resulting noise and vibration, can be avoided. Ducts should be sized to avoid excessive velocities while maintaining the necessary transport velocities to prevent the settling out of particulate matter during operation.

Fan vibration can be minimized via vibration isolators and inertial mountings. It should be noted that use of these devices must be carefully coordinated with the structural designers because seismic design requirements sometimes prohibit their use. Some structural designers require hard-mounting of fans where continued operation during and after an earthquake must be considered.

To minimize transmission of vibration from fans, flexible connections between fans and ductwork are often employed and recommended. These must be designed to resist the high static pressures often incurred in HVAC systems, particularly in those parts of the system under negative pressure, e.g., near the inlet of large exhaust fans. In addition, consideration must be given to the leakage and potential failure that can occur with flexible connections. Commercial applications commonly use heavy-duty canvas. Canvas is not suitable for nuclear facility applications. Consideration should be given to using at least two layers of a leak-proof material (e.g., rubber or neoprene, sometimes reinforced with higher-strength materials such as fiberglass and Kevlar®).

Finally, the ductwork system must be balanced after installation, not only to ensure the desired airflows and resistances, but also to "tune out" any objectionable noise or vibration that may be inadvertently introduced during construction. DOE nuclear facilities should adopt and apply the concepts and practices of predictive maintenance. DOE Order 433.1[14] requires all DOE contractors to institute a predictive maintenance program.

5.3 Dampers and Louvers

5.3.1 Damper Descriptions

By definition, a damper is a device used to control pressure, flow, or flow direction in an air or gas system. See ASME N509[13] and AG-1, Section DA.[1] Different types of dampers can be used, depending on specific functional requirements. **Table 5.7** lists the types of dampers and their functions, and **Table 5.8** lists the damper configurations. **Figures 5.5, 5.6, and 5.7** are examples of industrial-quality dampers. Selection of the proper damper type and blade configuration is important to achieve the required damper performance. The type and configuration of damper can significantly impact pressure drop, leakage rates, and controllability.

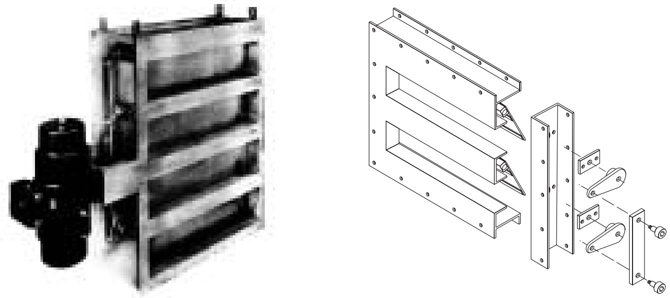
Table 5.7 – Classification of Dampers by Function

Designation	Function
Flow control damper	A damper that can be continuously modulated to vary or maintain a given level of airflow in the system in response to a feedback signal from the system, or from a signal fed to the damper operator via a manually actuated control or switch.
Pressure control damper	A damper that can be continuously modulated to vary or maintain a given pressure or pressure differential in the air cleaning system or in a building space served by the system in response to a pressure signal.
Balancing damper	A damper set (usually manually) in a fixed position to establish a baseline flow or pressure relationship in the air cleaning system or in building spaces served by the system.
Shutoff damper	A damper that can be completely closed to stop airflow through some portion of the system, or opened partially or fully to permit airflow (the flow control damper may also serve this function).
Isolation damper	A high-integrity shutoff damper used to completely isolate a portion of a system from a contained space, or from the remainder of the system with a leaktight seal. In the case of confinement isolation, butterfly valves are used in lieu of dampers.
Back-draft or check damper	A damper that closes automatically or in response to a signal to prevent flow reversal.
Pressure-relief damper	A damper that is normally closed, but will open in response to overpressure in the system or in the contained space served by the system to prevent damage to the system.
Fire and smoke damper	A damper that interrupts airflow automatically in the event of fire or smoke so as to restrict the passage of flame or smoke through the air system, in order to maintain the integrity of the fire-rated partition or other fire-rated separation.
Tornado damper	A damper that controls airflow automatically to prevent the transmission of tornado pressure surges.

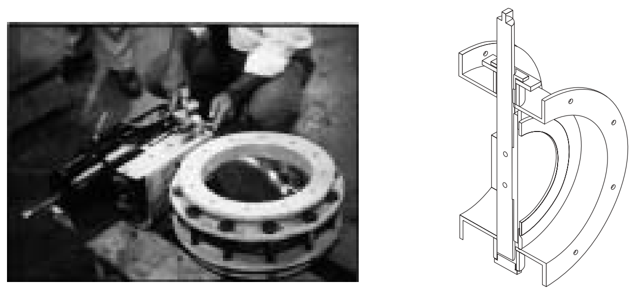
Table 5.8 – Classification of Dampers by Configuration

Designation	Configuration
Parallel blade damper	A multi-blade damper with blades that rotate in the same direction (AMCA 500).[a]
Opposed blade damper	A multi-blade damper having adjacent blades that rotate in opposite directions (AMCA 500).[a]
Butterfly damper	A heavily constructed damper, often a valve, that is used in piping or duct systems and is usually round in cross-section and designed for high-pressure service (25 psi minimum pressure rating), with one centrally pivoted blade that can be sealed.
Single-blade balanced damper	A damper, usually round in cross-section, with one centrally pivoted blade.
Single-blade unbalanced damper	An accurately fabricated, often counterbalanced damper, usually rectangular in cross-section, with one eccentrically pivoted or edge-pivoted blade.
Folding blade, wing blade, or check damper	A damper with two blades pivoted from opposite sides of a central post that open in the direction of airflow.
Poppet damper	A weight or spring-loaded poppet device that opens when the pressure differential across it exceeds a predetermined value.
Slide or gate damper	A damper similar to a gate valve, with a single blade that can be retracted into a housing at the side of the damper to partially or fully open the damper.

[a] AMCA 500-D-1998, *Laboratory Methods of Testing Dampers for Rating,* Air Moving and Conditioning Association, Arlington Heights, IL, 1998.[15] Also AMCA 500-L-1999, *Laboratory Methods of Testing Louvers for Rating,* Air Moving and Conditioning Association, Arlington Heights, IL.[15]



(a) Bubbletight Dampers (rectangular)



(b) Bubbletight Dampers (round)

Figure 5.5 – Bubbletight Dampers

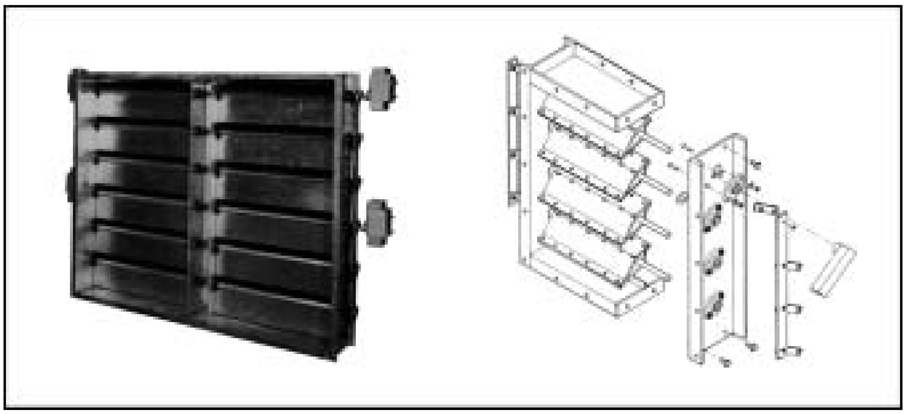


Figure 5.6 – Backdraft Dampers

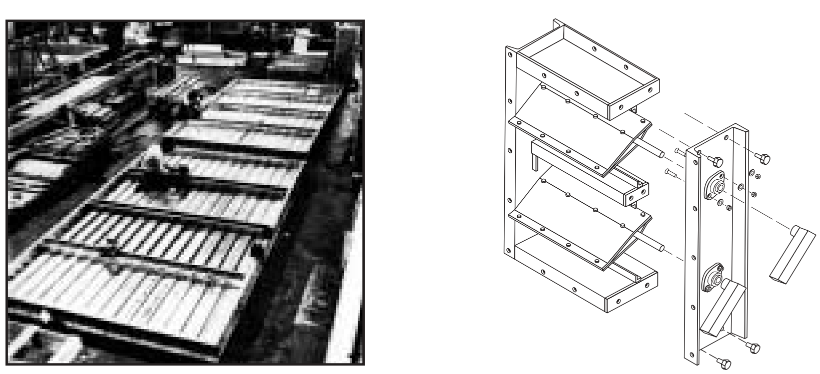


Figure 5.7 – Tornado Dampers

The following factors must be considered in the selection or design of dampers for nuclear applications:

- Damper function,
- Construction type,
- Dimensions and space limitations,
- Pressure drop for open position and across closed damper,
- Normal blade operating position,
- Method of mounting damper,
- Blade orientation relative to damper frame,
- Operator type and power source,
- Seismic requirements,
- Requirements for position indicator,
- Limit switches and other appurtenances,
- Damper configuration,
- Permissible leakage through closed damper,
- Space required for service,
- Airstream environmental parameters (temperature, pressure, relative humidity, etc.),
- Damper orientation in duct,
- Airflow direction and velocity,
- Failure of mode and blade position,
- Maximum closing and opening times, and
- Shaft sealing method.

5.3.2 Design and Fabrication

In conventional air conditioning and ventilating applications, damper procurement has been generally accomplished by specifying little more than the manufacturer's make and model number or “approved equal.” This is inadequate for nuclear and other potentially high-risk applications. Dampers for nuclear applications should be designed and constructed in accordance with ASME AG-1, Section DA.[1]

Clear, concise specifications must be established for mechanical strength, for leakage rate at maximum (i.e., DBA) operating conditions, and for performance under required operational and emergency conditions. The operability of linkages must be assured through specification of, and requirement for, cycling at minimum torque requirements under full load. Static testing of the closed damper should be required, where applicable, for those to be used in critical applications to verify strength and leaktightness. All features important to proper operation should be stipulated in detail, including construction materials, permissible lubricants, bearings, blade design and edgings (if permitted), indicating and locking quadrants, supports, operator type and capability, and the accessibility of operators, linkages, blades, and bearings for maintenance. A checklist of the minimum requirements that must be included in a damper design specification is given in ASME AG-1, Section DA.[1]

5.3.2.1 Structural Design

Previous editions of this handbook categorized dampers by construction type. Present construction criteria specified in Section DA of ASME AG-1[1] are categorized by performance requirements (seat or frame leakage, application, function, and loading combinations), as discussed in Section 5.3.3.

The structural design of dampers should be in accordance with Sections AA and DA of ASME AG-1[1] for the loading combinations and the service levels specified in the design specifications. The design should be verified by analysis, testing, or a combination of both for those dampers that must remain functional or retain their structural integrity during a design basis earthquake (DBE).

5.3.2.2 Design and Construction Considerations

A very important part of damper design is determination of damper torque and sizing and selection of damper actuator for the maximum torque. Actuator torque should be selected for a minimum of 1.5 times the damper maximum torque to provide margin and allow for degradation over the life of the damper. Actuators should be evaluated for damper blade movement in both directions, at the beginning of blade movement, and while stroking blades through the full cycle of movement.

The linkage mechanism must be designed to transmit actuator torque for the blades to achieve required leakage performance. Ganging of more than two damper sections for operation by one actuator is not recommended because of the potential problems in transmitting the torque equally to each section and blade. Experience has shown that ganging multiple damper sections has led to twisting of drive shafts and overtorquing of the blades closest to the actuator.

Conversely, ganging two or more actuators per damper can also cause operating problems if the actuators are not synchronized. Some blades may close tighter than others, since not all of the blades are linked together. Damper actuators should be factory-mounted whenever possible. Wherever actuators must be installed in the field or removed for maintenance, manufacturer's installation instructions should identify the necessary amount of retorquing required to achieve design leakage. The actuator shaft, coupling, and blade shaft should be “match-marked” for easy installation.

Seals are another important component of damper design. Dampers designed for low leakage rely heavily on blade and jamb seals to limit leakage. Seals typically are either metal (e.g., stainless steel) or elastomer. Design of seals should consider the required life of the damper assembly to minimize maintenance. For this reason, stainless steel seals are recommended for low leakage dampers in contaminated airstreams whenever possible (see Section DA of ASME AG-1).[1] To control frame leakage, either stuffing boxes or frame cover plates are required.

5.3.2.3 Damper Operators

Damper operators can be one of three types: pneumatic, electric, or electrohydraulic, as described below.

Pneumatic. These damper operators are used whenever controls rely primarily on compressed air (pneumatic) for moving operators or transmitting control signals. Most nuclear facilities only use pneumatic control systems and operators for nonsafety-related applications, as the control air is not usually an assured source during DBAs.

Electric. These damper operators are used whenever controls rely primarily on low voltage electric circuits to transmit control signals and are usually two-position. That is, they are either open or shut and cannot modulate. Most nuclear facilities use electric control systems and operators for safety-related applications because power can be obtained from the emergency electric power and control system.

Electrohydraulic. These damper operators are the same as the electric type described above, except they have the ability to modulate. Experience has shown that these operators require significant maintenance to keep them functional. They use an electric control signal to position a hydraulic system that, in turn, positions the damper.

5.3.2.4 Limit Switches

Limit switches are usually provided directly on the damper to detect the open and closed position of the damper blade. The switches are housed in enclosures defined by National Electrical Manufacturers Association, NEMA 250.[16] The contact rating must be properly selected for the electrical load. The force required to operate the limit switches must be considered to properly size the damper actuator.

5.3.3 Performance Requirements

The dampers for nuclear air cleaning systems must be designed to meet the following required performance requirements:

- Seat leakage,
- Frame leakage,
- Pressure drop,
- Closure (or opening) time, and
- Fire rating and closure.

Seat and frame leakage must be in accordance with ASME AG-1, Section DA,[1] for Leakage Class I (low leakage), II (moderate leakage), III (normal leakage), and IV (applications where leakage is of no consideration). Seat leakage class should be determined by the engineer based on radiological and health physics analysis and known or estimated airborne concentrations within the duct system. Frame leakage is also based on radiological assessments of the effect of airborne concentrations inside and outside the ductwork, as well as the system configuration. For further guidance on leak class determination, refer to ASME AG-1 Code, Section DA.[1]

Pressure drop of the damper has an important impact on proper system operation. Dampers with high-pressure drop, especially for counterbalanced pressure relief dampers, may restrict airflow and affect space pressurization. The pressure drop characteristics of dampers as a function of airflow rate or velocity indicates the ability of each particular type of damper to control airflow. Preferably, the pressure drop/airflow characteristic should be as close to linear as possible to achieve controllability. Opposed blade damper pressure drop characteristics make this type of damper well suited for flow or pressure control compared to parallel blade or butterfly dampers.

For fire dampers installed within duct systems where the airflow normally flows continuously and the damper must isolate portions of the duct system in case of fire, the damper must be designed for closure under airflow. This requirement has caused difficulties with past damper construction. Recent tests have shown that different manufacturers' dampers react differently based on their particular design. Some dampers are sensitive to air velocity, such as the shutoff dampers shown in **Figure 5.8**. **Figure 5.9** shows dampers with actuator options. These dampers are more sensitive to duct pressure upstream of the damper when they are closing.

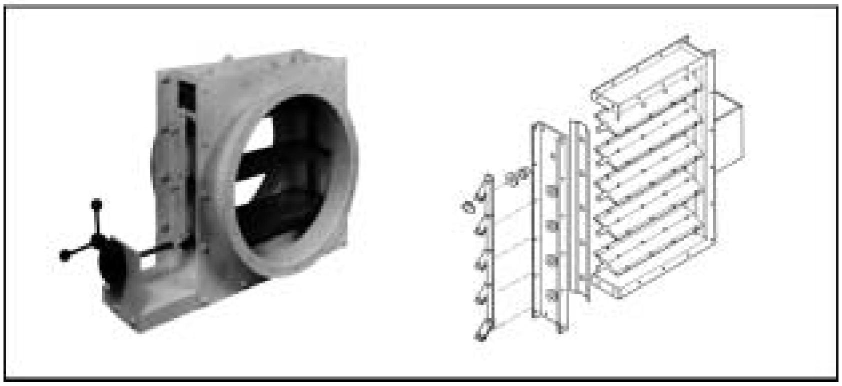


Figure 5.8 – Shutoff Dampers

5.3.4 Qualification Testing

Qualification consists of performing prototype or preproduction-model tests to verify the design, performance, and operational characteristics of the dampers. In the case of the Air Moving and Conditioning Association (AMCA)-rated dampers, these tests essentially consist of pressure drop and airflow determinations at various degrees of blade opening. The AMCA rating is generally considered sufficient evidence that suitable qualification tests have been performed. For dampers not listed by AMCA, the manufacturer should be required to provide performance data obtained under conditions equivalent to those used in the AMCA 500-D[15] test standard. One particularly important piece of information that can be obtained by qualification testing is the resistance of the fully open damper and the resistance versus blade-position curve from full open to full closed. Resistance must be included in the air cleaning system design calculations in the same manner as other system resistance. Qualification tests must be performed prior to fabrication and, if possible, prior to award of a contract.

Production units should be subjected to acceptance tests to verify that the units are in good operating condition and to document their ability to meet performance requirements such as leakage and closure time. Repetition of other qualification tests to demonstrate operational characteristics is generally unnecessary and unwarranted. Dampers should be cycled through the full range at least 10 times, with all accessories attached, to verify the free and correct operation of all parts and the correct adjustment, positioning, and seating of the blades. Maximum time for operation of any of the cycles should be not more than the specified cycle time. Limit switches, if used, should be checked for proper operation. Adjustments should be made as necessary during the test to correct deficiencies. Shop leakage tests for seat and frame leakage should be performed when applicable. Seat leakage testing should be performed after cycle testing is completed. Tests should be

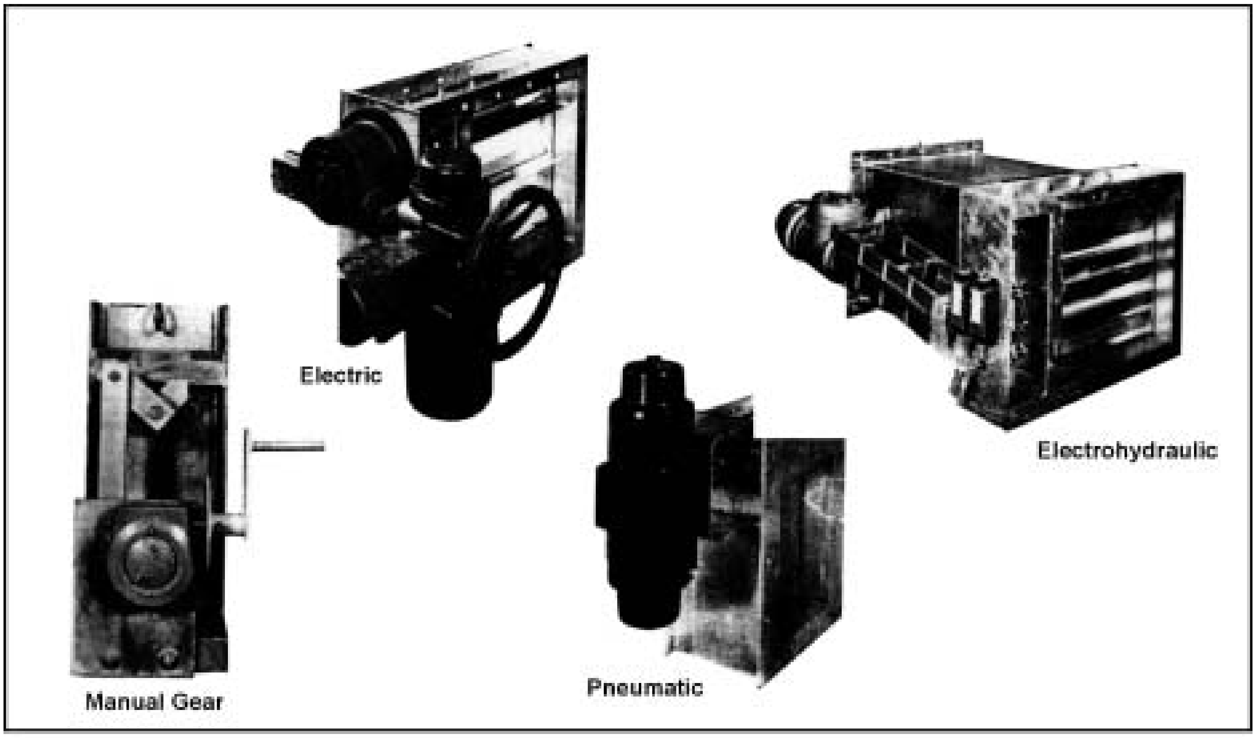


Figure 5.9 – Actuator Options

performed in accordance with ASME AG-1, Section DA[1]. Because damper operators are generally furnished to the damper manufacturer as a purchased item, a test to verify the torque characteristics of the operator is desirable after installation of the damper in its service position, particularly for control, shutoff, and isolation dampers for all safety-related dampers.

Fire dampers must be qualified for closure under airflow by testing in accordance with AMCA 500-D[15] for both plenum-mounted and duct-mounted configurations. The damper must close completely at maximum airflow rate for various sizes of dampers and for maximum static pressure. Fire and smoke dampers must be tested in accordance with UL-555[17] and UL-555S,[18] respectively, when dampers are required in fire- or smoke-rated barriers.

5.3.5 Louvers

The function of louvers is to keep rain, snow, and trash from being drawn into outside air intakes of air handling systems. They can be either fixed-blade or movable-blade design. The vast majority of louvers are of the fixed-blade type. If shutoff or modulation of the airstream is necessary, dampers can be used downstream of the louvers. If operable louvers are used and shutoff or modulation is required, then an operator is required (see Section 5.3.2). Architects usually are consulted when specifying louvers because the louvers are located on outside walls or roofs and should blend in with the architectural features of the structure.

It is important to account for the size of the area that the louver blades take up when sizing the louvers. Blades typically take up 50 percent or more of the free area that affects the velocity of the air entering the intake. The usual maximum velocity to prevent water and snow entrainment in the airstream is less than 500 fpm. Therefore, if 1000 cfm of air is being drawn into an intake and the louvers take up 50 percent of the free area, then the square footage of the opening required is:

$$1000\ \text{ft}^3/\text{min} \times 1/500\ \text{ft}/\text{min} \times 2 = 4.0\ \text{ft}^2 \text{ opening required}$$

In addition to the free area and velocity considerations, the pressure drop of the intake louvers must be included in the system pressure drop calculations.

For louvers on exhaust openings, the velocity is not usually a primary concern, with the exception that the higher the velocity, the higher the pressure drop that has to be accounted for in the system pressure drop calculations.

Finally, louvers must meet the same structural requirements as the rest of the air cleaning system. That is, they must meet the seismic loading requirements if they are required to function during and after a DBA. Louver testing must conform to AMCA 500-L.[15]

5.4 Fans and Motors

The selection of fans and motors for air treatment systems is a very important part of the design of the systems. An air cleaning unit may be properly designed and arranged, the duct system may be nearly leak-free, dampers may be properly constructed, and controls may be functioning correctly, but if the fan is not sized and selected properly, then the system will not perform its design function. For example, the system resistance must be correctly calculated, the effect of parallel or series fans must not result in surging, and the fan must be selected for the applicable range of airflow and pressure. ASME AG-1, Section BA,[1] contains a list of the design parameters necessary to properly specify and/or select a fan and motor.

For types of fans commonly used in air cleaning systems, refer to ASME AG-1.[1] Guidance on proper fan sizing, fan arrangement, connection to duct systems, leakage, mounting, and qualification testing is briefly discussed below. All of these factors must be considered when designing, selecting, and installing these fans. A synopsis of these factors and determinations are presented below. Actual determinations would require the use of the documents referenced.

5.4.1 Fan Types and Applications

Fan types can be classified as centrifugal, vaneaxial, and high-pressure blowers. Centrifugal fans can be further classified by blade type as airfoil, forward curve, radial, and backward inclined/backward curved. Vaneaxial fans can be classified as either fixed or adjustable pitch. All fans can be furnished as either direct or belt drive. Note that, for nuclear power plant applications, fans located inside the confinement are usually direct drive to minimize the maintenance and adjustments associated with belt drives (because confinement entry is limited).

High-pressure blowers may be required when airflow rates are low (10,000 cfm or less) and pressure is high (10 to 15 in.wg). This may dictate a radial-bladed centrifugal fan selection.

Vaneaxial fans are typically used in larger built-up systems when the fan is located as part of the duct system rather than part of the filter housing. Vaneaxial fans are best suited for airflow rates greater than 30,000 cfm and pressures less than 10 in.wg. Whenever possible, vaneaxial fans should be located downstream of filter units because the fan motor is in the airstream.

Fans should be selected such that fan power requirements are nonoverloading (i.e., the fan brake horse power does not increase with increasing airflow) unless provisions are made to prevent overloading the motor (e.g., airflow control and high limit trip). Radial-bladed and forward-curved centrifugal fan power increases with increasing airflow.

Belt drives should be used only in areas that are accessible for maintenance during normal and accident conditions. Multiple belts should be provided so that loss of one belt does not impair system function. For constant flow systems, variable pitch sheaves should be changed to fixed pitch sheaves after air balancing. Belt driven fans that must operate during and after dynamic events (e.g., seismic events) should be qualified for operation by testing.

Fans for general heating, ventilating, and air conditioning (HVAC) duty (e.g., air supply systems and small exhaust systems), are selected using the guidance for such systems found in sources such as the ASHRAE *HVAC Applications Handbook*,[19] the ASHRAE *Systems and Equipment Handbook*.[2] These systems can range in size from a few hundred cfm to over 100,000 cfm, and are usually low-pressure systems (less than 5 in.wg).

5.4.2 Fan Performance

5.4.2.1 Fan Sizing

Pressure Drop Determination

Much has been done in the HVAC industry to improve the analysis of system resistance. The ASHRAE *Handbook of Fundamentals*[3] has expanded what used to be one table of fitting loss coefficients to more than 30 pages of fitting data. ASHRAE discusses methods for designing industrial exhaust systems and balancing branch duct resistance either by utilizing balancing dampers or by sizing ductwork. For systems handling highly radioactive particulate, self-balancing is recommended to eliminate particulate accumulation in the duct system. This recommendation must be considered against the potential for changes to duct runs during installation.

Use of the calculation method presented in the ASHRAE *Handbook of Fundamentals*,[3] Chapter 34, is recommended to determine fan pressure requirements. Acceptable methods are equal friction, static regain, and T-Method optimization. A total pressure grade line, summarizing the branch and main duct pressure drop, should be prepared for each fan system to analyze the system total pressure at various points. This grade line is also useful for reviewing or establishing the duct design (static) pressure (total pressure – velocity pressure in duct fitting).

If the fitting design does not match one of those in Chapter 34 of the ASHRAE *Handbook of Fundamentals*,[3] another useful reference is the ASHRAE *Duct Fitting Database*.[20] This is an interactive computer file on a 3.5-inch diskette containing loss coefficient tables for 228 fittings.

Sufficient margin should be included to cover the potential field modifications that may be necessary during initial installation, as well as any modifications that may be necessary throughout the life of the facility (see the following section on “System Effect Factors”).

Equipment (coils, dampers, filters, air diffusion equipment, etc.) resistance must be included in the pressure drop calculations. Whenever possible, calculations should be based on actual purchased equipment and, where possible, tested components. Preliminary calculations should be prepared with estimated pressure drop values and updated with final values.

System Effect Factors

The inability of fans to perform in the field in accordance with published ratings has long troubled the industry. This problem arises partly because the ratings are based on idealized laboratory conditions that are rarely encountered in the field, and partly because of design and/or field compromises that are made to accommodate the field situation. Many fan operation problems stem from poorly designed connections to the duct. Close-coupling, “too short” transitions between unmatched (in size) duct and fan inlets, square-to-round connections, and poorly designed inlet boxes create a vertical or eccentric flow into the fan impeller, resulting in noise, vibration, and reduced efficiency. A 45-degree spin in the direction opposite fan rotation can reduce fan delivery by as much as 25 percent and require a compensating increase in fan pressure of 50 to 55 percent. **Figure 5.10** shows the effects of various inlet conditions on fan performance and the resulting increase in fan capability (fan static pressure) to compensate for these effects. Too often, these effects are not considered when calculating fan requirements, with the result that neither the fan nor the filters can perform to the desired design levels. Outlet connections also affect fan performance, as indicated in **Figure 5.11**.

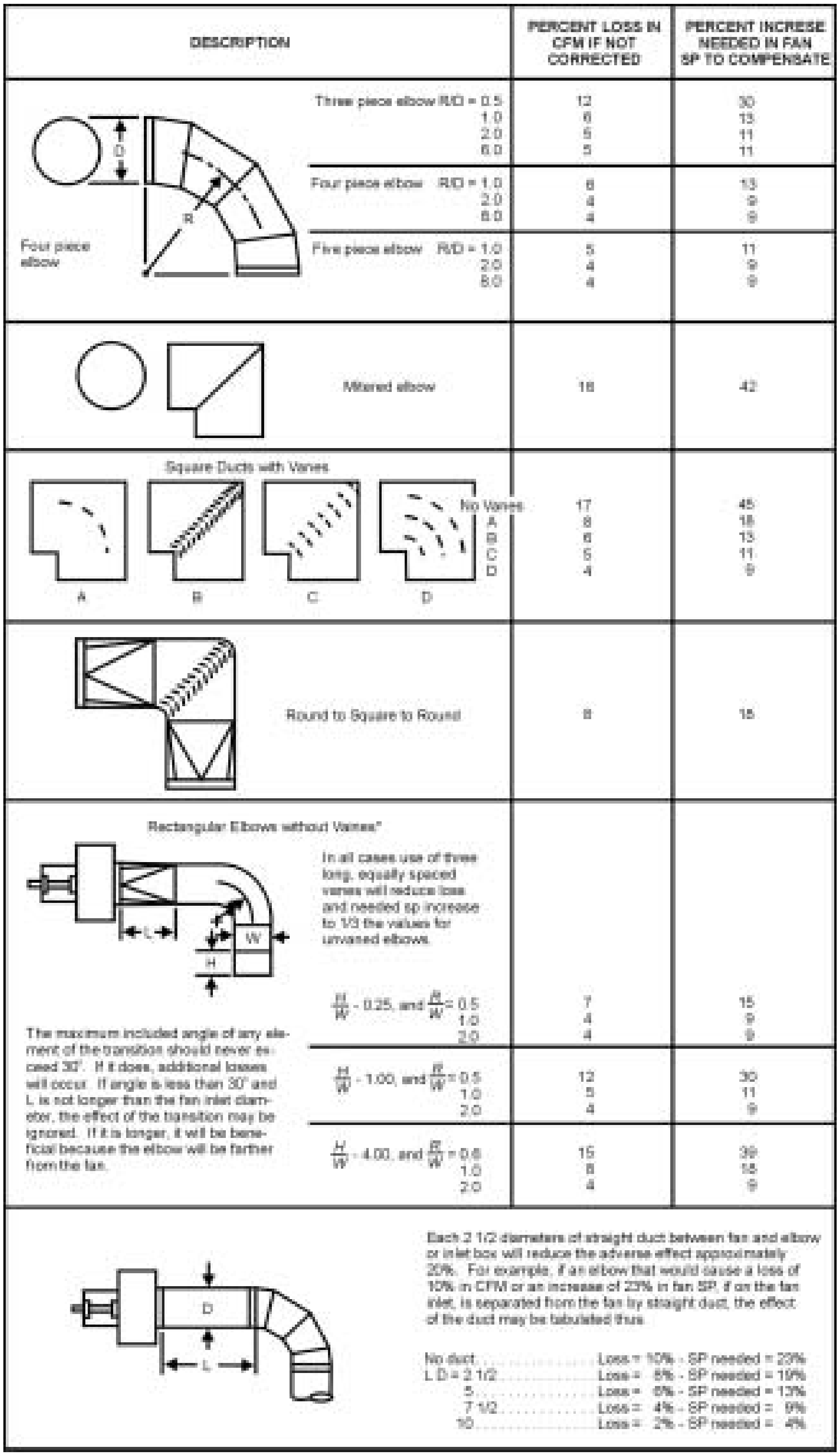
Note: For further details about system effects curves, refer to AMCA, *Fans and Systems*, 1990, AMCA 201[21] or the fan manufacturers' data. It is extremely important that the system effects be considered for any enclosed fan. Fan performance published in catalogues is based on free-standing test data that does not consider system effects and cannot be considered for system performance.

To alleviate the situation, AMCA has published a *Fan Application Manual*,[22] Part 2 of which includes a set of "system effect curves" which the designer can use to predict the effects of design features (such as the inlet and outlet conditions illustrated in Figure 5.11) on fan performance and, when needed, to allow for them in initial fan selection. System effects are the losses in fan performance that result from the fan being installed in a less than ideal configuration. These effects must be considered by the designer to obtain a realistic estimate of fan performance under "real life" conditions. **Figure 5.12** illustrates a deficient fan-system interaction resulting from one or more undesirable design conditions. It is assumed that pressure losses in the duct system were accurately estimated (point 1, curve A), and a suitable fan, based on published ratings, was selected for operation at that point. However, no allowance was made for the effect of the fan connections on fan performance (i.e., the interaction between the fan and the system as designed). To compensate for the system effect (capacity loss resulting from unfavorable interaction between the fan and its connections), a system effect factor must be added to the calculated system pressure losses to determine the actual system characteristic curve. It will then be possible to select the fan required to produce the required operating characteristics.

Testing to establish the capability of the fan in a nuclear air cleaning system, as originally installed, is recommended by ASME AG-1, Section TA.[1] Part 4 of the AMCA *Fan Application Manual* [22] provides guidelines for such testing, including examples of the application of system effect factors for various system configurations. Planes of measurement, measurements to be made, average test readings, calculation of test results, and corrections to overcome deficiencies disclosed by the tests are all covered in detail. It is preferable to apply such system effect factors before selection, purchase, and installation of a fan to prevent the incorporation of unfavorable features into the system design. In applying system effect factors, it must be recognized that those factors given in the AMCA manual are only guidelines and general approximations, although many have been obtained from research studies. Fans of different types and fans of the same type that are made by different manufacturers will not necessarily interact with the system in exactly the same way. It is necessary, therefore, to apply judgment based on experience using system effect factors.

5.4.2.2 Fan and System Curves

A major requirement for a fan operating in a high-efficiency air cleaning system is its ability to perform safely and efficiently over a much larger variation of resistance than more conventional ventilation systems. This variation of resistance is caused by dust loading of the HEPA filters and may double from the time of filter installation to the time of filter change, or may increase as much as five times in some systems (see the discussion of particulate filter change frequency in Chapter 2). The increase in resistance across the HEPA filters is usually the major factor influencing the pressure flow relationships of high-efficiency air cleaning systems. Fan performance (airflow versus pressure capability) and system resistance versus airflow are represented by characteristic curves such as curves A, B, and C of Figure 5.12. The volume of air that can be delivered by the fan is determined by the intersection of the fan and system characteristic curves. The flow represented by this point of intersection is the only flow that can be delivered by the fan under the given operating conditions. In most cases, a fan with a steeply rising characteristic (curve A, Figure 5.12) is



DESCRIPTION	PERCENT LOSS IN CFM IF NOT CORRECTED	PERCENT INCRESE NEEDED IN FAN SP TO COMPENSATE
Four piece elbow; Three piece elbow R/D = 0.5	12	30
1.0	6	13
2.0	5	11
6.0	5	11
Four piece elbow R/D = 1.0	6	13
2.0	4	9
6.0	4	9
Five piece elbow R/D = 1.0	5	11
2.0	4	9
6.0	4	9
Mitered elbow	16	42
Square Ducts with Vanes: No Vanes	17	45
A	8	18
B	6	13
C	5	11
D	4	9
Round to Square to Round	8	18
Rectangular Elbows without Vanes*: $\frac{H}{W}$ - 0.25, and $\frac{R}{W}$ = 0.5	7	15
1.0	4	9
2.0	4	9
$\frac{H}{W}$ - 1.00, and $\frac{R}{W}$ = 0.5	12	30
1.0	5	11
2.0	4	9
$\frac{H}{W}$ - 4.00, and $\frac{R}{W}$ = 0.6	15	39
1.0	8	18
2.0	4	9

In all cases use of three long, equally spaced vanes will reduce loss and needed sp increase to 1/3 the values for unvaned elbows.

The maximum included angle of any element of the transition should never exceed 30°. If it does, additional losses will occur. If angle is less than 30° and L is not longer than the fan inlet diameter, the effect of the transition may be ignored. If it is longer, it will be beneficial because the elbow will be farther from the fan.

Each 2 1/2 diameters of straight duct between fan and elbow or inlet box will reduce the adverse effect approximately 20%. For example, if an elbow that would cause a loss of 10% in CFM or an increase of 23% in fan SP, if on the fan inlet, is separated from the fan by straight duct, the effect of the duct may be tabulated thus:

No duct	Loss = 10% - SP needed = 23%
L D = 2 1/2	Loss = 8% - SP needed = 19%
5	Loss = 6% - SP needed = 13%
7 1/2	Loss = 4% - SP needed = 9%
10	Loss = 2% - SP needed = 4%

Figure 5.10 – Effect of Fan Inlet on Performance

desirable to maintain reasonably constant airflow in the system over the entire life of the HEPA filters. If a fan with a broad, flat characteristic is chosen, it will be less capable of delivering the required airflow as the filters become dust-loaded (curve 1 to curve 2), and either system performance (i.e., airflow) or filter life will

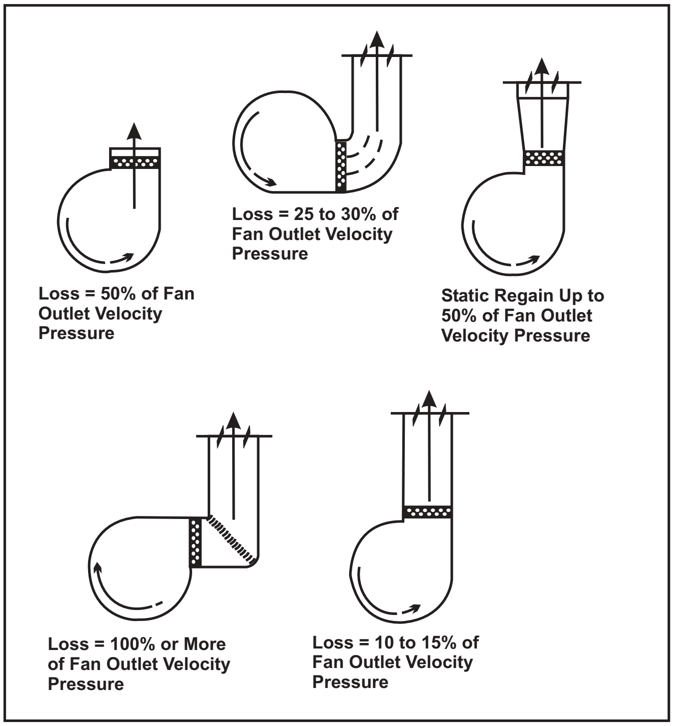


Figure 5.11 – Effect of Fan Outlet Connection on Fan Performance

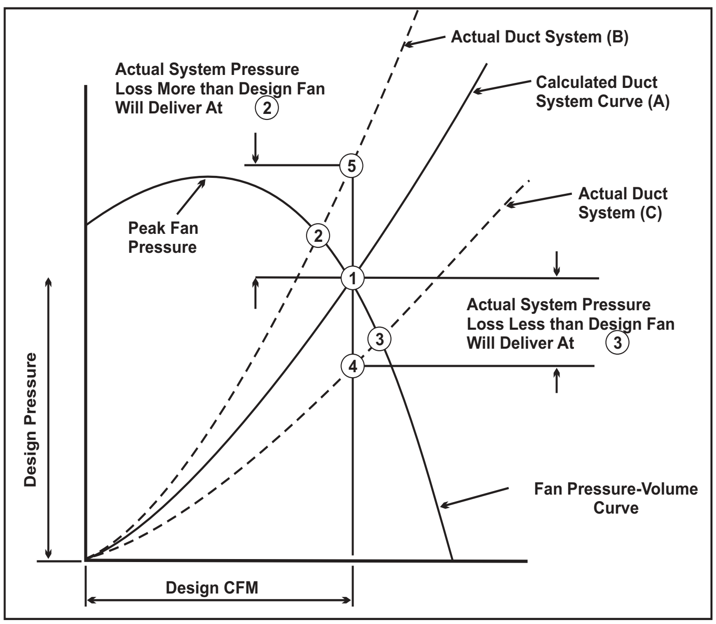


Figure 5.12 – Duct System Curve Not at Design Point

have to be sacrificed. Any decrease in filter life will, of course, be accompanied by higher change frequency and corresponding increases in operating and maintenance costs. If a pressure-equalizing device (damper) is installed to balance system pressure against filter pressure drop in order to maintain a constant pressure-airflow relationship in the system, a penalty in operating (power) costs will result.

5.4.2.3 Fan Leakage

Flexible Connection Leakage

Vibration created by fans, motors, and drives can be isolated by using flexible connections between the fan and ductwork on both the fan discharge and suction. Where such connections are used, a frequent problem has been tearing and pulling-out of the fabric (from which the flexible connection is made) at the connector clamp and an associated increase in leakage. The flexible connection design shown in **Figure 5.13** can overcome these problems. The fabric shown consists of two layers of 30-ounce neoprene-impregnated fiberglass cloth, lapped so that the ends are displaced from one another, and glued. Flexible materials reinforced with fiberglass or other products are also available. Flexible connections should be periodically inspected (visually) to ensure the connection is intact (no tears or holes). Eliminating leakage at the flexible connection is important to the effective operation of the unit. With the fan located properly with respect to the contamination concentration, the leakage on the suction side should not impact personnel dose, but could impact system effectiveness by reducing the flow rate of the discharge leakage through the connection at the point of contamination. This could affect the local derived air concentration (DAC) levels, depending on the relative concentration between the space and the duct.

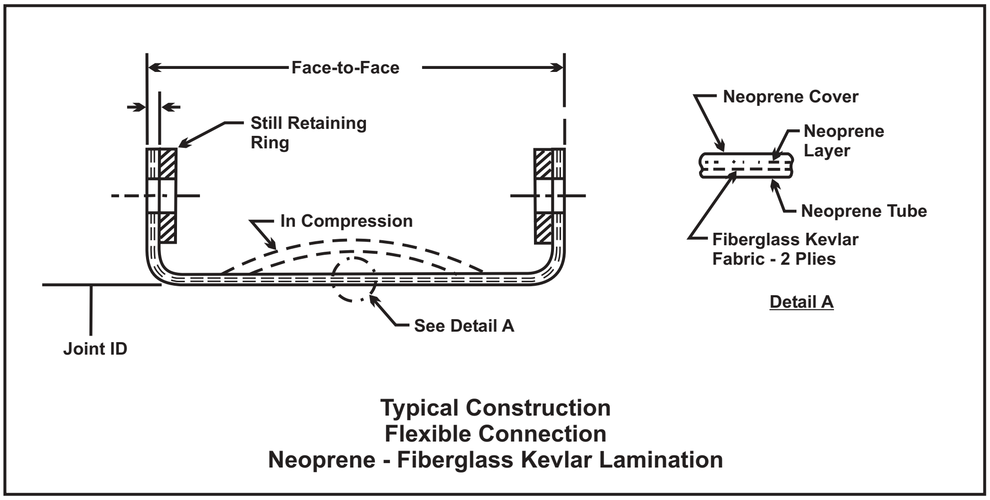


Figure 5.13 – Flexible Connection Design

Flexible connections should be qualified for the temperature, pressure, RH, and contaminants that will be encountered. However, since the flexible connections are exposed to continuous stresses due to airflow turbulence and fan vibration, the flex connections should be replaced frequently throughout the life of the plant. A maintenance frequency should be planned based on the results of the periodic surveillance inspections for each specific fan.

Shaft Leakage

Fan shaft penetration of fan housings should be designed to minimize leakage. When the fan is located properly so that leakage does not impose a contamination burden on the space, or the fan is located in the space supplied by air from the fan, then no special sealing is required. However, if there is a potential for a significant increase of DAC levels or a significant impact on airflow rate from the space the air is being induced from, then shaft seals should be installed. Shaft seals should limit leakage to 0.01 percent of design airflow rate per inch of fan operating pressure or 0.5 cfm, whichever is greater.[1] The safety analyses should be consulted for allowable leakage for safety class designs, especially for systems with multiple HEPA filter banks. If the fans are located downstream of the HEPA banks, or if in a potentially contaminated area, extremely small levels of fan shaft in-leakage (< 0.001 cfm) may be unacceptable for maintaining the desired level of removal.

Fan Housing Package

Fan housings should be specified to be leaktight, including all penetrations and access doors. Access doors should be bolted and gasketed.

5.4.2.4 Fan Arrangement

Fan Location

The location of the fan in the system relative to the filter housing is an important consideration in minimizing the effect of system leakage. Fans in contaminated exhaust systems installed immediately downstream of the filter housing and as close to the exhaust stack as possible place most of the system under negative pressure. Leakage is into the system, thus ensuring greater personnel dose protection. In addition, the fan handles cleaner air, thus reducing maintenance personnel dose during fan repair or overhaul.

For habitability systems with the filter housing located outside the protected space, the fan should be located on the upstream side of the filters. This eliminates system in-leakage that could bypass the filters.

Fans have been located within the filter housing to reduce noise transmission and, more importantly, shaft leakage concerns. However, adequate space must be provided for air inlet conditions. Further information is covered in Section 5.4.2.3, "Fan Leakage."

Multiple Fan Installation

Installation of two fans in series is sometimes desirable where a steeply rising pressure-airflow characteristic is needed. However, caution must be exercised in such a design. In theory, the combined pressure-volume characteristic of two fans operating in series is obtained by adding the fan pressures at the same volumetric airflow, as shown in **Figure 5.14**. Care must be taken in designing the connection between the fans, because a significant loss of efficiency can occur in the second-stage fan due to nonuniform airflow into its inlet, particularly if the two fans are closely coupled. Manufacturers may be able to install two fan wheels in series within a single housing, which is longer than a single-wheel fan. Fan manufacturers should provide certified fan performance curves for these multistage fans.

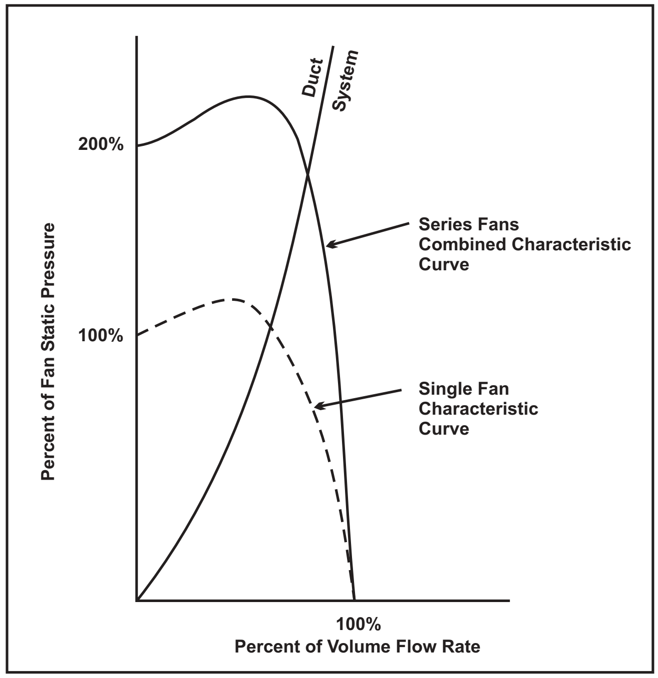


Figure 5.14 – Typical Characteristic Curve of Two Fans Operating in Series

For fans installed in series and not in a common plenum, a bypass duct is recommended so that a failed fan can be isolated from the system for repair and to avoid additional system resistance due to the failed fan wheel. Two or more fans are often operated in parallel to move large volumes of air, to enhance the control of segmented air cleaning facilities, or to limit the installed capacity (i.e., filters, adsorbers) of any one unit of the air cleaning system. The combined volume-pressure curve in this case is obtained by adding the volumetric capacity of each fan at the same pressure (**Figure 5.15**).

One concern in parallel fan installations is that some fans have a positive slope in their characteristic curves to the left of the peak pressure point (Figure 5.15). If the fans are operated in the pressure-volume regime of this positive slope, unstable operation may result. This is shown by the closed loop to the left of the peak pressure point in Figure 5.15 (this loop is obtained by plotting all of the possible combinations of flow at each pressure). If the system's characteristic curve intersects the fan characteristic in the area of this loop, more than one point of operation is possible; this may cause one of the fans to handle more of the system airflow than the other and result in a motor overload. The unbalanced flow conditions tend to shift rapidly so that the fans intermittently load and unload. The pulsing that results from such loading and unloading generates noise and vibration and may cause damage to the fans, motors, and ductwork. In addition, if more than two fans are operated in parallel, the designer and/or fan manufacturer should review the fan performance curves and system curves for possible combinations of fans, assuming one or more are out of operation for maintenance, filter change-out, or repair. Fans should be selected for stable flow throughout the service conditions (clean to dirty filter pressure drop) and combinations of fans.

Mounting

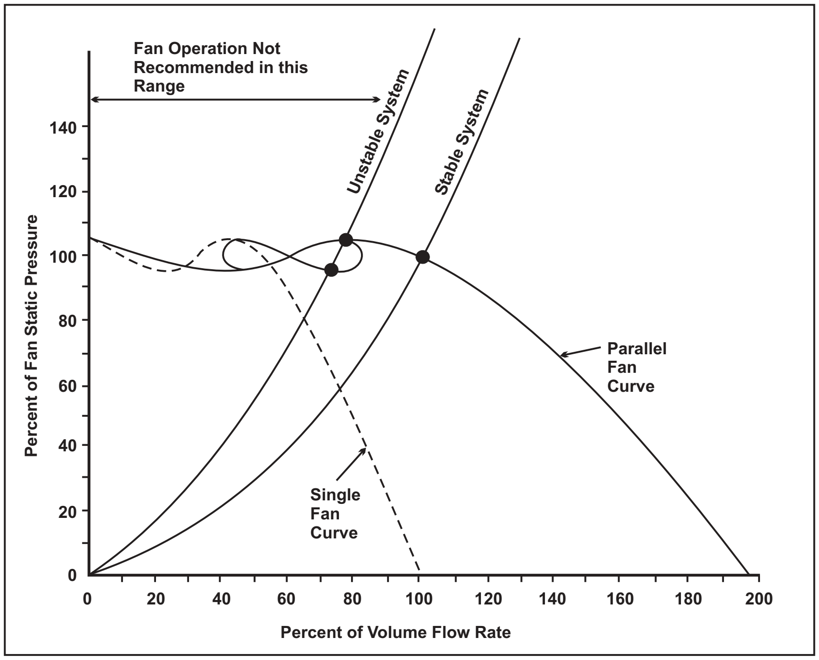


Figure 5.15 – Parallel Fan Operation

Proper mounting of the fan will minimize noise and vibration, and reduce maintenance costs. Noise is objectionable in supply and exhaust systems, and is often difficult and costly to eliminate after the system goes into service. Excessive noise in exhausts and air cleanup systems is often accompanied by vibration and pulsation. These conditions may be harmful to filters, adsorbers, and other components. Flutter of HEPA filter separators, for example, is a common cause of filter failure, and vibration of activated-carbon-filled adsorbers can result in settling and crushing of the granules and, eventually, carbon loss that can cause bypassing of contaminated air.

When practicable, mounting of the fan and motor on a common base designed for isolation of vibration is recommended. The fan and motor are mounted on a concrete base that acts as an inertial pad to limit the amplitude of vibration and to dissipate vibrational energy. The pad is mounted on spring isolators, which will provide a high degree (99 percent or more) of vibrational damping. For some systems, positive amplitude limiters may be required to restrain the base from excessive movement under extreme conditions (such as the accelerations imposed by a DBE). Some designers require hard-mounting of fans where seismic requirements and continued operation during and after an earthquake must be considered. Infiltration may be reduced by designing a tighter building structure. Careful balancing of the fan shaft and impeller to minimize vibrations that cannot be isolated via installation design is particularly important in this latter design.

Building Pressure Effects

Sizing of supply and exhaust fans must recognize the interaction of these fans with each other in order for nuclear air-cleaning systems to maintain proper space pressure relative to surrounding areas. See Section 2.4.1 of this Handbook for additional information concerning these interactions.

In push-pull systems (i.e., systems containing both supply and exhaust fans that operate at the same time), the space pressure depends on the relative capacity of the fans. If supply flow exceeds exhaust, the space is positive. If exhaust exceeds supply, the space pressure will be negative. When space pressure is required to be negative, the exhaust fan capacity should compensate for infiltration, pressure surges, wind effects (i.e., pressure variations in the building and ductwork due to variable wind conditions exterior to the building), as well as temperature variations between supply and exhaust air, to eliminate any possibility of over pressurizing the building via the supply fans. The pressure effects of other building ventilation systems serving adjacent spaces should also be considered.

Improper fan operation can be avoided by carefully evaluating system pressure drops and interactions under all predictable operating conditions, and by specifying the type and size of fan that matches the demands of the duct system as installed. Control must be exercised over the installation of ducts and fans to prevent field compromises that can reduce the ability of the system to perform as intended.

5.4.2.5 Fan Construction

AMCA has developed standards for fan construction. In general, these standards are applicable to the construction of fans for nuclear air cleaning systems. In addition, fans for nuclear air cleaning systems should be constructed in accordance with ASME AG-1, Section BA,[1] which defines additional specific features that are required for nuclear applications.

5.4.2.6 Qualification and Testing

Fans for nuclear air cleaning systems should be qualified, rated, and tested for the following:

- Performance,
- Structural capability,
- Vibration,
- Sound,
- Leakage, and
- Environmental conditions.

ASME AG-1 Code, Section BA,[1] provides inspection and testing requirements for fans and motors. AMCA 210[23] defines the methods for testing fans for rating purposes. Environmental qualification and testing of electrical components should be in accordance with IEEE-323.[24]

Standard motor tests that include "First Unit of A Design" and "Routine Motor Tests" (all motors) should be performed in accordance with IEEE 112[25] and ASME AG-1, Section BA.[1] Documentation of test results should be prepared in accordance with the above references.

5.4.2.7 Fan Reliability and Maintenance

Operational reliability is an important consideration in selecting fans for nuclear applications. Even when the system is planned for part-time or intermittent operation, continuous operation may be required after the system goes into service. This should be a consideration in the design and procurement process.

Adequate access for maintenance and service is imperative, and fans installed above floor level must have sufficient clear space around and below for personnel to get to them with the aid of ladders and/or scaffolding. Permanently installed ladders and galleries are recommended to ensure ease of access for maintenance and repair.

Procedures should be developed for periodic, preventative maintenance based on the fan manufacturer's recommendations and actual field operational experience. These procedures are critical for the reliability of the fan and its operational readiness in the event of a DBA.

5.4.2.8 Special Duty Considerations

Temperature, Pressure, and Humidity

Fans are constant-volume machines whose airflow rate can be impacted by variables such as temperature, pressure, and RH because they affect the mass flow rate of air being moved. It is necessary to identify and specify these variables for both normal and accident conditions so the fan manufacturer can make proper fan and drive selections. In addition, temperature, pressure, and humidity can affect fan components such as the bearings and bearing lubricant. Therefore, the fan manufacturer must know these properties to make proper material selections for fan components.

Material Moving

Fans that are required to move particulate matter require identification and specification of the properties of the airstream. Particulates can be abrasive, require high transport velocities, or be composed of corrosive, explosive chemicals. These materials can affect the fan wheel, casing, shaft, bearings, bearing lubricant, etc., and the fan manufacturer must know these properties to make the proper material selections for the fan components.

Contaminated Air Moving

Fans that are required to move contaminated air (primarily radioactive particles in nuclear facilities) also need to have these properties identified and specified. Radioactive contaminants can affect some of the materials used in fan construction (primarily bearing lubricants) or in ductwork components that are attached to the fan (flexible connections and gaskets). Another primary concern is contaminated leakage into or out of the fan (see Section 5.4.2.3 for information concerning leakage). The fan manufacturer must know the properties of the contaminated air so that proper material selections and leakage provisions can be provided.

5.5 Air Intakes and Stacks

5.5.1 Locating Intakes and Stacks

The design and location of exhaust stacks and air intakes have an important bearing on system performance. If air intakes are too close to the ground, blowing sand, dust, grass clippings, and other particulate matter may be drawn into the building, plugging the supply-air filters and/or reducing their life. Exhaust fumes from vehicles passing nearby or standing close to the building may also be drawn into the building. Intakes must be sited to protect them from snow, ice, and freezing rain during the winter, and baffles or louvers must be provided to give protection from driving rain and to minimize the effect of wind. Architectural louvers should be designed and tested in accordance with AMCA 500-L[15] for pressure drop and water penetration (see Section 5.3.5 for additional information concerning louvers). Wind pressure can have an appreciable effect on flow rates in a low-head ventilation system and can cause pulsations that may disrupt or reverse differential pressure conditions between the zones of the building.

Average wind direction and weather conditions that are likely to cause stack discharges to areas close to the ground (known as looping and fumigation) must be analyzed when establishing the location of stacks and intakes. This analysis is necessary to ensure that stack effluents cannot be drawn back into the building or into an adjacent building. Intakes should be located upwind of stacks (i.e., based on the prevailing wind for the site). Intakes downwind of shipping docks may be prone to drawing vehicle exhaust fumes into the building. Intakes located close to a roof or in a roof penthouse may have the same problems as those located too close to the ground.

Considerable guidance on the location of intakes and exhaust stacks is given in Chapter 16 ("Airflow Around Buildings") of the 2001 ASHRAE *Handbook of Fundamentals.*[3] The flow around adjacent structures is complex and is affected not only by a building's dimensions, but also by the topography surrounding a building. Proper consideration should be taken regarding the wind and stack flow patterns for a single rectangular building. Air intakes located within the recirculation zone or contaminated region will re-entrain the effluent. Computational fluid dynamics models could be developed to determine flow patterns around the building.

Intakes located on the sides of buildings may also be affected by the pressure (positive or negative) at those points. Ventilation systems should be designed and sized to account for this pressure, especially if a negative pressure is possible for a supply system or a positive pressure may exist for an exhaust system. A static pressure at least equivalent to the surface pressure associated with the design wind velocity for the specific location should be included in system pressure calculations. Pressure controls (described in Section 5.6.4) also should be used to regulate flow fluctuations occurring due to the wind velocity and surface pressure.

In northern climates, intakes should be designed to minimize snow entrainment. Even at low velocity through louvers, snowflakes can enter and clog prefilters located close to the louvers. In addition, hoarfrost can form on operable louvers and prevent their operation. Hoarfrost can also block louver screens. To prevent such potential problems, it may be advisable to heat the areas adjacent to the louvers. If snow is blown or otherwise induced into the ventilation system and no provision is made for settling or dropping out snow or ice particles, the filters can become clogged.

To reduce the potential for this problem, whenever possible, intakes should not be located on the windward side of buildings. Consideration should be given to modeling flow around buildings and intake structure designs if snow entrainment is causing operating problems that do not have conventional solutions.

The following factors should be considered when locating stacks:[19]

- High stack velocity is a poor substitute for proper stack location. A stack velocity to wind velocity ratio of 4:1 is required to discharge effluent out of the recirculation cavity boundary for a stack located flush to a roof.

- If an enclosure is needed around the stack, the stack should extend above the building zone of the enclosure and should not be flush to the enclosure.

- A circular stack shape is recommended. Nozzles may be used at the tip of the stack to increase exit velocity.

- Stack caps that deflect effluent downward are not recommended. High exit velocities will prevent rain from entering. Some drainage provision is recommended instead of rain caps.

- For both stacks and intakes, provision should be made for drainage of water or melted snow that may be induced into the system.

- Stacks should be located where they cannot damage the facility they serve or other important nearby structures.

5.5.2 Sizing Intakes and Stacks

Air intakes should be sized to minimize pressure drop and maintain air velocity through the free area below the velocity at which water droplets may be entrained (usually less than 500 fpm). Manufacturers should be requested to provide pressure drop and water penetration test results for louvers tested in accordance with AMCA 500-L.[15]

Sizing of stacks is even more important to prevent re-entrainment and ensure proper dispersion. Dispersion calculations should be performed to determine whether elevated, ground-level or mixed mode effluent release is required to maintain offsite personnel exposures within the plant environmental permit, Technical Safety Requirements, and applicable Federal, State, and local regulations. The term “elevated release” typically refers to stacks that are situated well above the tallest building. Ground level releases are typically exhaust points located on the building wall or roof. "Mixed mode" refers to stacks that are marginally higher than the tallest building. In each case, location of the stack should be based on the factors discussed in Section 5.5.1. When calculating pressure drop tornado and other missile barrier needs, the need to prevent access by unauthorized personnel should be considered. For further guidance, see Section 5.5.3 and 5.7.1.

The exit velocity of the stack should be at least 1.5 times the wind velocity to minimize downwash. Stacks may need to be partitioned or sectioned if multiple systems discharge into the stack and individual system operations do not occur at the same time or frequency. A minimum stack exit velocity of 3,000 fpm is recommended to prevent downwash from winds up to 22 miles per hour (mph), to keep rain out, and to prevent condensation from draining down the stack. If condensation may be corrosive, a stack velocity of 1,000 fpm is recommended with a drain at the bottom to remove condensation and a nozzle at the top of the stack to maintain high exit velocity. High exit velocity from a stack, however, does not remove the need for a tall stack.

5.5.3 Structural Design Aspects

Louvers designed for conventional ventilation and air conditioning applications are usually acceptable for use as air intakes for nuclear air cleaning systems. If louvers are required to remain in place following DBAs (such as earthquake or tornado), they should be designed in accordance with the requirements of ASME AG-1, Section DA.[1]

Stacks should be designed in accordance with the requirements of ASME AG-1, Section AA,[1] and ASME STS-1-2000, *Steel Stacks*.[26] Loading due to design wind, tornado, hurricane, and other abnormal meteorological conditions should be included in the structural analysis, as well as dynamic loads due to seismic excitation whenever applicable. Even if not required to remain functional, stacks should be designed so they do not collapse and cause unacceptable damage to surrounding structures, systems, or components. Stiffeners for stacks should be located on the outside to avoid providing ledges for potential "buildup" of radioactive material, even though the air has been "cleaned." The structural design of stacks should be qualified by analysis in accordance with AG-1, Section AA.[1] Care should also be exercised in the structural design so that stacks do not "crimp" or bend and cut off the effluent flow if they are subject to a strike by high wind- or tornado-generated missiles.

Openings in nuclear-safety-related structures for either air intakes or exhaust stacks should be protected from the effects of high wind or tornado missiles if such a missile could damage a nuclear-safety-related component and prevent it from functioning. Missile protection typically involves utilizing staggered building wall structures or a lattice of steel bars to prevent a straight-through missile path. Sufficient space must be allocated for these intake structures. Free-area reduction caused by the use of the staggered walls or steel bars in the openings must be considered when sizing the openings, particularly intakes, so that velocity requirements are not exceeded. For security needs at air inlets, see Section 5.7.1.

For metal exhaust ducts, see the American Conference of Governmental Hygienists, *Industrial Ventilation, A Manual of Recommended Practice,* Chapter 5, "Exhaust System Design Procedure."[4]

5.6 Instrumentation and Control

5.6.1 Codes and Standards Requirements

Instrumentation and control systems, components, and equipment should meet the requirements of ASME AG-1, Section IA.[1] In addition, they should be qualified according to the requirements of IEEE 336,[27] 383,[28] and 384.[29]

5.6.2 Functional Requirements

The function of the instrumentation and control systems associated with nuclear ventilation and nuclear air cleaning systems is to control the environment of the space served within the limits of the controlled variable and to monitor the performance of the system and its components to ensure safe, efficient, reliable operation. The design of instrumentation and control systems should consider the consequences of single failure as well as environmental conditions.

The primary variables by which nuclear air cleaning systems are controlled are temperature, airflow rate, and pressure. Temperature, pressure, flow, and radioactivity levels are monitored to indicate system performance and alarm abnormal conditions.

Effluent air cleaning systems typically are controlled to maintain a minimum negative pressure or building pressure around a preselected flow rate. Habitability systems are usually controlled to maintain a constant airflow rate that is selected to maintain a positive pressure in the space served. Temperature is also usually controlled for habitability systems.

Instrumentation should be provided to monitor the radioactivity levels of effluent discharged into the atmosphere. Each discharge point that could potentially have concentrations exceeding Technical Safety Requirements limits should be monitored. Monitoring of emission airflow rates and concentrations is also required. Values in excess of established high limits should be alarmed in the control room. In addition, airflow rates and radioactivity levels for habitability systems should be monitored and alarmed.

The best indicator of system performance for continually operating systems is the level of radioactivity. Monitoring flow rates and concentrations both before and after air cleaning units could indicate trends in filter degradation. The controls recommended in ASME AG-1, Section IA,[1] should be provided to assist the operators in monitoring system performance.

5.6.3 Airflow Control

Airflow control is one of the most important control variables for nuclear air cleaning systems. Nuclear air cleaning system pressure could vary by as much as 25 to 30 percent, depending on system components, clean filter pressure drop, and the change-out pressure drop**.** It is recommended that airflow rates be maintained within $\pm$10 percent of design to maintain proper fan performance. The airflow rate is usually required to be automatically controlled by: (1) discharge or inlet control dampers, (2) variable inlet vanes, or (3) variable speed control.

To control the airflow rate, the flow first must be accurately measured. Flow should be measured where the air velocity profile is uniform. AMCA 210[23] and 203,[22] as well as ACGIH *Industrial Ventilation*[4] provide guidance on the proper location of airflow sensing devices. Several manufacturers produce airflow measuring devices that can provide accurate averaged velocity pressures, as well as the instrumentation to convert velocity pressures to airflow rates.

An alternative method of controlling the airflow rate within $\pm$10 percent of design is to select a fan that has a steep performance curve such that a 25 percent change in pressure will not result in more than a 10 percent change in flow rate. This is difficult to achieve, however, due to system margins, system effect factors, and the ability to accurately calculate system pressures.

The choice of control dampers or inlet vanes will depend on fan type, required pressure reduction, and airflow uniformity. Control dampers must be sized to provide controllability. Flow stability must be maintained to avoid a controller “hunting” (i.e., control instability).

If the pressure reduction required is 40 percent or more of the fan static pressure at the operating point, inlet vane control may be desirable. An inlet vane control damper costs about three times more than equivalent parallel-blade or opposed blade dampers but, at a capacity reduction of 50 percent or less, it produces power savings that can average 25 percent compared to parallel-blade or opposed blade control dampers. Another factor that favors the inlet vane damper over a control damper in the duct is that it permits operation of the fan for long periods at reduced load. Full-open inlet vane dampers cause the fan to operate at some penalty to airflow, static pressure, and horsepower.

AMCA 210[23] recommends the use of variable vane inlet dampers when the fan is to be operated for long periods at reduced flow. The effectiveness of this damper stems from the fact that the inlet vanes generate a forced inlet vortex that rotates in the same direction as the fan impeller; similarly, any restriction of the fan inlet reduces the fan performance. Inlet vane dampers are of two types: integral (built-in) and add-on. The resistance and system effect of inlet vane dampers in the wide-open position must be considered in the original fan selection and system functional design. System effects of inlet vane dampers should be available from the fan manufacturer; if not, the system effect curves of AMCA 210[23] should be applied to account for pressure losses due to the use of these dampers.

Although variable vane inlet dampers generally provide smooth airflow control down to less than 30 percent of operating-point flow, there have been instances of severe vibration on large fans when the vanes were positioned between 30 and 60 percent opening. Because vibration is aggravated by system turbulence, consideration must be given to ways of ensuring smooth airflow patterns in the duct entering the damper and leaving the fan when inlet vane dampers are employed in high-velocity systems. Variable-pitch vaneaxial fans may also be used to maintain system flow under varying pressure conditions. Variable pitch fans, however, may not qualify for safety-related seismic applications that require environmentally qualified components.

With the increase in variable air volume air conditioning systems, much has been done to improve variable speed controls for fans. Variable frequency controls, eddy current clutch motors, and mechanical adjustable speed drives are various methods of speed controls for fans. For variable air volume air conditioning systems, the airflow rate is varied to maintain a constant system pressure. For nuclear air cleaning systems, the speed of the fan is varied to maintain a constant airflow under varying system pressures.

Adjustable frequency drives are becoming more economical due to lower-cost solid state electronic components. The speed of the fan motor is directly proportionate to the frequency of the motor. Since the horsepower of the fan is a function of the cube of the speed, there can be significant secondary benefits of saving energy by using frequency drives, as well as better matching of fan performance to changing system pressure requirements.

One disadvantage of these types of speed control is a potential lack of environmental qualification data and quality assurance programs, which may be required for safety-related equipment. However, for nonnuclear-safety-related applications, these requirements do not apply and speed control is a possible option to consider.

5.6.4 Pressure Control

Effluent air cleaning systems are typically controlled to vary the system flow rate to maintain building (or space) pressure. This is accomplished by maintaining constant supply airflow and varying exhaust flow by adjusting control dampers and inlet vanes, and through speed control similar to the techniques described in Section 5.6.3. Accurately sensing building pressure and outside air pressure are important for achieving a stable operating system. The sensing system should incorporate a "dead leg" to dampen the system reaction to wind gusts. Multiple outdoor and, if necessary, indoor sensors should be provided to obtain an average outside air pressure. To maintain a building at a negative pressure with respect to the lowest outside air pressure, the outdoor sensors should be located on each exposure. The system should then be designed to control flow based on the highest positive pressure sensed (the one that would result in the most infiltration).

Sensors should be located with due consideration given to local pressure fluctuations, eddy currents, and the turbulence that can be experienced at building corners and roof edges. The ASHRAE *Handbook of Fundamentals*[3] provides guidance on determining turbulent zones due to airflow around buildings. This information must be considered in locating the sensors.

5.6.5 Qualification and Testing

All instruments used in safety-related nuclear air cleaning systems must be qualified for environmental and seismic conditions in accordance with ASME AG-1, Section IA,[1] IEEE 323,[24] and IEEE 344.[30] All instruments and devices must be calibrated and tested in accordance with the manufacturer's test procedures. In addition, all power wiring internal to control panels, except control or shielded cable, should be subjected to a high-potential test to demonstrate freedom from ground and correct wiring connections.

It is recommended that extensive onsite pre-operational testing be performed on all instrumentation and control systems associated with nuclear air cleaning systems prior to placing the systems in service. Pre-operational testing should be performed to confirm correct installation and design and to ensure correct operability of the control system and operated equipment.

5.7 Other Considerations

5.7.1 Security

Ductwork, openings for intakes and exhaust stacks, and other types of building penetrations and pathways must be properly protected against security threats. Security measures for these openings and pathways are addressed in specific site security guidelines.

5.7.2 Energy Conservation

Specialized products and components for energy conservation may be appropriately used for facility HVAC systems. In employing these components, care must be exercised to avoid using products that cannot be decontaminated or would otherwise limit the ability of the air cleaning systems to perform their design basis functions.

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CHAPTER 6

SMALL AIR CLEANING UNITS

6.1 Introduction

This chapter discusses the installation of internal components, primarily high-efficiency particulate air (HEPA) filters, in systems that require only a single filter per stage of each air cleaning unit. HEPA-filtered vacuum cleaning (HEPA-Vac) systems are not considered small air cleaning units and should not be utilized as such. The items described in this section should be manufactured under a quality assurance (QA) program that meets all the basic requirements of American Society of Mechanical Engineers (ASME) NQA-1, *Quality Assurance Program Requirements for Nuclear Facilities*.[1] Although installation requirements are generally the same and should be tested similar to those for multifilter housings, the use of questionable practices in some older systems and the proliferation of commercially built off-the-shelf housings (side-access housings) make a separate discussion of this subject desirable.

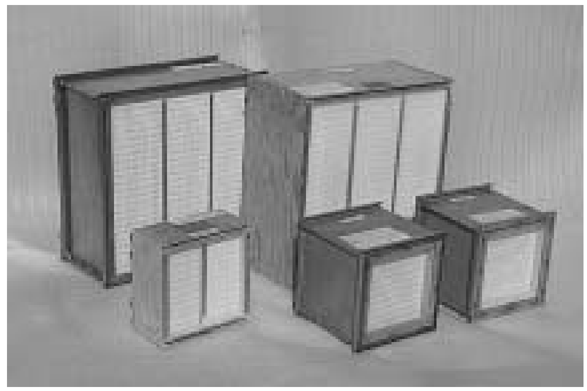

Figure 6.1 – Open-faced Rectangular HEPA Filters

Single-filter (nonparallel) installations are employed in the supply, exhaust, and recirculating air cleanup systems of rooms, gloveboxes, hot cells, chemical fume hoods, and other contained spaces; in the off gas lines of process vessels and radiochemical operations; and in other applications in which the airflow is 1,500 cfm or less. Single-filter installation for gloveboxes is a separate topic and is covered in Chapter 7. Although much of the discussion in this chapter focuses on installation of HEPA filters, it also applies to adsorber cells and other components, for which better than average installations are necessary.

Figure 6.2 – Open-faced Cyclindrical Flow HEPA Filter

The design of the filter (adsorber) installation is a function of the configuration of the filters (adsorbers) used. General HEPA filter configurations include open-faced rectangular (with wood or steel case and double-turned flanges on each face, as shown in **Figure 6.1**) and open-faced cylindrical flow (with molded-phenolic or metal case and with or without flanges on one or both faces (see **Figure 6.2**). The rectangular open-faced filter is most commonly used in both large-volume (multifilter) and low-volume (single-filter) applications; this chapter deals mostly with the low-volume, single-filter type. Another design approved by the U.S. Department of Energy (DOE) Standard 3020, *Standard for HEPA Filters used by DOE Contractors*,[2] is the radial flow HEPA filter shown in **Figure 6.3**. The radial flow design has a circular filter pack that is sealed into end caps and inner and outer grills. Under

Figure 6.3 – Radial Flow HEPA Filter

normal conditions, airflow is from the inside of the filter to the outside, although airflow from either direction is possible. Installation of cylindrical open-faced filters is discussed in Section 6.4.

Single-filter installations can be grouped into three broad categories: (1) in-wall (filter mounted in or to a wall penetration of a room, glovebox, hot cell, or other contained space); (2) in-duct (filter installed "in line" between two sections of duct, with or without transitions); and (3) duct-entrance (filter installed at the opening of the duct leading from a room, glovebox, hot cell, or other contained space). In-wall installations are generally employed to clean the air entering a contained space, to prevent backflow of contamination in the event the contained space becomes pressurized, or both. The filter may be installed bare (sides of case exposed) or in a partial enclosure. As in other installations, a prefilter is recommended upstream of the HEPA filter. Duct-entrance filters are strongly recommended to maintain the cleanliness of contaminated exhaust and air cleanup ducts. These filters should be mounted in or close to the entrance of the duct and, like the in-wall type installation, may be installed either bare, as shown in **Figure 6.4**, or in a partial enclosure.

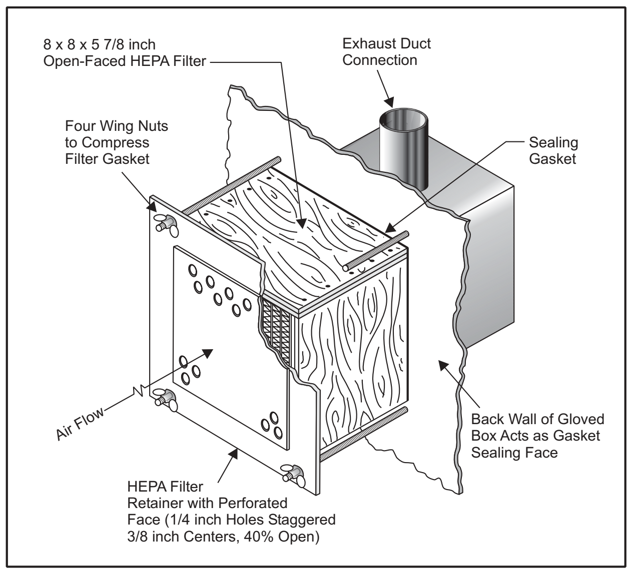

Figure 6.4 – Mounting of Duct-Entrance Filters

In-duct open-faced filters should be installed in totally enclosed housings or side-access housings, as shown in **Figure 6.5**. Taping or clamping the filter between two sections of duct or a pair of transitions with the case exposed is not recommended. Such installations provide no secondary confinement in the event of a breach of the filter case, gaskets, or tape seals, and (particularly for wood-cased filters) fail to meet the requirements of Underwriters Laboratory (UL)-181A, *Closure Systems for Use with Rigid Air Ducts and Air Connectors* [3] and National Fire Protection Association (NFPA) 90A, *Standard for the Installation of Air Conditioning and Ventilating Systems*.[4]

Figure 6.5 – Correct Mounting of In-Duct-HEPA Filter Housing

Enclosed filters are sometimes referred to as encapsulated (nipple-connected, closed-face, or self-contained) HEPA filters (see Chapter 3, Figure 3.8). They are not specifically recognized by applicable codes and standards and fail to meet all the requirements contained in DOE-STD-3020.[2] The uniformity of the velocity across the filter face is difficult to verify.

6.2 Housings

Housings for in-duct installations may be as small as the side-access housing for a 25-cfm HEPA filter or as large as the complete multistage air cleaning unit containing demister, prefilter, two stages of HEPA filters, and adsorber (**Figure 6.6**). Probably the most common single-component housing today is the bag-in/bag-out side-access type, which is commercially manufactured by a number of companies to a similar standard configuration.

Figure 6.6 – Complete Multistage Air Cleaning Unit

Commercially made side-access housings, like other air cleaning system components, are not items to be selected "on faith." Designers have been prone to look upon these as "black boxes," assuming that, because they are off-the-shelf items, they are adequately designed to be suitable for any nuclear application. This is not the case, and some users have been faced with replacing or upgrading many such commercial enclosures over the past several years. Features that must be checked carefully when purchasing standard commercial housings include the filter (component) mounting frame and clamping device, the rigidity of the box and its cover, the method of cover sealing and clamping, access to the installed component, the rigidity and construction of duct connections, and the materials of construction of all parts, including the component clamping mechanism. These same features are important in the design of one-of-a-kind shop-built housings. Provisions for in-place testing should be provided on all filter housings.

6.2.1 Component Installation

Requirements for installing components are basically the same as those for bank installations. These include structural rigidity, flatness, and accuracy of the sealing surface construction; positive, reliable sealing of the component to the frame; specification of and strict adherence to close tolerances in fabrication; and leaktight welded construction (see Chapter 4, Section 4.3.2). A minimum sheet-metal thickness of 0.078 inch (No. 14 U.S. gauge) is recommended for the sealing surface of commercially made and shop-fabricated housings. For gasket-sealed housings, the sealing surface must be seal-welded into the housing such that no warping of the filter (component) sealing surface will result. There should be a right-angle bend all around the seating surface to provide reinforcement and to ensure flatness. **Figure 6.7** shows a portion of the turned-angle filter sealing surface of a commercial housing, and **Figure 6.8** shows a schematic of the four-bar-linkage gasket seal clamping mechanism that is operated by means of a wrench (shown in **Figure 6.9**) from outside the housing. Other clamping systems are acceptable, so long as they provide the required amount of clamping force on the gaskets.

Figure 6.7 – Turned Angle, Gasket Sealing Filter Surface for a Commercial Housing (left-hand side of the photo) [Note: Right-hand side of this photo shows the four bar-linkage gasket.]

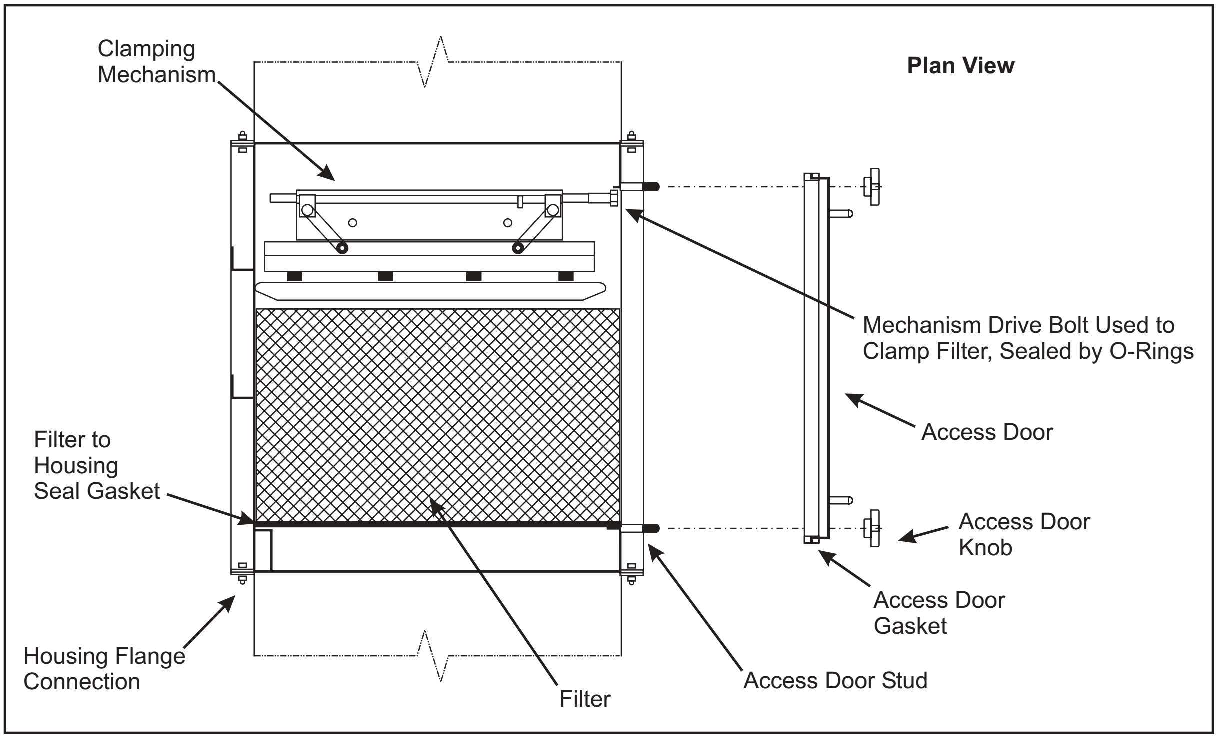

Figure 6.8 – Four-Bar-Linkage Gasket Seal Clamping Mechanism

The housing should be constructed to prevent leakage where the clamping mechanism penetrates to the outside. The structural requirements of the mounting frame will be met if 14-gauge steel is used, particularly if combined with the stiffening flange (right-angle bend).

Flat gasket-to-knife-edge seals are not recommended because they tend to leak excessively if the knife-edge is nicked or if the knife-edge and the filter face are not parallel. The compression set produced by a knife-edge in only a portion of the gasket also results in leakage if there is any degree of relaxation of the clamping device. The gel seal design does not require special tolerances and has been proven to create a very effective filter-to-sealing surface method.

Figure 6.9 – Using Wrench to Operated Four-Bar-Linkage Gasket Seal Clamping Mechanism

A nonwelded mounting frame consists of a single 0.25-inch plate sealed by gaskets between the flanges of the body and the transition of a field-assembled housing. The filter is clamped by bolts and installed through a hatch in the side of the housing. A gasket compression of at least 80 percent is needed to create a reliable seal between high-efficiency devices such as a HEPA filter or radioiodine adsorption cell. This requires a gasket loading of something over 20 pounds per square inch of gasket area for a total loading of over 1,400 pounds for a 24- × 24-inch filter; 1,050 pounds for a 12- × 24-inch filter; or 700 pounds for a 12- × 12-inch filter. Such loadings can be accomplished with the bolted clamping method. It is important for the designer to verify that the clamping mechanism of the commercial housing being considered can develop the loading required and is adjustable. All parts of the mechanism should be stainless steel to prevent rusting and seizing under operational conditions (including springs, which tend to break when rusted). The only exception to this rule is that, if nuts are used, they should be brass, bronze, or another material that will not gall in contact with the stainless steel male-threaded part (**Figure 6.10**). Clamping mechanisms should be on the clean side of the filter, and operator shafts, when required, must be sealed by O-rings or glands. A rest or guides, stops, or some other means for aligning the filter prior to clamping should be provided within the housing.

For gel seal housings, the knife-edge sealing surface must be seal-welded into the housing so that warping of the filter (component) sealing surface will not result. There should be a right angle all around the knife-edge sealing surface to provide reinforcement and ensure alignment. **Figure 6.11** shows a portion of the knife-edged filter sealing surface of a commercial housing. The gel seal housing clamping mechanism is operated by hand from the side of the housing. All parts of the mechanism should be 300 series stainless steel to prevent rusting and seizing under operational conditions.

The clamping pressure required to properly seal a gasket-sealed HEPA filter or adsorber cell must be both high and uniform, as noted in Section 4.4.6. However, this requirement is substantially relaxed when gel seal systems are used. As shown in **Figure 6.12**, the filter element has a groove filled with a non-Newtonian (i.e., nonflowing) gel. The filter is pushed against the knife-edged flange of the mounting frame so that the gel envelops the knife-edge, forming an airtight seal. The clamping pressure only needs to be sufficient to prevent the filter from backing away from the knife-edge (which would break the seal) under any foreseeable differential pressure across the filter in either normal operating or system upset conditions. The gel, a silicone compound, has been tested and found to be capable of maintaining an adequate seal under the fire and hot air conditions of UL-586, *Standard for High Efficiency, Particulate, Air Filter Units*,[5] and the radiation exposure requirement of ASME AG-1, *Code on Nuclear Air and Gas Treatment*, Section FC.[6] Either the flat-gasket-to-flat-flange or the gel seal are recommended.

Figure 6.10 – Filter Locking Mechanism Drive Bolt Located at the Front Exterior of the Housing

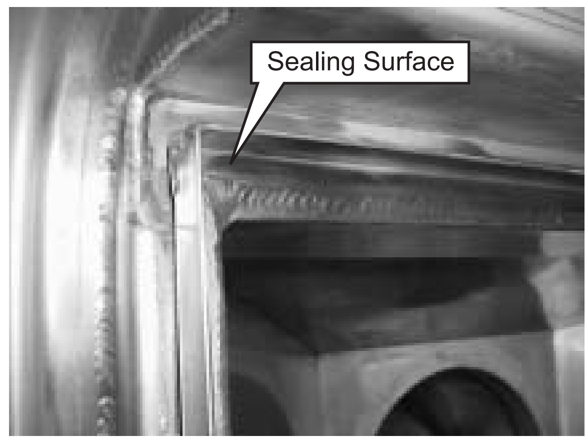

Figure 6.11 – Gel Seal Commercial Housing Filter Sealing Surface

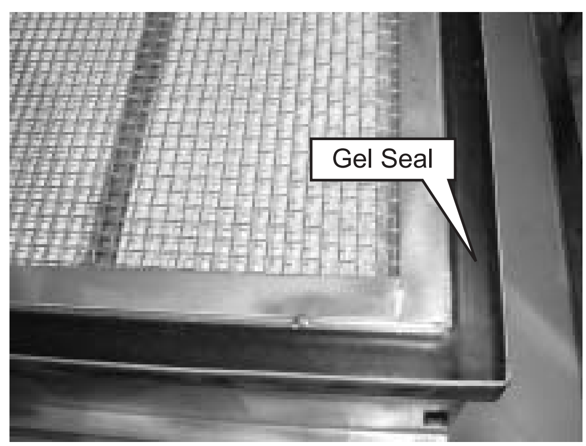

Figure 6.12 – Gel Seal System

6.2.2 Housing Construction

The walls of the housing must be sufficiently strong to prevent "oil canning" and overstressing under an alternating positive and negative pressure equal to at least 1.5 times the maximum gauge pressure to which the housing will be subjected under the most severe conditions for which it is intended. A minimum design pressure of 10 in.wg is generally recommended. In general, the recommended design features listed in Section 4.5.2 and the leaktightness recommendations of Section 4.3.4 are applicable to housings of these smaller dimensions. In purchasing commercial housings, the designer should check the details of construction to verify that the design proposed is fully adequate for the intended application, i.e., that the walls of the housing (or the cover) will not "oil can" and that stresses in the walls or clamping mechanism will not exceed a value of 0.7 times the yield strength of the material from which they are made under a housing pressure of 1.5 times the design pressure.

Many failures of commercial housings can be traced to corrosion. The filter housing is a common point where corrosives tend to condense, collect, and concentrate. When the filter housing is to be installed in a line that, under either normal or abnormal conditions, may contain corrosive fumes or vapors, stainless steel construction should be employed. In any event, all parts of the clamping device (including springs, but not nuts) should be stainless steel. Whenever housings are painted, the coating should comply with American Society for Testing and Materials D5144, *Standard Guide for Use of Protective Coating Standards in Nuclear Power Plants*.[7] The designer should determine which coating has to be used and should be personally satisfied that it is adequate for the application.

Figure 6.13 – Access Door Hand Knobs

Hand knobs of the type shown in **Figure 6.13** should attach to the housing access door. Attachment of covers with machine bolts or nuts may be cheaper, but will be a constant problem to the user. Nuts get lost and threaded bolts get damaged under service conditions. The result is often an inability to seal the housing properly, and the need to remove and replace a large number of nuts or bolts inhibits access and proper service. For access door clamping, the door must have a 2-inch-deep lip or flange all around for stiffening (Figure 6.7). The cover must also be stiff enough or sufficiently reinforced so that it will not "oil can" under the pressure variations to which it may be subjected. The cover and the cover-clamping mechanism must be capable of sealing the cover opening whether or not a bag is in place.

6.2.3 Bagging

Most commercially manufactured and some one-of-a-kind shop-built housings are designed for bag-in bag-out filter replacement. **Figure 6.14** describes this procedure step-by-step. Shutoff dampers are needed upstream and downstream of the filter (or other component being replaced) to permit isolation of the housing during the change and to limit ballooning or sucking in of the bag when the access door is opened due to a pressure differential between the inside and outside of the bag. A small, valved, breather vent can be specified on the clean side of the filter to control pressure in the housing; a slight negative pressure (0.25- to 0.5-in.wg) helps ensure inward leakage in case the housing becomes pressurized due to pumping of the bag. When sealing change-out bags, two seals about 0.25-inches apart are usually made so that, when the bag is cut between them, both the housing opening and the enclosed filter are sealed from the room environment. The end user's safety officer will determine the method of sealing the change-out bag that best suits the facility.

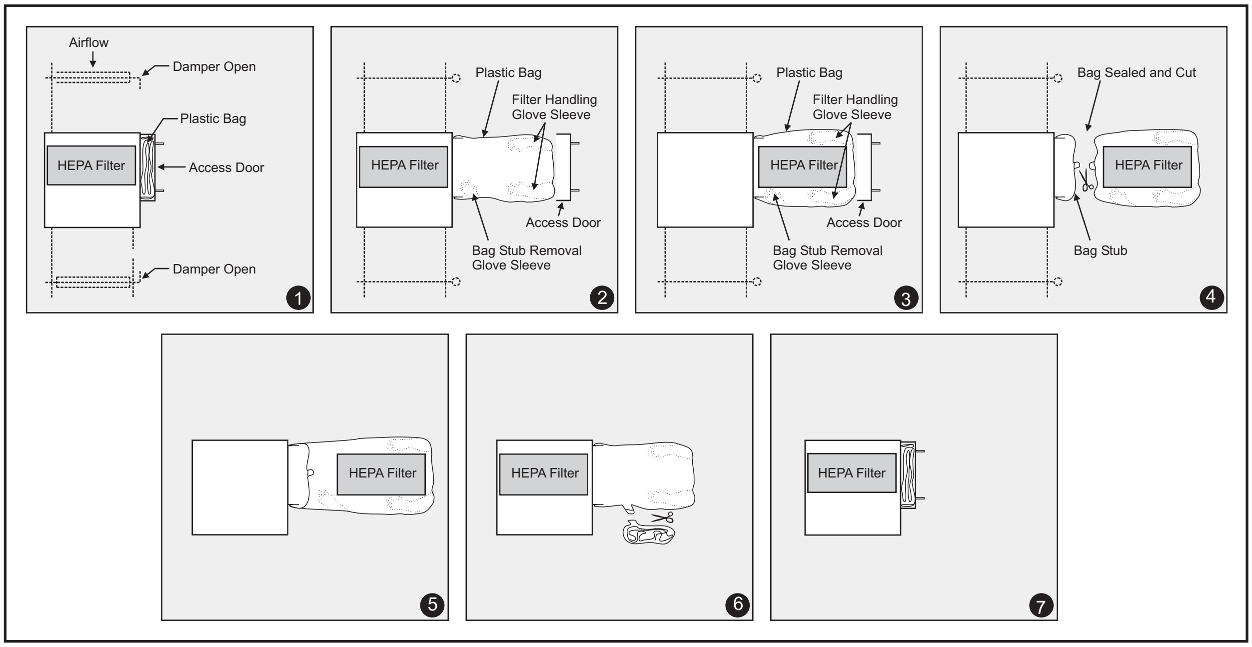

Figure 6.14 – Bag-In Bag-Out Filter Replacement

Bags should be clear plastic, typically polyvinyl chloride (PVC), to permit the worker to see what he is doing. In some housing designs, the worker has to manipulate the filter clamping mechanism through the bag as shown in **Figure 6.15**. Bagging materials are PVC or polyethylene. Radiation levels may limit the use of PVC. Bags should be a minimum of 0.008-inch thick. Thinner bags could tear, particularly when used with metal-cased filters or adsorbers. Care must be taken when carrying out the procedure with larger (24- by 24- by 11.5-inch) items. Housings should be installed in a location that can be isolated as a contamination or radiation zone in the event of a bag tear and resulting spill. The excess bag material that remains after a new filter is placed into the housing is folded carefully against the side of the filter element (shown in Figure 6.14) to prevent any portion from getting into the airstream or being pinched between the housing cover and bagging ring. After folding the bag within the filter housing, it must be isolated from system airflow on the clean side of the filter because the plastic can be damaged from continued exposure to the airstream. The covers of bag-out housings must be capable of sealing the housing with and without the bag installed and must be kept closed when the system is in operation to protect the bag that remains in the housing. Bagging should not be considered an automatic solution to the contamination hazard, and the user is cautioned to take proper precautions during filter changes. **Figure 6.16** shows possible dress for personnel engaged in a bag-out filter change when there is a possibility of high contamination levels (note the personal protection equipment). Again, the end user's Health

Figure 6.15 – Use of Clear Bags

Figure 6.16 – Personnel Dress for Bag-Out Filter Change

and Safety/Radiation Protection personnel will determine the method of bag-out filter change that best suits the facility.

6.2.4 Housing Installation

Horizontal airflow with filter faces in a vertical position is recommended for large (24- by 24-inch face dimensions) HEPA filters. This recommendation is not so important for smaller filters designed with media support that is inherently sufficient to resist gravitational pull on filter core and collected dust. When vertical airflow (filter face in a horizontal position) is unavoidable, upflow design is recommended over downflow design because filter media sagging is offset to some extent by air pressure and because there is less chance of cross-contamination from the dirty side to the clean side of the system. With the downflow design, contaminated dust dislodged during a filter change can fall into the clean side of the system. A downflow design should be avoided where there is a potential for liquid to collect in the system. Liquid collected in the filter pleats of a downflow system will eventually seep through the media and carry dissolved contaminants into the clean side of the system. On the other hand, upflow systems may require withdrawal of contaminated filters into the clean zone. When horizontal installations must be used, filters should be designed to seal on the upper side of the mounting frame so that their weight will load rather than unload on the gasket or gel-sealing surface (**Figure 6.17**). Installation of the filter on the clean side (i.e., downstream) of the mounting frame is always recommended for single-filter installations.

Figure 6.17 – Horizontal Filter Installation

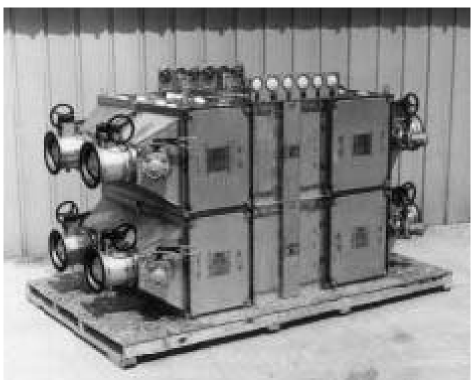

Figure 6.18 – Four Individual Housing Units Grouped as One Assembly

Figure 6.19 – Flexible Connection

For multistage installation, components may be installed in a single housing (as shown in Figure 6.17) or grouped as one assembly (**Figure 6.18**). Although bolted, gasketed joints are recommended, flexible connections (see **Figures 6.19 and 6.20**) are suitable for housings connected directly to a fan. Duct-taped seals between housings and ductwork are not acceptable. Multistage installations can create problems related to periodic surveillance testing of HEPA filters and adsorber cells. Even though a flange-to-flange installation (**Figure 6.21**) is undoubtedly the least expensive option when considering materials and space occupancy, sufficient room should exist between components to introduce a well-mixed test agent, to obtain a satisfactory upstream sample, or to probe for leaks on the downstream faces of the components. Careful planning of filter and adsorber test procedures before completion of installation design is essential, particularly for multistage installations. Although some housing specifications require and some vendors routinely furnish sample ports in the housing itself, such ports should not be automatically assumed to meet the requirement for preplanned and preinstalled test ports. As noted in Chapter 8, the test agent injection port must be located well upstream of the filter or adsorber to achieve good mixing of the air and test agent. Upstream samples must be taken from a point in the duct that is immediately upstream of the filter or adsorber. Downstream samples must be taken at a point far enough downstream to obtain good mixing of the air and test agent that penetrates the filter or adsorber. This point is at least 10 duct diameters downstream (or preferably downstream) of the fan. [Note: Fire protection is discussed in Chapter 10.]

Figure 6.20 – Flexible Connection

To sidestep testing problems related to having 10 duct diameters upstream to inject the test agent and 10 duct diameters downstream to sample, in-place filter test sections are available. These test sections (shown in **Figure 6.21**) allow testing without requiring test personnel to enter the contaminated air space. The test sections should be the same height and width as the housing that contains the filter or adsorber being tested, and the length of the test sections should be 24 to 28 inches long.

Figure 6.21 – In-Place Filter Test Section

The in-place test sections should be designed, manufactured, and tested using the same criteria as the filter housing. The test housing will use apparatus and devices supplied as an integral part of the test section, including mixing devices and sample ports. The upstream and downstream test chambers must contain identical mixing devices to mix and disperse a uniform challenge air/aerosol ahead of the filter and the effluent from the filter being tested. Challenge aerosol inlet ports and upstream and downstream sample ports must be provided for each HEPA filter space and must be labeled for identification.

6.3 Enclosed Filter Installation

The enclosed HEPA filter design is not intended or recommended to replace or serve as a confinement housing.

6.4 Cylindrical Filter Elements

Cylindrical filters may be either cylindrical or radial flow. The cylindrical flow HEPA filter configuration frequently offers an ideal solution to certain installation requirements. One manufacturer makes a spiral of the filter material and a separator; the others make a conventional pleated-medium-and-separator core that is trimmed to a cylindrical shape. In both designs, the core is slipped into a molded or welded-seam cylinder (**Figure 6.22**) and sealed by catalyst-activated plastic foam or urethane. Cylindrical flow HEPA filters can be obtained with or without flanges on one or both ends. The filters with interference seals, but without flanges as shown in **Figure 6.23**, are used in push-through

Figure 6.22 – Open-Faced Axial Flow Cylindrical HEPA Filter

Figure 6.23 – Radial Flow HEPA Filter

Figure 6.24 – Open-Faced Axial Flow Cyclindrical HEPA Filter with Flange

Figure 6.25 – Clearance Between Radial Flow Filter and Housing

(i.e., incessant) installations. The filters are sealed into a cylindrical opening with one or more half-round circumferential gaskets (fixed to the filter) that make a slight interference fit with the receiver. As the filters are often out-of-round and a reliable interference fit between filter and receiver is impracticable, push-through installations are often unreliable under system-upset conditions. Push-through filters are subject to being blown out of the receiver if pressure differentials become high. Flanged cylindrical HEPA filters (**Figure 6.24**) can be installed in pipe openings by bolting them to a flange on the pipe or by clamping the filter flange between mating pipe flanges. Conventional neoprene sponge gaskets are used for sealing (see Section 4.4.6). Because filter flanges and cases are characteristically made from light-gauge sheet metal with the flange seal-welded to the cylinder, these filters often leak at the flange-to-case weld. The flange often becomes deformed. Either condition results in an installation that is difficult to seal.

Cylindrical HEPA filters cost substantially more than rectangular HEPA filters of equivalent airflow capacity. There are no current standard dimensions or airflow capacities. No cylindrical filters are listed for axial or radial flow filters in any of the standard specifications for HEPA filters [e.g., DOE-STD-3020,[2] ASME AG-1,[6] Institute of Environmental Sciences & Technology (IEST)-RP-CC001.3, *HEPA and ULPA Filters*].[8] DOE-STD-3020[2] allows for the use of special filters in a footnote stating that HEPA filters not listed in Table 1 of the standard: "(e.g., round, rectangular, radial, etc.) which conform to the requirements listed in this Standard (5.2 Performance Requirements, 5.3 Materials Requirements, and 5.4 Filter Construction) are acceptable for use at DOE nuclear facilities."

There are two methods of installing cylindrical filters, one a duct-entrance design and the other a hot-cell exhaust design. In the hot-cell exhaust design, the mounting is sloped to permit runoff of any liquid accidentally spilled on the shield that protects the filter and to facilitate handling by the cell electromechanical manipulators. Where cylindrical HEPA filters are used, liberal clearance (at least 1/8-inch all around) between the case and receiver is necessary to accommodate the characteristic out-of-roundness (see **Figure 6.25**). The advantage of cylindrical filters is close conformance to round ducts and pipes, which can both permit the use of smaller, cheaper duct transitions and require less space. For inline installations, however, except where the filter has flanges on both faces and is installed as a spool piece, provision must be made to extract the filter from the duct or pipe after the connection is broken, thus risking loss of the space advantage over an equivalent open-faced rectangular filter. Spool-piece filters must have flanges and withstand the forces imposed by the duct or piping system and the flange bolting.

Cylindrical filters are often used in radioactive vacuum cleaners and portable air purifiers. The air purifier shown in **Figure 6.26** is a single-use device that is discarded when the contamination level or pressure drop of the collectors becomes greater than the pre-established design level.

Figure 6.26 – Cylindrical Filter Air Purifier

6.5 Installation

6.5.1 Human Factors

The recommendation to install filters vertically with horizontal airflow is discussed in Chapter 4. When practicable, single-filter installations should be located where they can be reached for service and testing without workers having to climb ladders or scaffolding. This requires consideration of human engineering factors. Analysis of the recommended weight limits indicates that handling a 1,000-cfm HEPA filter in the body positions often encountered in filter-change operations is at the upper range of personnel capability, and that handling of adsorber cells is well beyond the limits for one person.

Consideration must be given to the positions that a worker must assume to perform the required task. If the worker must hold his hands overhead for any length of time, fatigue may result. If crouching, bending, or squatting is required, the worker will soon become stiff, which will contribute to loss of efficiency. If a worker has to hold a heavy weight while performing a precision operation (e.g., supporting the weight of a filter or adsorber cell while trying to fit it between duct transitions or into a restricted opening), the stress of the combined task will become fatiguing and a mistake could occur.[9] All of these factors are compounded when the worker must wear protective clothing and respiratory protection. In addition, protective clothing adds to the worker's spatial requirements and limits mobility. For HEPA filter and adsorber cell installations, location of the filter or housing at an elevation between knee and shoulder height is recommended.

6.5.2 Fume Hood Filter Installations

The wide, often unpredictable variety of chemical operations conducted in laboratory fume hoods makes selection and installation of HEPA filters difficult and uncertain. Corrosive fumes may damage the filter and its mounting, and moisture and heat from hood operations may accelerate that damage. Operations that produce steam or moisture should be restricted to minimize condensation in the filter or the carryover of water and/or chemical droplets to the filter. The system should be designed so that any droplets will be vaporized prior to reaching the HEPA filter.

Some facilities install fume hood filters in the attic, usually directly above the hood served. Where this design is employed, the attic space should be designed as a confinement zone for easy cleanup in the event of a spill, and should not be used for extraneous purposes such as storage and experimental work when radioactive materials are handled in the hood.

Hood installations in which perchloric acid and certain other chemicals are handled should be provided with washdown facilities to permit periodic decontamination of the hood and ductwork (perchloric acid hoods should not be used for handling other materials because of the explosion hazard (see Chapter 11, Section 11.1.3, for more detail on perchlorates). Off gas scrubbers are often provided in hoods. Both washdown facilities and scrubbers generate substantial quantities of water droplets. Provision of demisters that meet the requirements given in Chapter 3, Section 3.6, should be considered to protect the filters and their mountings. Moisture collected in the demister should be conducted to a hood drain rather than permitted to fall into the workspace of the hood. Demisters should have adequate handling space and be easily accessible for cleaning, inspection, and replacement. Where incandescent particles or flaming trash can be released to the hood exhaust stream, a spark arrester may be needed to protect the HEPA filter. This arrester can be either a commercial flame arrester, a metal-mesh graded-density demister, or at minimum, a piece of 40-mesh metal cloth. In any event, it is recommended that the arrester be located at least one foot ahead of the HEPA filter and must have easily accessible for cleaning, inspection, and replacement.

Heat sources such as heating mantles, furnaces, and Bunsen burners are common equipment in laboratory fume hoods and should be planned for in the initial hood and exhaust system design. Designers should control heat-producing operations by limiting the size of heat sources, insulating furnaces, etc., or using air cooling methods. [Note: Chapter 10 discusses operational control for fire prevention and heat control in HEPA filter systems.]

6.5.3 Portable Air Cleaning Units

The use of portable HEPA filtration systems has become quite prevalent within the nuclear industry. Radiation protection standards stress the use of engineered controls, principal localized ventilation, and confinement as the primary means of controlling occupational exposure to airborne contaminants. Decontamination and decommissioning activities utilize supplemental ventilation to control the large amounts of dust generated by demolition activities, especially as existing facility ventilation systems are decommissioned. Portable air filtration systems pose their own unique challenges to both the designer and the end user. As with commercial side-access housing, well-designed portable filtration systems (shown in **Figure 6.27**) are much more than "black boxes." Careful evaluation of system requirements, selection and integration of components, and attention to construction methods are all required to ensure a functional, effective, user-friendly system. This process has been made somewhat more difficult, however, due to a lack of industry standards that specifically address portable HEPA filtration units.

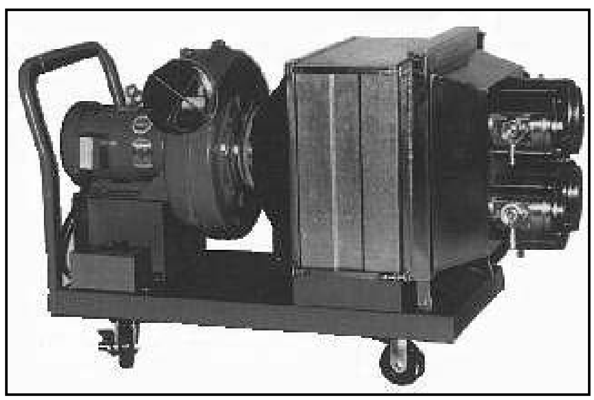

Figure 6.27 – Portable Filter Unit

Most procurement specifications for portable HEPA filtration systems should be developed by using ASME AG-1[6] and the more recent ASME AG-1.[6] These standards address the in-place safety systems for nuclear facility ventilation. While many aspects of these standards are applicable to portable systems, wholesale application without consideration of the unique features and functionality of portable systems may result in unrealistic specifications that are difficult, costly, or impossible to meet. Compromises need to be made, but without sacrificing the overall functionality and safety of the equipment.

6.5.3.1 Operational Considerations

Certain operational considerations should be addressed when selecting or specifying portable HEPA ventilation units for use in environments where nuclear or another hazardous contaminant is present. Like any other ventilation system, a portable HEPA filtration system must be designed to move and effectively clean the appropriate amount of air, required to maintain adequate environmental conditions within the workspace. Unlike permanently installed facility systems, however, the ultimate applications of portable systems are rarely known. They may be used for ventilating confined spaces, providing general area air exchanging, or providing high, localized, capture velocity in support of cutting, burning, grinding, or other mechanical and maintenance processes. Unless the system is intended for “one time, one application” use, it must be designed and constructed with sufficient flexibility to perform well under a variety of operating conditions. Thought must be given to the anticipated use of the equipment, and some basic operational questions should be asked to better define the required features. Examples include:

- Is particulate the only contaminate of concern, or will gas adsorption also be required?
- Is the expected operating environment or contaminant corrosive, or does it contain other contaminants that might affect the construction materials?
- Will the unit be used indoors or outdoors?
- What will be the ambient and process air temperature extremes?
- Will the unit be used in areas where there is high relative humidity or entrained water?
- Will the unit be used in areas where potentially explosive concentrations of gases or dust will be present, requiring special hazard class electrical components?
- Does the process or contaminant warrant redundant (series) HEPA filtration for added protection?
- Will the unit be subjected to high system losses due to using long lengths of temporary, flexible ducting and/or multiple filtration stages?
- Is heavy dirt loading expected that might require larger, more robust prefiltration capacity?
- Does the relative hazard of the contaminant require the added protection of bag-in/bag-out filter changing?
- What power is available to run the equipment? (Low voltage and amperage as well as single-phase power supplies can severely limit the capacity of the ventilation system.)
- How much space is available to stage the equipment? Is a single larger unit supporting multiple exhaust points more workable, or are smaller units placed local to the work more appropriate?
- What is the duration of the project or operation that will be supported by the portable system? Is the unit intended for reuse many times over years, or is it a one-time application? (Durability and ruggedness of construction can be greatly impacted.)

- What sampling is expected from the unit?

Careful consideration of these types of questions will better define which compromises must be made in designing a usable system.

6.5.3.2 Component Considerations

Fan Assemblies

The fan forms the heart of the system. Portable systems typically use centrifugal fans. These relatively compact fans are available in a wide range of performance capabilities and construction materials. Cast aluminum housing and wheels are common, as well as fabricated steel. Fiberglass, PVC, and other nonmetallic fans are available for processing air with corrosive contaminants. Regardless of the type of fan used, it's performance should be matched with the intended application. A fan with high static capabilities at the required flow rate is needed for a portable system that will be expected to operate with high system losses (e.g., large amounts of flexible ducting on the inlet or discharge; periods of high filter loading). Likewise, if the unit is only intended to provide local recirculation without high system losses, a fan with lower static pressure capabilities is acceptable. Fan performance should be developed using Air Moving and Conditioning Association (AMCA) 210/American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 51[10] (both organizations now issue only one common standard).

Fans are typically direct-drive systems. Due to advances in motor and solid state controller design, speed control by variable frequency drive has become popular and cost-effective for three-phase motors. Motors with appropriate hazard class ratings should be specified to protect them from internal contamination. If frequent washdown with high-pressure water is expected, appropriate duty motors should be specified. Likewise, motors with appropriate hazard class ratings should be used in hazardous locations in accordance with NFPA-70-02, the *National Electrical Code*. [11]

Motor starters should be mounted on the unit. National Electrical Manufacturers Association (NEMA) enclosures should be selected for the intended service, and NEMA enclosures and liquid-tight conduit should be specified for units intended for outdoor application or where direct water wash of the unit is expected. Reference NEMA Publication 250, *Enclosures for Electrical Equipment (1000 volts max)*,[12] for electrical enclosure testing requirements. Alternate enclosure testing standards such as International Electrotechnical Commission (IEC) Publication 60529, *Degrees of Protection Provided by Enclosures*,[13] are equally acceptable. The important point is that the electrical enclosures and wiring should be suitable for the intended operating environment, including any special NEC hazard class requirements. Overload protection is suggested for all electrical starters. Special attention should be paid to using three-phase motors and starters. Due to differences in wiring methods between the power supply and the portable systems, starter fan rotation can be easily reversed with three-phase motors.

Fan and motor assemblies should not be rigidly mounted to the system's cart or the filter housing/transitions. Vibration isolation should be used for the motor, and a flexible boot or other vibration-isolating connection should be placed between the filter bank and the fan. Vibration isolation will reduce noise significantly. The fan always should be mounted on the downstream side of the filters to ensure the filters and ductwork are at negative pressure with respect to the environment. All motor fan assemblies must have appropriate safety guards, including the fan inlet and outlet (if normally accessible), the shaft, the pulley, and the belts (if used).

Filters and Filter Housings

Any single, standard-sized, HEPA filter can be readily incorporated into a portable filtration system rated 1,500 cfm or less. HEPA filters should meet the requirements provided in Chapter 3, Section 3.2. Since the size of the portable system is quite important, small, non-standard-sized HEPA filters are more appropriate for low-volume ventilators. The same basic construction requirements described in Section 3.3.2 should be used for these filters as well. Gasketed and gel seal filters can both be used in portable systems, provided the clamping/holding mechanism stays engaged as the unit is moved.

One unavoidable consequence of the compromises made when constructing a portable air cleaning system is that the fan performance and filter ratings may not always match. A portable system designed to support a long length of ductwork and other system losses will move considerably more air when it is operated with lower system losses. The fan may be capable of moving air at a considerably higher rate than the filter's rated capacity. The portable air cleaning system should be able to maintain the rated flow through the HEPA filter as the differential pressure of the filter increases due to loading. As velocity increases, efficiency decreases. [Note: The rated flow of the HEPA filter must not be exceeded. A flow device should be included in the portable air cleaner, and the flow of the unit should be administratively controlled.]

The fan curve will indicate the system's maximum potential flow rate. The free airflow rate, or the flow at zero in.wg static pressure, is the maximum flow that most fans can develop. Since the fan is connected to a filter bank, some system losses are present, so the free air rate is not a good indication of maximum flow. The flow rate at the expected operating pressure is a better indication of the maximum flow that the fan/filter system can be expected to deliver.

The filter housing can be as simple as a side-access housing. A housing with bag-in/bag-out features provides added protection from high-risk contaminants or for units used outside. Depending on the contaminants present, the use of a side-access housing may not be warranted. Considerable size, weight, and cost can be saved with alternative filter-retaining methods. Filter sealing/housing arrangements or traditional side-access housings have been successfully used for many years. **Figure 6.28** depicts several portable system arrangements. Whichever method is used, the filter frame and clamping method should meet the standards previously discussed in Section 6.2. The sealing surface must be flat, square, fully welded, and ground smooth. The filter sealing surface must be fully welded to the pressure boundary of the filter housing. The clamps or latches retaining the HEPA filter should exert the recommended sealing force [20 pounds per square inch (psi) of gasket area], and should use a spring-loaded or tension method to ensure a positive clamping force is maintained (this is unnecessary when gel-sealed filters are used). Since portable systems are designed to be moved, the chosen clamping or housing method should adequately protect the filters and prevent unclamping or dislodging of the filter due to cart movement. The system's cart should be sufficiently rigid in construction to limit the amount of flexing seen in and by the filter frame and housing. When the filter is exposed, only metal-cased HEPA filters should be used.

Figure 6.28 – Typical Portable Systems

Prefiltration should be integral to the portable system. Prefilters should be accessible independent of the HEPA filter and should not require unclamping of the HEPA filter during change-out. Additional inline prefiltration may be needed for heavy dirt loading applications such as concrete-cutting and abrasive blasting. [Note: A spark arrester must be added to the prefilter for plasma arc cutting or any other type of spark-producing activity.] Moisture separation also may be required. This can be addressed using either demisting pads that are integral to the portable system or supplemental dehumidifiers in line.

Adsorber beds can be configured on portable carts as well. The carbon cells can be adapted as part of the portable filter system or as a separate stand-alone assembly that is interconnected with the filter unit on an as-needed basis.

6.5.3.3 Construction

Portable equipment used in an industrial setting is subject to abuse. As such, construction of a portable filtration system needs to be rugged and suitable to a harsh industrial environment. Transitions and housing pressure boundaries should be fully welded. Properly designed gasketed and bolted connections, especially on transition to and from the filter, are necessary to avoid loosening over time. Assembly should allow access for decontamination purposes. Construction materials should be compatible with the operating environment. Stainless steel is highly recommended, especially for those components that come directly in contact with the contaminated airstream.

Quality wheels and casters should be used on wheeled equipment. At least one set should have a brake or some other means of securing the cart in place. Wheels should be compatible with the surface where the equipment will be used. Hard wheels are suitable for indoor use and are more readily decontaminated, while large pneumatic wheels may be more appropriate for outdoor applications. Wheel design should allow replacement if the wheel becomes contaminated or damaged. On larger units, channels for fork truck lifting or lifting eyes will facilitate handling. Lifting points should be conspicuously marked. A stout push handle is a desirable feature. Tow bars can be used for larger skids, allowing the cart to be pulled like a trailer.

Flow control dampers should be incorporated into the unit, especially on systems with multiple connection points. Dampers located in the ductwork close to the work area may be advantageous if frequent flow adjustments are necessary. Dampers should include a positive lock to ensure that the damper will not move once the desired flow balance is achieved. Blast gates, quadrant control, and butterfly styles are all suitable for flow control dampers on portable systems. If possible, dampers should be installed so that in the event of a failure, they fail in place or open, thus preventing a sudden loss of flow in the event of damper failure.

Tapered transitions add considerable length to a portable system, so abrupt transitions are frequently used on portable systems where size is a concern. If abrupt transitions (e.g., no taper) are used, a plenum space of at least 4 inches should be left in front of and behind the HEPA filter. This space will allow for airflow expansion, thereby reducing air velocity prior to entering the filter.

Duct connection points should be undersized to allow connection of flexible ducting. Allow 1/8 inch less than the nominal size of the flex ducting used. For example, a 7 7/8-inch outside diameter connection would be required if 8-inch diameter flex ducting were used. A roll bead, round bar, or other protrusion fabricated into the duct connection point will help secure the duct when a hose clamp is installed behind it. **Figure 6.29** shows a typical duct connection with a roll bead.

Differential pressure (DP) gauges should be installed to monitor dirt loading on the HEPA and prefilter. Individual gauges for both stages of filtration are desirable. Since the flow rate through a portable system can change significantly depending on ductwork routing and damper adjustments, the user must be aware that observed changes on the DP gauge may not be due to dirt only, but may instead reflect a change in the air velocity through the filter element. For this reason, it is necessary to ensure that, when assessing dirt loading on the filters over time, DP readings are taken under the same flow conditions. Alarms that indicate high filter DP, as well of loss of airflow (which can be indicated by a very low filter DP), are also good features. The same general caution about the affect of air velocity on filter DP would apply to these alarms as well.

6.5.3.4 Portable HEPA Filter Systems Testing and Inspection

Figure 6.29 – Duct Connection with Roll Bead

Portable air cleaning units require a great deal more periodic inspection and in-place leak testing than permanently installed systems. This is due to the inherent fragility of portable units and lack of stringent manufacturing standards for them. The rough handling and shock they can be expected to experience during transport makes careful inspections and functional tests, including in-place leak testing, mandatory prior to each use at installation. Also, anytime these units are moved or jarred after they are put into service, careful inspections and functional tests—including in-place leak testing—must again be performed. The testing of these units is covered in Chapter 8. Temporary, portable ductwork is fragile and may be subject to degradation, especially if exposed to sunlight, chemical vapors, or heat. It should be inspected and checked for leakage frequently, depending on the application, a daily or weekly schedule may be appropriate.

6.5.3.5 Vacuum Cleaning Systems

HEPA-Vacs are most commonly used to control friable particulate before it becomes airborne. They are also used to control airborne particles and liquids in and around work areas and to locally control loose debris when work operations could potentially spread contamination. When used in the nuclear industry, HEPA-Vacs are commonly referred to as nuclear or radiological vacuum cleaners.

Figure 6.30 – HEPA Filter Vacuum

Description of Radiological Vacuum Cleaners

Radiological vacuum cleaners are generally well-constructed, well-sealed devices with a HEPA filter on the exhaust. They are normally mounted on a cart with a comfortable handle and lockable and steerable wheels for portability and control during use. The power module consists of a fan powered by an electric motor and controlled by an onboard switch. The filter module consists of a positively mounted and sealed HEPA filter, protected by a prefilter. All units should have a positive plenum (tank)-to-vacuum head seal. Vacuums that have latches but provide a loose head-to-tank seal that depends on the vacuum force to provide a positive seal (i.e., many commercially available shop vacuums) should not be used.

Some vacuum cleaners are equipped with controllers that allow the worker to regulate the flow. This works well in providing negative ventilation in small glovebags. Using HEPA filtered vacuum cleaners can significantly improve how contamination is controlled.

An inline HEPA filter can be installed in the suction hose to collect radioactive material before it reaches the vacuum cleaner. Fittings can be made to connect the vacuum cleaner hose to the HEPA filter. As debris is sucked into the hose, it is deposited on the inline HEPA filter instead of the HEPA filter inside the vacuum cleaner. Temporary shielding should be installed around the inline filter before operation, as the filter becomes highly radioactive.

Figure 6.31 – HEPA Filter Vacuum

If a large amount of debris will be collected, installation of a waste drum in the suction hose should be considered to ensure the debris collects in a waste drum and not the vacuum cleaner. Commercial systems are available, or one can be constructed by welding two pipes into a spare drum lid. As each drum is filled, the lid can be swapped to a new drum and a regular lid can be installed on the full drum. Personnel radiation exposures are reduced because the debris is collected directly into the waste drum instead of the vacuum cleaner.

Vacuum cleaners should be constructed of a material that is easily decontaminated without damage to components. Units that use silicone-based material to prevent leakage should not be used. All hose connections should provide positive seals and should be constructed of a material that will not be damaged by repeated use or rough handling.

HEPA filters should have a positive seal and pass in-place leak testing prior to use at the site. This is necessary as these units are usually transported to the site in pick-up trucks and are dragged up flights of stairs and along rough floors and walkways. This is an invitation for filter leakage so careful handling is important. The filter holddown clamps should provide the required force (20 pounds per square inch) to seal the filter and prevent dislodging during rough handling and repeated use. They should be constructed of a material that will not warp or bend with repeated use.

The HEPA filter replacement method should be simple and should be performable in minimum time to reduce exposure and the chance of radioactive contamination. The vacuum cleaners should be designed to ensure HEPA filter integrity under all conditions of use and to prevent unauthorized or accidental access to the inner surfaces of the vacuum. Units should be constructed with no sharp edges or burrs that could injure personnel or damage protective clothing.

HEPA filters used in HEPA-Vacs should meet the efficiency and construction requirements for HEPA filters in DOE STD 3025[14] and ASME AG-1.[6] The maximum flow rate of the device should not exceed the flow rate at which the HEPA filter was efficiency tested. The HEPA filters should be certified at the DOE Filter Test Facility.

Operation

HEPA-Vacs are used to cleanup radioactive debris in the work area. Improper use of HEPA-Vacs may result in generation of airborne radioactivity, loose surface contamination, or high dose rates. HEPA-Vacs used for radioactive material should be marked "For Radioactive Service Only."

A nuclear criticality safety review must be performed and documented prior to use of a HEPA-Vac for fissile material.

HEPA-Vacs must be appropriate for the type and amount of radioactive material involved. The health physicist is responsible for determining the levels of filtration required on the exhaust. Programmatic organizations are responsible for the following:

- Maintaining control of HEPA-Vacs.

- Ensuring that HEPA-Vacs are tested on a frequency consistent with their use. This frequency should not exceed 1 year. HEPA-Vacs must be retested if the integrity of the filter media or the sealing surface of the HEPA filter is compromised, if the HEPA filter is exposed to water or high levels of water vapor, or if the HEPA-Vac is transported to another area or site.

- Ensuring that HEPA-Vacs are properly labeled, controlled to avoid improper use, and serviced or emptied only by individuals trained to do so, and that the health physicist is contacted before the HEPA-Vacs are opened.

HEPA-Vacs used in contaminated areas should be equipped with HEPA-filtered exhausts or with exhausts that are directed to installed systems equipped with HEPA filters. Such provisions may not be necessary when these systems are used in areas where only tritium or radioactive noble gases are present or when the material to be vacuumed is wet enough to prevent the generation of airborne radioactive material or removable surface contamination. Extended use of air handling equipment may cause a significant buildup of radioactive material in the ductwork and filters. Periodic sampling of the exhausted air and surveys of the accessible surfaces of the equipment should be performed to assess the radiological impact of equipment operation. While use of the devices discussed above has been proven effective in reducing contamination spread and associated decontamination costs, these benefits must be weighed against the potential costs. Use of engineering controls may require expenditure of worker doses to set up, work in, maintain, and remove the device. There may be financial costs associated with device purchase or manufacture, worker training, possible reduced productivity, and device or component maintenance and disposal.

Testing and Periodic Maintenance

Problems with operating HEPA-Vacs are often not visually observable or detectable by onboard instrumentation. Therefore, filter replacement and testing are important to the continued safe operation of the unit. In-place testing is designed not only to validate the HEPA filter, but also to verify the integrity of associated seals, gasketing, ducting, and housings to leakage. Testing of HEPA-Vacs is covered in Chapter 8.

6.6 References

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CHAPTER 7

GLOVEBOX FILTRATION

7.1 Introduction

Gloveboxes are enclosures that enable operators in various industries (e.g., nuclear, biological, pharmaceutical, microelectronics) to use their hands to manipulate hazardous materials through gloves without exposure to themselves or subsequent unfiltered release of the material to the environment. In the nuclear industry, gloveboxes provide primary confinement for radioactive material handling and process protection and are used to handle a diverse range of chemical, oxygen-sensitive, pyrophoric, hazardous, and nuclear materials. [Note: There are many other factors, (e.g., seismic, shielding, etc.,) that could impact glovebox filtration design and operation. Secondary confinement may be provided by the room or building where the gloveboxes are located.]

Ventilation is the heart of the glovebox system. Nuclear materials requiring handling inside a glovebox usually present little or no penetrating radiation hazard, but emit radioactive particles that could be dangerous if inhaled. Gloveboxes prevent operators from inhaling radioactive particles as they work with various nuclear materials and help provide a clean, controlled, safe working environment. For glovebox ventilation to be effective, however, proper design pressures and flow criteria must be maintained. Glovebox pressures range from mostly negative (for confinement) to positive pressure environments (for process protection). Failure to maintain correct operational pressures or to follow established operational procedures could render a glovebox both ineffective and unsafe.

This chapter discusses filtration of air or other gases associated with glovebox ventilation. The discussions in this chapter are not meant to be application-specific, but are intended to provide general information that may be useful in glovebox design and operations (i.e., specifics related to activities such as plutonium or beryllium operations will affect glovebox ventilation design).

7.1.1 Glovebox Descriptions

To understand the importance of glovebox filtration, a clear understanding of glovebox characteristics and functions is necessary.

A glovebox (**Figure 7.1**) is a windowed, airtight (sometimes gas-tight) enclosure that may be capable of positive or negative internal pressure. It is equipped with one or more flexible gloves for manipulation of materials and performance of operations inside the enclosure from the outside, uncontaminated environment.

Figure 7.2 defines and lists characteristics of gloveboxes, with a focus on their use in the nuclear industry. Originally, many gloveboxes were vendor-designed, so the designs were proprietary. As a result, many older boxes have unique ventilation designs. Today, professional societies such as the American Glovebox Society (AGS) have documentation such as AGS-G001, *Guidelines for Gloveboxes*,[1] which was written by Government employees and vendors who work with, manufacture, and design gloveboxes. This document contains useful information on subjects ranging from the need for a glovebox to related quality assurance acceptance programs.

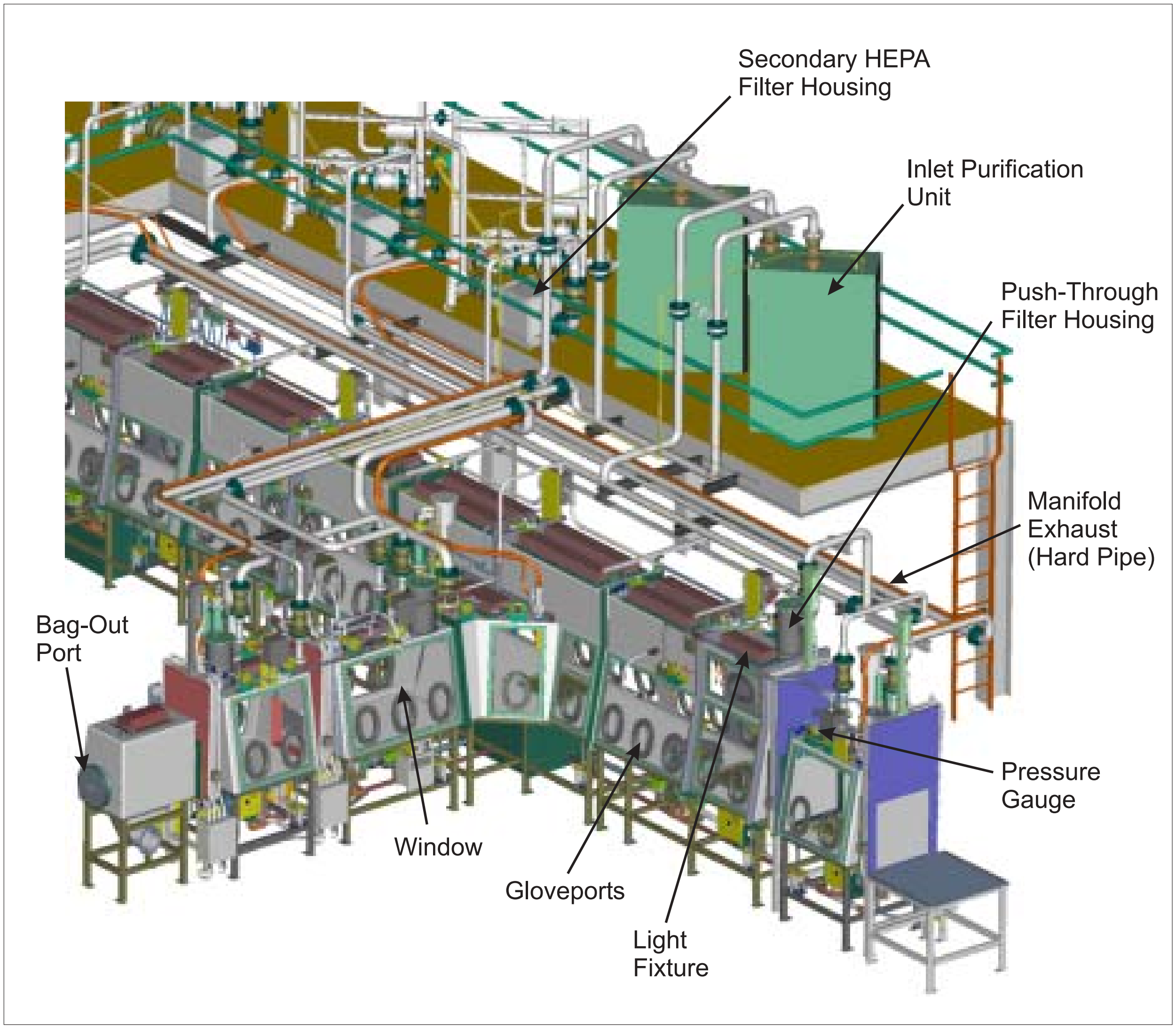


Figure 7.1 – Typical Glovebox Showing Major Features

There are still manufacturers who produce "research-type" gloveboxes in the United States today. These boxes can be used by some U.S. Department of Energy (DOE) facilities, but it is not advisable to use them for nuclear activities, as most are not equipped with a method for safely changing the high-efficiency particulate air (HEPA) filters and may not meet the provisions of this chapter. [Note: The HEPA filters used on some of these gloveboxes do not meet the recommendations provided in Chapter 2 or American Society of Mechanical Engineers (ASME) AG-1.][2]

Ongoing development of gloveboxes for use by the nuclear industry has resulted in many changes through the years. Gloveboxes have evolved from the somewhat standard sizes to larger custom systems containing all of the process-related equipment. The larger gloveboxes cited in this Handbook have some unique characteristics. Some are as large as 150 feet long, 4 feet deep, and 15 feet tall. See **Figure 7.3** for a portion of the type of glovebox. Note the numerous gloveports which allow access to all points in the box. Their ventilation design includes side-access filter housings (see Chapter 4) instead of the designs described later in this chapter. Other design philosophies place drive motors, equipment, and electrical devices externally, thereby reducing maintenance, heat loading, size, and disposal costs. Seals are used to pass drives and electrical controls through the glovebox pressure boundary. In some cases, the design philosophy has been

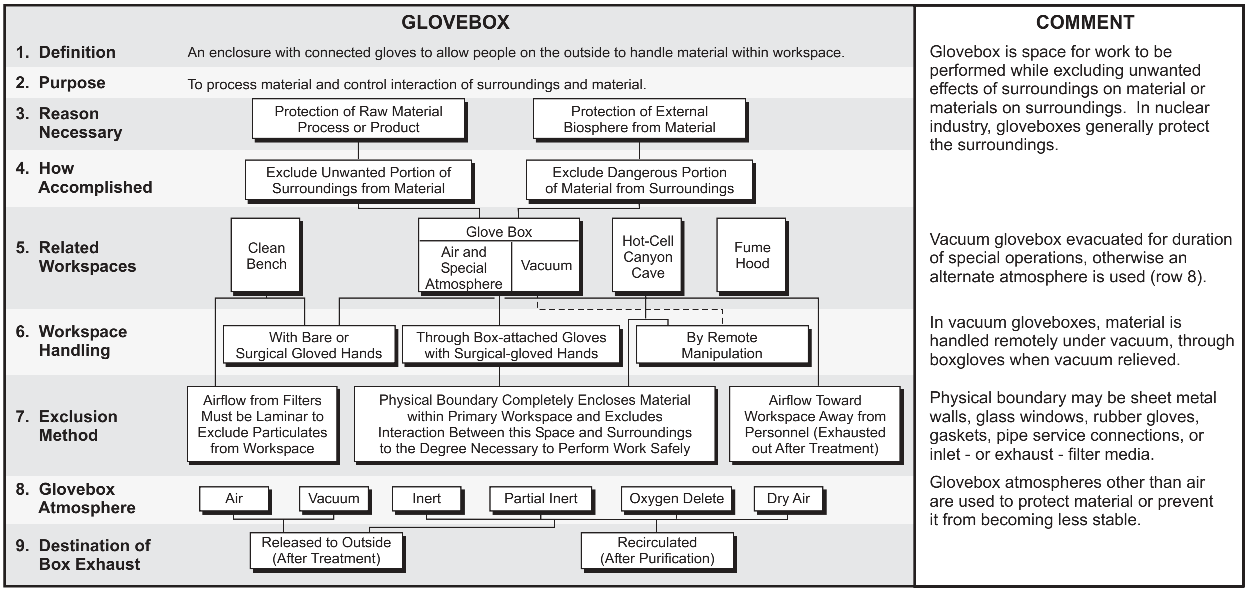


Figure 7.2 – Characteristics of Gloveboxes

to size the glovebox for a specific process to minimize volume and service requirements. In all cases, ergonomics and confinement are critical to the performance of daily operations and routine maintenance.

Gloveboxes generally have several common characteristics. They are often no deeper than 26 inches (as far as most arms can reach—it is desirable to be able to reach most areas of a glovebox). If deeper space is needed, a dual side-access design may be selected. These contain one or more safety glass, laminated-glass, or polymer viewing windows located on at least one side. Gloveports (window-mounted or in the stainless steel shell) are usually available in multiples of two at various locations in the glovebox walls. Interior workspace is reserved for primary operating purposes on the box floor between the gloveports and within reach of a gloved hand. Remote handling capabilities, other than tool extensions for the gloved hand, are usually not provided.

Gloveboxes are normally kept at a negative pressure of 0.3 to 0.5 inches water gauge (in.wg) relative to their surroundings. The maximum safe operating differential pressure between the interior and exterior of the box is usually less than 4 in.wg; greater differential pressure may damage or rupture a glove or window, causing subsequent loss of confinement. Operators experience fatigue when pressures inside a glovebox are greater than 0.5 in.wg, and performance of intricate tasks becomes tedious. Material and HEPA filter transfers between glovebox interiors and exteriors are commonly made through a bagging port which, although time-consuming and user-dependent, is still the safest practical way of maintaining confinement. New versions of this technology use a banding system. Other material transfers use rapid transfer ports (RTPs), which allow simple docking from glovebox to glovebox. This is a reliable method of maintaining confinement as long as the seals are maintained and undamaged. [Note: Transfers of powders can egress past the seals if exposed. Such powders should be contained in a secondary container and the seals protected during operations.] Gloveboxes with RTPs are still equipped with bagging ports for filter changes and waste disposal.

HEPA filter installations must adapt to limitations while still providing reliable service. Hybrid glovebox-shielded cells, vacuum gloveboxes, room-high gloveboxes, glovebox "trains," etc., are often encountered, and all require reliable filter installations.

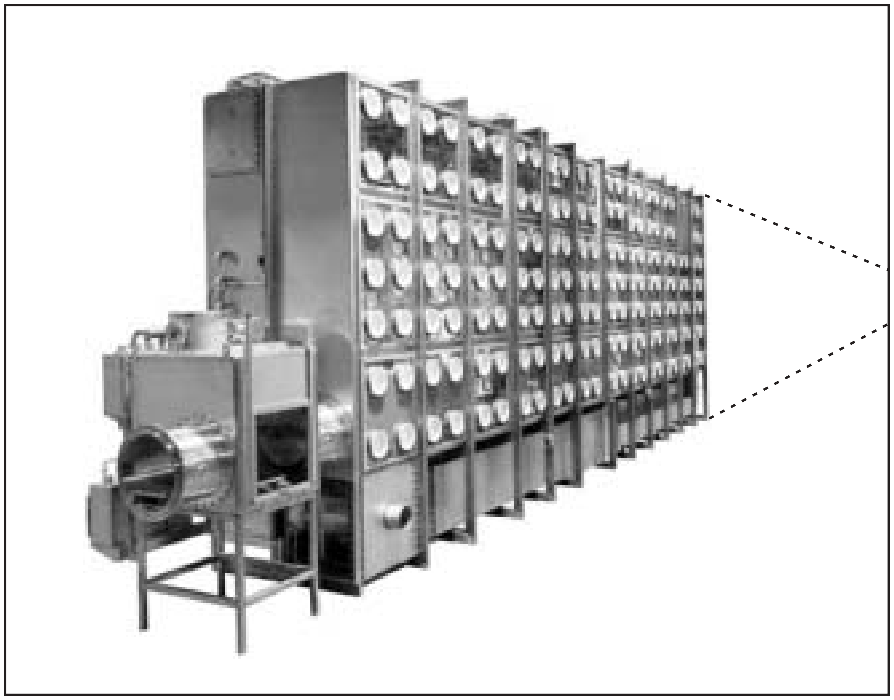


Figure 7.3 – Glovebox with Multiple Gloveports to Facilitate Access

Special atmospheres such as inert gas and dry air are often used in gloveboxes for fire suppression and for oxygen-sensitive and/or moisture-sensitive materials and processes. Gas purification systems are commonly used in conjunction with inert environments to maintain environmental control. These units purify and dry the environment to prevent consumption of large volumes of inert gas and desiccant. It is important to protect these devices from contamination because they constantly recirculate the volumes of the gloveboxes they serve.

7.1.2 Importance of Glovebox Ventilation and Filtration

Operations conducted in gloveboxes often provide the elements for unstable conditions (e.g., fire and pressurization). A properly designed and operated glovebox ventilation system minimizes these instabilities as well as the possibility of an accidental release of airborne radioactive material. Room air is a safe glovebox environment for many applications. On the other hand, operations with pyrophoric materials such as plutonium or the presence of reactive gases such as hydrogen may require a special environment (e.g., low oxygen, inert gas, and moisture control).

For air-atmosphere boxes, ventilation at relatively low flow rates provides sufficient dilution of the limited combustible volatiles found in well-operated gloveboxes. The correct airflow volume, along with the proper location of supply and exhaust filters, minimizes the likelihood of fire while providing sufficient dilution to prevent the buildup of explosive gases. Good glovebox ventilation dictates that HEPA filters are operated at their designed airflow [cubic feet per minute (cfm)]. It is important that HEPA filters are tested and certified at the manufacturers' rated airflow. As airflow increases, efficiency decreases.

Normal air changes through a glovebox remove some of the heat generated by equipment inside the box and help maintain reasonable working temperatures for the operator. However, this convective cooling may be insufficient to remove all of the process heat generated in the box, and auxiliary cooling or higher airflow volume may be required. Most glovebox ventilation systems include some form of pressure relief and adequate pressure control to maintain proper pressure differentials between the glovebox and its surroundings. If a glove should tear or accidentally come off, there should be an assured, sufficient ingress of air through the gloveport to prevent egress of contamination until the port is closed. This safety feature is inherent if the glovebox ventilation is designed and operated properly. Pyrophoric operations, however, should have appropriate safeguards to prevent air intake from starting a severe reaction.

Proper instrumentation should be provided to warn of inlet/exhaust filter blockage and loss of pressure/confinement. Pressure gauge/transducer line filters should be used to protect this instrumentation.

HEPA filters have been used on gloveboxes to contain radioactive materials since the early days of the nuclear industry. History has shown that, as a rule, they have been adequate; however, submicron-sized particles of some materials can pass through HEPA filters. In such cases, it is critical to have knowledge of the material properties. Technology should be used to help determine the type of filters and efficiencies that can be used for a proper filtration system.

In summary, the glovebox ventilation and filtration system must be capable of reliable performance to assure glovebox operators that they may safely operate the box without fear of exposure to airborne contamination to themselves, other facility personnel, and the environment.

7.2 Design of Glovebox Ventilation Systems

The principals of glovebox confinement are basic. Airflow of 125 ± 25 feet per minute (fpm) through a breached (8-inch diameter) gloveport will maintain confinement. This is an inherent (defined as “real time, at the moment of failure”) safety feature that should be incorporated into the glovebox system. Most nuclear, biological, and pharmaceutical facilities in the United States are designed to provide this capability (within a range of 10 percent). It is important to understand how this is achieved.

A glovebox is basically a closed volume. When the blower unit draws air (negative side) from the box, the box is under negative pressure. The filters help regulate this pressure. Filters are essentially controlled leaks that allow airflow through them while trapping the particulates they are designed to filter out. The inlet filter establishes the actual glovebox working pressure, while the exhaust filter system establishes the inherent safety feature. It is therefore critical for the exhaust filter to be properly engineered into the system to perform its inherent duty. When a gloveport breach occurs, by design the inlet filter is bypassed and the breached gloveport becomes the inlet.

The air change rate is an important consideration for all gloveboxes. As glovebox volume increases, airflow should increase. Nonetheless, the inherent safety feature of 125 ± 25 fpm through a gloveport must be maintained. For normal operations, flow rate is based on the dilution of evolved combustible or corrosive gases and heat dissipation, as well as prior experience. The exhaust capability must be sufficient to provide safety under postulated abnormal conditions, including the gloveport breach. In certain other applications, the exhaust capability must be sufficient to provide safe access for planned activities.

Operating personnel, industrial hygienists, and radiation specialists can assist the designer in establishing realistic requirements, particularly when an existing system is being replaced or revised. The types and quantities of materials to be used inside the box and their toxicity and state (wet slurry, dry powder, etc.) must be considered when establishing the air exchange rate and velocity. When exposed radioactive material is handled inside a glovebox, the box becomes the primary confinement. When handling nuclear and pyrophoric materials, consideration should be given to whether pressure inside the glovebox should be positive or negative. A positive-pressured glovebox provides a motive force for airborne contamination to leak from the box into the secondary confinement (the room or facility). Negative pressure inside the box is essential to maintain glovebox confinement when working with radioactive material. It is not usually acceptable to design a normal operating condition that allows a primary confinement area to be positive to the secondary confinement area. However, in a unique or unusual application where an inert environment is used to control fire and explosion, the box may be slightly positive or even neutral, and the facility becomes the primary confinement. This suggests the need for a secondary confinement and also flags the need for personal protective equipment and appropriate procedures to protect the worker. The designer must design for failure (i.e., using the worse case scenario) to predict the consequences of a glovebox failure. The designer also must consider test and acceptance criteria.

7.2.1 Blowers

The blower is the motive force that provides the pressure and airflow requirements in a glovebox. Related principles are covered in Chapter 5. Glovebox blower requirements have different or additional requirements. Generally, the airflow is very low (approximately 35 cfm) for most applications. [Note: This is true for gloveboxes with volumes of less than 100 cubic feet (ft^3), and does not factor in heat or gas loading.] Blower selection must account not only for the breached gloveport scenario, but also for corrosive gases and filter loading.

The typical airflow for most gloveboxes is 35 cfm, assuming a standard 8-inch-diameter gloveport. A typical cartridge filter rated at 35 cfm will have an approximate 0.8-in.wg clean static pressure drop. When both inlet and exhaust filters are installed, the total pressure differential for the filter requirements is 1.6 inches water column (in.wc). [This does not factor in the ductwork and inlet configurations.] The filter loading factor for most facilities is sometimes greater than double the initial static pressure. In this situation, the blower must be able to perform within its blower curve at 1.6 to 3.2 in.wc and still produce 35 cfm. This is a higher pressure and lower flow than used for most fan and blower applications. A regenerative blower is often used in this application. These blowers operate similar to pumps in that the clearance between the blower wheel and blower housing is very small. If the blower is to service more than one glovebox, the blower should be sized to handle the additional requirements. Exhaust manifolds should use dedicated lines for each glovebox to prevent transfer of heat from one glovebox to another.

Regardless of the type of blower or manufacturer, the required airflow and pressure requirement must be attained for safe operation of a glovebox. Another criterion for blower selection and design is selection of a blower that does not exceed the pressure limits of the glovebox. Depending on their size, most stainless steel gloveboxes with 7-gauge walls are designed and tested at -4 in.wg. Exceeding this pressure may cause damage to the glovebox windows, seals, and shell. If the blower exceeds this limit, the glovebox should be equipped with a pressure relief device.

“Pressure recovery” is a term that evolved from quick insertion and removal of operators’ arms into and out of the gloves. Although the blower will deal with most of the volumetric changes caused by glove movement, loading the exhaust filter will prevent the blower from quick recovery. Exhaust filter and gloveport sizes also influence recovery. This is the reason for maintaining the inherent safety feature at the design phase of a glovebox project. If larger gloveports (greater than 8-inch-diameter) are selected, the need for additional airflow must be engineered. Site-specific filter housings and filters may not address the need for increased airflow.

Blower location depends on several variables in glovebox applications. If a scale or other vibration-sensitive device is used in the glovebox, the blower should be isolated from the glovebox shell with vibration isolators and a flexible inlet/exhaust connection. Although this works in most applications, some may require remote location of the blower away from the glovebox. Blower noise should be considered to prevent annoying the workers. Noise levels should be kept to less than 80 decibels A-weighted (dBA).

7.2.2 Filter Housings

It is imperative that the filter housing on a glovebox be designed to function correctly. It should incorporate designs for safety, ergonomics, and reliable operation. Filter change-out should be simple and should maintain a safe level of confinement. The design should prevent any form of contamination from reaching the downstream ductwork or secondary confinement (the facility). The design should satisfy the ergonomic requirements of filter changes and allow the operator to perform the operation safely (without exposure or injury). In most installations, the filter housings are located in areas of the glovebox that are awkward to reach. A top-mounted filter housing should be located as close to the front of the glovebox as possible and should be aligned with a gloveport. Although DOE-STD-1066, *Fire Protection Design Criteria*,[3] suggests locating the exhaust filter housing to a lower position in the glovebox for fire purposes, this may cause a loss of confinement in some applications. Process activities and materials could block the exhaust filter. Without the exhaust filter airflow, it would be difficult to maintain confinement. The filter housings on gloveboxes differ from most filter housings in that they are very small due to ergonomic limitations and low airflow requirements. Changing a glovebox filter is difficult because it must be performed through a gloveport with limited operator movement. Use of larger filters should be avoided because they are difficult to handle safely inside a glovebox without special tooling.

7.2.2.1 Types

The types of filter housings selected for use on gloveboxes have always been application-specific. See **Figure 7.4** for bag-in/bag-out port which allows for equipment removal. As many nuclear facilities function under different directives, filter housings have evolved to suit their respective applications. Early gloveboxes often had externally mounted HEPA filters. Because of the potential for spreading contamination during filter changes, this practice should be avoided.

Internal filter installations range in design, however, and all have a mechanism to restrain the filter (a HEPA filter) and a sealing mechanism. These mechanisms also vary; however, it is critical that the mechanism be free of sharp edges that can easily cut gloves. Cracks and crevices should be kept to a minimum since the location makes cleaning difficult. Filter housing construction typically requires clean, smooth finishes to allow cleanup of contaminated or potentially contaminated areas. Experience has shown that areas exposed to contamination can be impossible to clean. The rougher the surface of the housing, the more difficult it is to clean. Valves, located to the outside, are used to isolate the spent filters during filter changes. Most applications use a prefilter to protect the HEPA filter, as well as a fire screen when there is a potential for fire. Although diverse, the many prefilter and fire screen designs should meet the requirements imposed in DOE-STD-1066.[3]

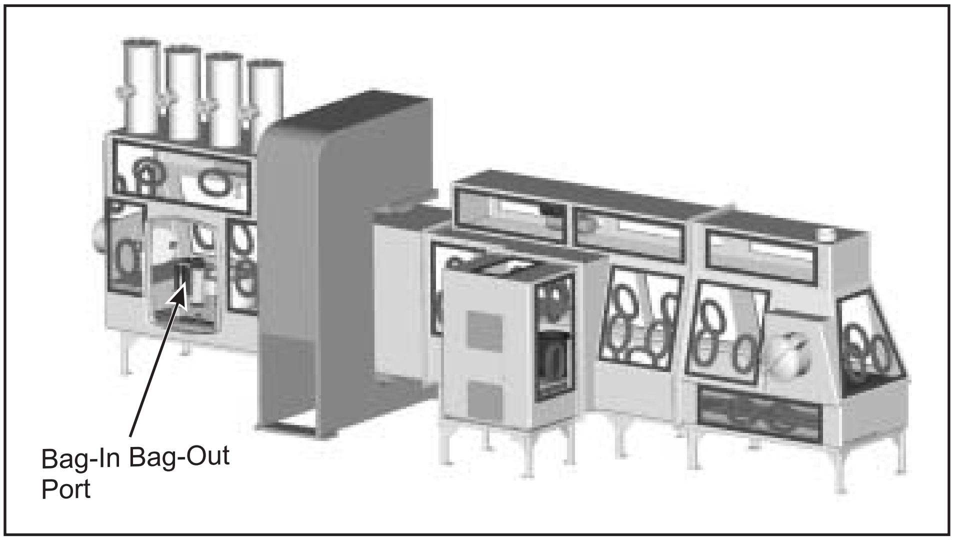


Figure 7.4 Bag-In/Bag-Out Port for Equipment Removal

The last basic requirement is a means and method to remove the contaminated filter from the glovebox. The most common method is the bag-in/bag-out method. Push-through filter housings differ in that they hold the standby filter in the filter housing. (See **Figure 7.5** for push-through filter housing). The filter is a cartridge type with chevron seals located at the inlet and the exhaust of the round cartridge filter. One of its advantages is that it is designed to maintain confinement during a filter change. A new filter displaces the spent filter as it is pushed through. The old filter and spacer are displaced to the inside of the glovebox. The

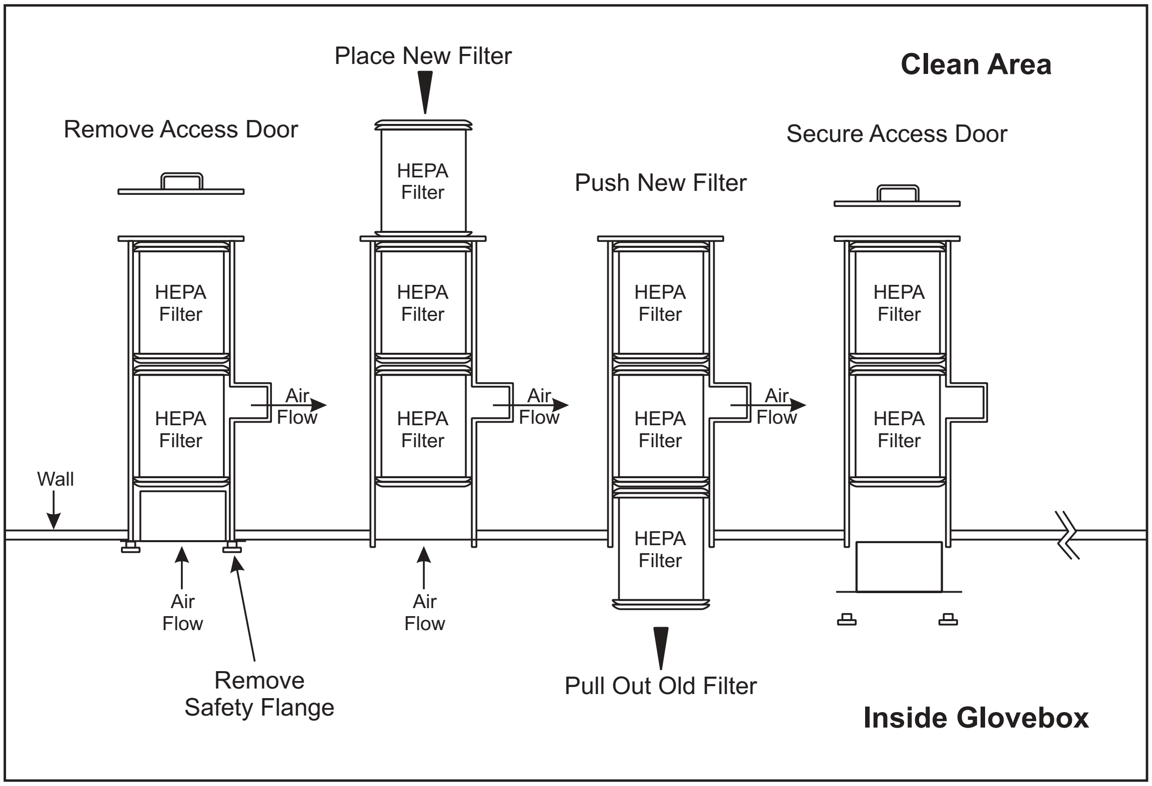


Figure 7.5 – Push-through Filter Housing

inner pipe "tube" of the housing is honed to obtain a smooth, round surface. The chevron seal, which is larger than the internal diameter of the tube, creates the seal. Although this system has been used with great success, seal quality and tube finish are critical to its proper operation. This filter housing design is vulnerable, however, when it is used for applications involving light, easily airborne materials. Such materials, if surface-deposited on the inside tube, can bypass the seals during a filter change because the seal can "roll over" the material. Another potential drawback of this design is its orientation. It should be installed in a vertical position for proper sealing. A horizontal installation will enable the seals to "take a set" and eventually bypass the filter. This filter housing has been used at nuclear facilities in the United States for many years with good reliability; however, its limitations should be noted.

Cartridge filters can be used for glovebox operations for both radioactive and nonradioactive applications. These filters incorporate the filter housing and filter as a single unit and are supplied from the manufacturer with options for pipe nipple connections on both the inlet and exhaust or on one end only. Test ports should be specified when ordering, as these filters range in size and airflows. Prefilters should be installed inside the glovebox for filters not already equipped with prefilters. A valve should be located on the outside of the glovebox filter housing.

Radioactive Applications

In some radioactive applications, the cartridge filter should be located on the inside of the glovebox for safe filter changing. The isolation valve is located on the outside of the glovebox filter housing.

Bag-in/bag-out side-access filter housings are used in some glovebox applications. They are available in sizes from 35 cfm on up and in rectangular or round configurations, as discussed in Chapter 4. For radioactive applications, it is desirable to mount the housing as close to the glovebox as practical. Long ducting or plenum runs are not desirable due to their lack of access for cleaning. Mounting the filter housing directly to the glovebox reduces the potentially contaminated surface area.

Redundant filter housings (**Figure 7.6**) are used when working with materials that, if released through the exhaust system, would be detrimental with respect to both safety and associated cleanup costs. All nuclear facilities use a secondary exhaust before discharging to the outside air; this method is a known as a "belt and suspenders" approach. In some older facilities, manifold systems were not designed for safe, clean decontamination. If contamination migrates into these systems' ducting, cleanup is both costly and time-consuming. As a result, use of a redundant filter should be considered. The design of a redundant system requires the use of an in-place-tested primary and secondary HEPA exhaust filter installation. Figure 7.6 shows two redundant filter housings—one filter changed from inside the glovebox (primary); the other (secondary) is shown as a bag-in/bag-out type changed from the outside.

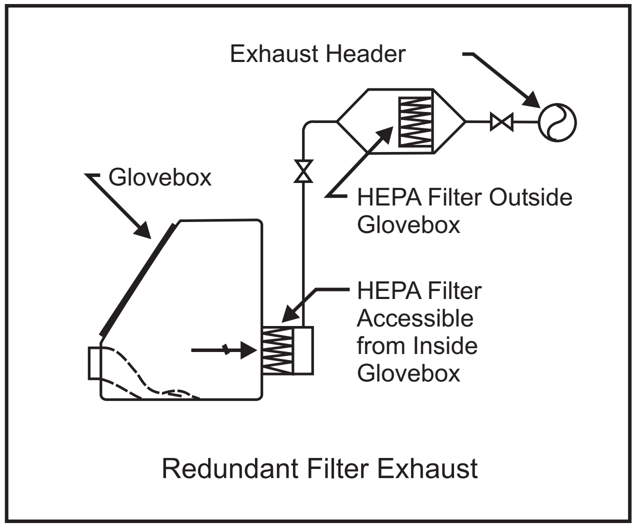


Figure 7.6 – Redundant Filter Housings

7.2.2.2 Materials

It is important to understand the construction materials used on the filters and filter housings for gloveboxes, particularly chemical processing gloveboxes. It should be clearly understood which chemicals and gases will be introduced into the airstream of the glovebox and where they will be processed if processing is required. If a bag-in/bag-out port is used, the bag material is subject to the same exposure to chemicals and gases as the rest of the ventilation. If the process performed in the glovebox changes or other materials are introduced into the glovebox system, the compatibility of the materials must be re-evaluated. Simply put, the materials, ducting, blower unit, etc., must be compatible with the chemicals and gases exposed to the exhaust airstream.

Filters are available in many different materials for different purposes. Wood, several different stainless steel and aluminum materials, etc., are commonly selected for different applications. Recently developed technologies such as stainless steel, ceramic, and Teflon® filter media have outstanding resistance to chemicals, heat, and gases. However, these recent developments have not gained wide acceptance in nuclear applications.

7.2.2.3 In-Place Test Ports

The size of a glovebox filter housing is relatively small compared to most filter housing installations. As with any HEPA filter installation, test ports should be placed on the filter housing to validate the installation. The criteria for testing gloveboxes focus on the proper location to inject the challenge aerosol, upstream, and downstream samples. The test ports should be designed to be sealed after each use and to be as cleanable as possible. This is usually a 3/8- to 1/2-inch half-coupling/nipple with the appropriate plug/cap. The weld and finish of a test port should emphasize clean smooth surfaces, especially from the inner diameter of the port to the filter housing. Cracks and crevices in this area are next to impossible to clean via access through gloveports.

7.2.2.4 Bag-in/Bag-out Ports

Bagging ports are used on gloveboxes for multiple purposes such as transferring materials and equipment and removing the waste generated during operations. Significantly, they are also used to transfer new or spent filters while maintaining confinement. It is important to size the bagging port to accomplish this purpose, and it is desirable to use a cylindrical bagging port because this design is much more “operator friendly.” A typical bagging port should have two outer-raised ribs around the outer circumference to prevent the bag from being easily pulled off during operations. The ribs are normally raised approximately 1/4- to 3/8-inches above the outer circumference and 1 to 1.5 inch apart. A safety-restraining strap should be used to prevent the bag from being easily pulled off. It should be installed whenever the bagging port is being used, and should be removed only when performing the bag-in/bag-out (new bag installation) procedure. The strap is secured between the two ribs. A cinching strap may be used to prevent the bag from being sucked into the glovebox due to negative pressure. It is installed when the bagging port is not being used. An internal access door may be used to isolate pressure surges and to act as a secondary confinement for the bag. The door should have a seal to prevent egress of contamination from the glovebox. An external cover may also be used to protect the bag and keep it out of the way of other operations. A “bagging kit” should be supplied with a bagging port. It should contain the components, tools, and procedures to perform the operation. These items are covered in Section 7.4.

7.2.2.5 Sealing Mechanisms

There are multiple sealing methods for filter housings and filters used on gloveboxes. These can be application-specific or site-specific and either gasket- or fluid-sealed. The designer should consider chemical, gas, radioactivity, and heat as deciding factors in determining which sealing mechanism to employ. In some applications, the filter housing is welded and incorporated into the glovebox. In others, the filter housing is a bolted, gasketed installation. The bolted design is more versatile by design; however, a potential crack at the gasket interface may make decontamination difficult. It should be noted that a push-through filter housing should be bolted due to the housing manufacturing process. Filter seals vary by application. HEPA filters can be supplied with many different gaskets and fluid sealing systems.

7.2.2.6 Blower Connections

If a dedicated blower is to be installed on a glovebox, several installation considerations should be addressed, including vibration, exhaust connection configuration, and blower discharge configuration. It is generally accepted practice to use a flexible connection in most ventilation applications; however, DOE-STD-1066[3] outlines the need for fire protection and the requirements associated with such installation. Vibration from the blower will transmit to the filter housing and subsequently to the glovebox. If a flexible connection is used to isolate vibration from the blower, there is a potential for heat damage to the connector. Noncombustible materials should be selected for this application. Blower designs vary. Selection of the exhaust and inlet connection should prevent severe effects on blower capacity. Obstructions at the immediate inlet and outlet will grossly affect blower capacity. Elbows and tees at the inlet will also affect capacity and should be avoided.

7.2.3 Dilution of Evolved Gases

A high air exchange rate is often required to dilute fumes generated in an air-ventilated glovebox. When evolved gases, vapors, and particles are not flammable, toxic, or corrosive, flow rates sufficient to maintain a negative pressure (with differentials from 0.3 to 0.5 in.wg in the box) may be employed. However, when fumes or vapors are hazardous, a higher ventilation rate is necessary. The maximum generation rate of hazardous substances must be determined to establish the minimum airflow rates needed for dilution. The following equations can be used to determine minimum safe airflow rates.[4]

$$Q = \frac{R(10^6)(S)}{L}, \tag{7.1}$$

where:

Q = required dilution flow rate, cfm

R = contaminant generation rate, cfm

S = safety factor (4 to 10 is suggested, depending on volatility, flash-point temperature, degree of mixing, and risk)

L = limit value of contaminant, volume parts per million (vpm) [use threshold limit value (TLV) for toxic vapors and lower explosive limit (LEL), 4 converted to vpm, for combustible vapors].

If the contaminant vapor is evaporated from a liquid, the contaminant generation rate, *R*, can be determined using the rate of liquid evaporated where:

$$R = \frac{W}{M}(359)\frac{t+460}{492} \tag{7.2}$$

W = liquid evaporation rate, pound of solvent per minute

M = molecular weight of contaminant

t = air temperature, degrees Fahrenheit

Equation (7.2) above assumes that a pound mole of gas will occupy 359 ft^3 at 32 degrees Fahrenheit and standard pressure. The dilution flow rate, *Q*, in Equation (7.1) assumes that the dilution air is free of the contaminant under consideration; otherwise, the background concentration of the contaminant in the dilution air (in vpm) must be subtracted from the limit value, *L*, in the denominator.

Concentration gradients can easily be formed during rapid vaporization if the hazardous gas is much lighter or heavier than air and there is poor mixing. Safety factors above 7 should be used in such cases. For example, 1 pound of acetone evaporated in a box in 1 hour requires a dilution rate of 5.1 cfm multiplied by the safety factor, *S*, to ensure dilution below the lower explosive limit.[5] Since acetone evaporates rapidly and has a flash point of 0 degrees Fahrenheit and an LEL of 2.2 percent, a safety factor of 10 should be used. In operation, minimal amounts of a solvent like acetone should be permitted in the glovebox at any one time. It should be assumed that the entire contents could be spilled, thus creating an event. Consideration should also include feed-throughs where flammable liquids and gases are pumped or released into the glovebox environment. The feed lines should be constructed of materials that are resistant to the gas or liquid. It is preferable for these lines to be hard-piped to the glovebox, although this is not always practical. An isolation valve should be provided to shut off the feed system in an emergency. It is preferable to use an automated failsafe feature, with appropriate sensors, if the equipment located inside the glovebox is not explosion proof. This is also preferable when the equipment is not monitored for long periods.

7.2.4 Heat Dissipation

It is important to understand the importance of heat removal as it applies to ergonomics. Operators access the inside of the glovebox using gloves that are often awkward to use and gloveports that limit their operations. When higher than normal heat conditions exist in a glovebox, it leads to higher fatigue levels. This limits the operations that can be performed in the glovebox environment. For worker comfort, sufficient air should be exchanged through the box to limit the inside temperature to no more than 15 degrees Fahrenheit above room temperature. When the calculated airflow rate for cooling exceeds the exhaust cfm, consideration should be given to higher airflow (larger filters or more filters), supplementary cooling, better insulation of heat sources, cooling coils, or chill blocks for hot materials. In the design phase of a glovebox project, the designer should be aware of the heat load presented by the equipment that must be located in the glovebox. It is desirable, when practical, to determine whether items like electric motors can be placed to the outside of the glovebox. This can reduce the heat load inside the glovebox significantly, as well as simplify maintenance and serviceability and reduce disposal costs. Operations to be performed in a glovebox should be determined ahead of time. Airflow velocities can affect the operation of sensitive equipment and cause materials like powders to become airborne. [Note: Negative pressure also can cause equipment problems.] There are practical limits to the amount of cooling that can be accomplished by airflow, since high airflow rates can create strong air currents if not properly diffused. Where possible, operators should be protected from objectionable sources of radiant heat by surrounding the heat source with reflective shields or conductive jackets. Exhaust airstreams may be routed through such shields to permit the maximum pickup of convected heat before leaving the box.

When the heat load to the glovebox has been determined, the required cooling airflow rate to dilute the hot gases is calculated using the following equation.

$$Q = \frac{H}{C(t_2 - t_1)}, \tag{7.3}$$

where:

Q = airflow, cfm

H = sensible heat change (by conversion), British thermal units (BTU)/hour (1W – 3.41 BTU/hour)

t_1 = temperature of entering air, degrees Fahrenheit

t_2 = desired average temperature inside box, degrees Fahrenheit

C = conversion factor for sensible heat change, BTU/(cfm x hr)(degrees Fahrenheit)

Both the density and specific heat of air at room conditions depend on the humidity ratio of the air. The density also depends on the temperature. In a room at 75 degrees Fahrenheit and 50 percent relative humidity (RH), the air density is 0.073 pounds per cubic foot (lb/ft^3) and the specific heat is 0.24 BTU per pound. Therefore, C is 1.1 BTU/ (cfm)(hr)(degrees Fahrenheit) and Equation (7.3) becomes:

$$Q = \frac{H}{1.1(t_2 - t_1)}. \tag{7.4}$$

Long-term operation of high-heat-producing equipment can damage filters when exhaust air temperatures approach the temperature limit of the filters for continuous exposure to heat (see Chapter 3, Tables 3.5 and 3.6).

7.2.5 Empirical Flow Rates

It is important to design the ventilation system to provide a safe, ergonomically practical, and reliable unit. Experience has shown that filter pressure drops will vary, ductwork loss will be greater, and blower performance may be slightly different in actual working conditions (other variables also are discussed in this chapter). If the glovebox ventilation system does not perform as designed, it should not be used or commissioned until it meets the minimum safety requirements of this document and other referenced documents.

Troubleshooting an installation should include the inspection of the ductwork and installation of the blower (including wiring); the prefilter, inlet, exhaust HEPA filters; and the manifold (if equipped). Common problems with new installations include debris lodging in the ducting, blower housing, and filter housing and finding the blower motor wiring reversed. Long flexible connections will also affect performance since a bend can dramatically choke off airflow.

7.2.6 Exhaust Requirements

The maximum airflow rate from the glovebox determines the required capacity of the filters and the size of the equipment for the entire downstream portion of the ventilation system. The airflow resistance of the exhaust-air path must be sufficiently low so that pumping of gloves (pressure recovery) by operators in the box will not result in positive pressurization**.** In small low-flow boxes such as those with inert atmosphere, pressure surges due to glove pumping may be a serious problem. Fast insertion of the gloves can cause the glovebox to reach a zero or positive pressure. Although this is typical for most applications, another method called "passive recirculation" can be used to retain the inherent safety feature and larger filters for air cleaning functions. [Note: This method should not be used with pyrophoric materials because the inert environment will be lost during a glove breach.] Typically, the glovebox is fitted with an inlet and exhaust filter in a room air application. Another filter "emergency discharge" is added and fitted between the blower discharge and the inlet air filter. The blower installation connects the exhaust filter housing to the negative side of the blower, and the inlet filter installation connects to the positive side. When the installation is complete, the emergency discharge filter is in a standby condition. The ventilation unit basically recirculates the inert gas. If a breach or leak occurs, the emergency discharge filter becomes naturally activated. The path of least resistance during a breach discharges exhaust air through the emergency standby filter, since the inlet is now the gloveport. This filter should also be sized for the gloveport "inherent safety feature." The filter should be rated for twice the cfm or half the pressure drop of the inlet filter. If the two filters, inlet and emergency standby, have the same airflow and pressure drop, the airflow will be directed to both instead of the emergency standby filter. If air is to be exhausted from the emergency standby filter, a bleed vent is necessary to prevent removing the inert gas and imposing additional negative pressure. When the glovebox ventilation unit is activated, there should be no flow through the emergency standby filter. If the secondary exhaust system is directly connected without a bleed vent, the glovebox pressure will become extremely negative. The vent allows room air to be removed until the emergency standby filter requires exhaust.

The maximum rate of exhaust flow from a room-air-ventilated glovebox is usually based on the required inlet flow when a glove is ruptured or inadvertently removed. The air velocity into the open port should be 125 ± 25 fpm. Good contamination control is more easily achieved in a glovebox with low air leakage. Gloveboxes should have a leakage of less than 0.02 to 0.5 percent box volume per hour, depending on the application requirements. In some applications, such as inert environments, a helium leak test is performed to ensure the integrity of the glovebox. The method, technique, and criteria for testing are given in AGS-G001, Section 9.11.4.[1]

7.2.7 Vacuum- and Pressure-Surge Relief

In some applications, gloveboxes must be protected against physical damage resulting from excessive pressure or vacuum. The exhaust and inlet supply system must be able to handle slowly manifested pressure or vacuum disturbances. Each glovebox containing service connections or internal equipment whose malfunction might cause a pressure surge should be equipped for prompt surge relief. This also applies to fire suppression systems, as outlined in DOE-STD-1066.[3] The response time and pressure-flow characteristics of the surge-relief device will depend on the flow and pressure characteristics of the pressure source, the free volume, and the relative strength of the gloves and glovebox. The relative strength is defined as the lowest pressure differential that will cause rupture of the glovebox pressure boundary at its weakest point. Depending on the design of the box, the weakest point will usually be a window or a glove. The

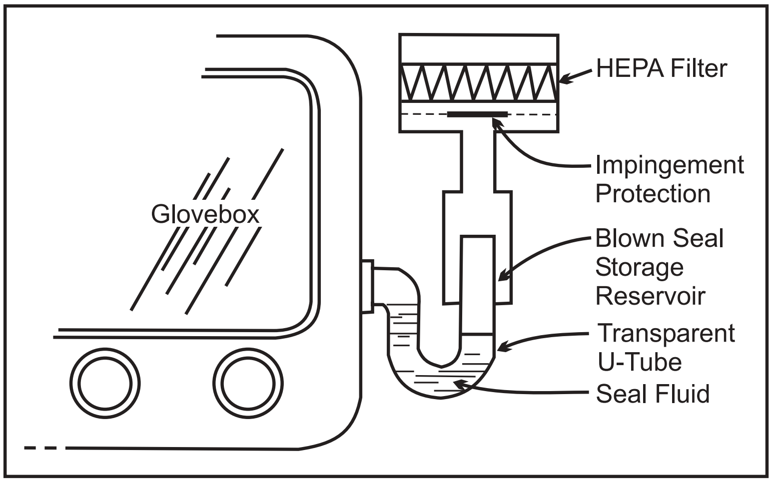


Figure 7.7 – Glovebox Vacuum-Pressure Surge Relief Device

surge-relief device can be a liquid-filled U-tube, as shown in **Figure 7.7**. The surge-relief flow capability should exceed the flow from the largest possible source of pressurization at the design relief pressure. The HEPA-filtered surge-relief line should not be connected to a glovebox exhaust manifold because this line will be subjected to the same pressure as the normal glovebox exhaust connection. A liquid storage reservoir is provided to handle the blown seal fluid. The filter and ductwork should be sized in accordance with the required cfm and pressure drop based on the pressure surge. The filter should be protected from impingement of the seal fluid. If room air cannot be tolerated in the glovebox, as is the case in some inert-atmosphere applications, a different vacuum surge-relief system must be used. A U-tube can be devised to restore its seal after relieving the surge, but such a system must include a feature to alert the operator that a pressure surge has occurred so that he can make the necessary safety checks. An inlet filter may provide surge relief if no backflow device or other restriction is provided. The filter face area would have to be about four times the area of an unfiltered port to achieve an equal venting effect.[3] [Note: Explosive venting is not covered in this Handbook.]

7.2.8 Glovebox Exhaust Manifold

A glovebox exhaust manifold is used when multiple gloveboxes will share a common ventilation system. This method reduces the amount of exhaust ventilation components for dedicated exhaust systems. The glovebox exhaust manifold includes all of the glovebox exhaust system downstream from the point where the exhaust from two or more gloveboxes joins and the airflow is combined. Sections 7.2, 7.3, and 7.4 discuss details of the exhaust system and illustrate working examples.

The glovebox exhaust manifold draws air or exhaust gas from each connected glovebox at a controlled pressure and airflow (interdependently), houses secondary treatment facilities, and transmits the air for further treatment or exhausts it to the outside atmosphere. Primary exhaust treatment should be applied inside or as close to the glovebox as possible and, in all cases, before connection of the exhaust line to the exhaust manifold. It is critical to protect the manifold from contamination due to the difficulty of cleaning and decontamination. In some systems, a portion or most of the cleaned or treated exhaust gas may be recirculated back to the gloveboxes.

[Note: The manifold system should be sized and controlled to accept a range of flow whose high extreme is the sum of: (1) the maximum normal flow from each box (Sections 7.2.1, 7.2.2, and 7.2.3), (2) the largest maximum flow under removed glove conditions from one of each of five connected boxes (Sections 7.2 and 7.2.6), and (3) an allowance for system growth. The low extreme is the sum of the minimum flows from each box. An allowance for system growth should be provided at not less than 20 percent of (1) plus (2) above for a new system. If this allowance exceeds 50 percent of (1) plus (2), other provisions such as installing an equivalent dummy flow should be considered.]

7.2.9 Exhaust Cleanup Requirements

Providing As Low as Reasonably Achievable (ALARA) exposure to radioactive material is the guiding principle for determining the design of a glovebox ventilation unit. Protecting the exhaust downstream of the primary HEPA filter is paramount for nuclear installations. Experience has shown that exhaust systems are not only difficult to decontaminate, but have led to unnecessary operator exposures. It is also true that, after filter breakthrough, nuclear particles can migrate to all the gloveboxes in the chain. As discussed earlier in this chapter, a filter installation is only as good as the entire ventilation system.

When corrosive gases or vapors are in the exhaust airstream, all of the filters in a series will be exposed. The impression that the life expectancy of a group of HEPA filters arranged in series is dependent upon the number of filters in the series may be false when chemical or heat degradation occurs. Under these conditions, when the first stage fails, there is a potential for others to fail from the same cause. Corrosive gases and mists from vats, scrubbers, and similar equipment must be neutralized and removed before they reach the HEPA filters.

Installation requiring redundant HEPA filters must have provisions for in-place testing. The requirements are provided in ASME AG-1, Section TA[2] and ASME N510, *Testing of Nuclear Air Cleaning Systems;* [5] and if chemical detection systems are required due to possible filter installation damage, the monitoring system should be HEPA-filtered to prevent damage to the instrument. Many manufacturers supply testable filters of this type. These should be specified with upstream and downstream test ports. The filter flow should be consistent with the monitoring instrument airflow.

7.3 Glovebox Filter Installations

For the most part, the glovebox filter systems discussed in this section are first-stage (primary) HEPA filters, although redundant filters located upstream from the exhaust manifold (if equipped) connection are also discussed.

Filters must be able to perform properly whether they are clean or dirty. A maximum dirty-filter resistance of three times the clean-filter resistance for HEPA filters and two times the clean-filter resistance for prefilters is generally used for design purposes. **Figure 7.8** gives the approximate airflow and pressure-drop relationships for clean open-faced HEPA filters. **Figure 7.9** shows common locations for HEPA filters near or inside gloveboxes. Type 2C shows the installation of inlet and exhaust filters inside the glovebox.

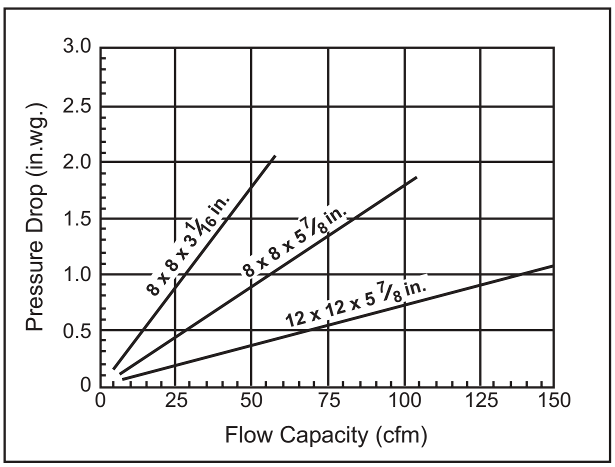


Figure 7.8 – Flow vs. Pressure Drop Relationship for Small, Clean, Open-face HEPA Filters

7.3.1 HEPA FILTERS

A detailed discussion of filter performance and construction materials is given in Chapter 3, Section 3.3. Operational experience with a particular system is the most reliable basis for filter selection for a particular service. For new and untried systems, the initial choice should be limited to the traditional site-specific, open-faced pleat, and should be constructed to the requirements of Section 3.2. These filters should also meet the requirements of ASME AG-1.[2] If exhaust streams are kept chemically neutral, as they

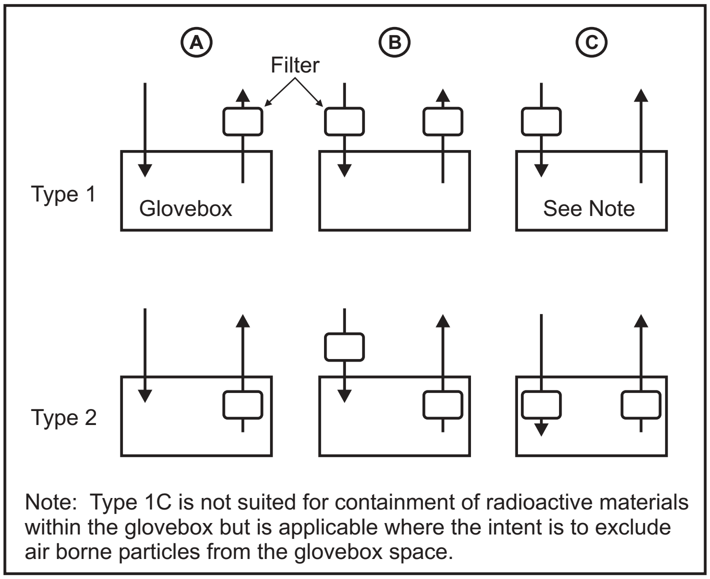


Figure 7.9 – Possible Arrangements of Filters Near or Inside Gloveboxes

should be for reliable exhaust system operation, HEPA filters of standard construction usually provide the most economical service.

A single-HEPA-filtered exhaust path is defined as a glovebox that does not involve highly toxic aerosols or potent, toxic, or radioactive materials, i.e., materials that do not pose a hazard to the operator during a filter change-out. A multiple-filtered exhaust path is defined as a glovebox requiring more than one line of defense from particle penetration. This occurs when the exhaust ductwork or manifold must be protected or the Most Penetrating Particle Size (MPPS) is well below the efficiency particle mean of the filters.

When continuous airflow is essential, two exhaust connections should be provided to avoid interruption of exhaust flow during a filter change and to provide standby protection in the event of system upset. The purpose of multiple exhaust connections is to allow an emergency connection to be made. **Figure 7.10** illustrates single- and multiple-filtered exhaust connections for a glovebox.

Multiple-filtered exhaust connections should be used when interconnected gloveboxes or a large enclosure with several compartmented work areas are needed. Compartmenting doors between work areas or between single boxes in an interconnected line must not isolate a work area with only one filtered exhaust connection. The multiple exhaust points required to handle total airflow in a line of interconnected boxes must be sized for maximum flow and valved individually for flow control. DOE-STD-1066[3] discourages the use of long lines of interconnected gloveboxes for fire control. Where they are necessary, fire doors between the gloveboxes should be provided. This would necessitate proper alarming and resolution of pinch-point concerns.

The glovebox designer should understand the limitations imposed by ergonomics. There is an art to designing the glovebox, ventilation service, and internal equipment operation and service. Some facilities build mockups of the glovebox concept to determine whether the operations can be done in a practical manner. It is critical to prove the practicality in some operator-intensive, hands-on operations and long-term production activities. Tasks performed within the confines of a glovebox should factor in the weight of the objects handled and the location of the operation(s) to be performed within. It is better to demonstrate the activities at the design phase than to wait for the glovebox to be built. Failure to do this can be very costly to repair and can seriously compromise operator safety.

The fatigue factor is high when working in a glovebox. The working pressure, heat, glove sleeves, gloveport location, and operations where the arms are outstretched all add to fatigue. Intricate or sensitive work significantly adds to fatigue because the operator cannot feel through the gloves. If visibility is poor or nonexistent, operations will be very difficult, if not impossible, to perform. Some operations with older gloveboxes used mirrors to perform some operations. [Note: This was done out of necessity due to poor design or a compromise with some other activity.] In glovebox terms, "extended reach" is used to describe an occasional operation where something is pulled forward to a working position or a simple operation such as turning a switch off or on (e.g., lowering or pulling out a spent filter for disposal). Extended reach should be avoided in repetitive or routine operations.

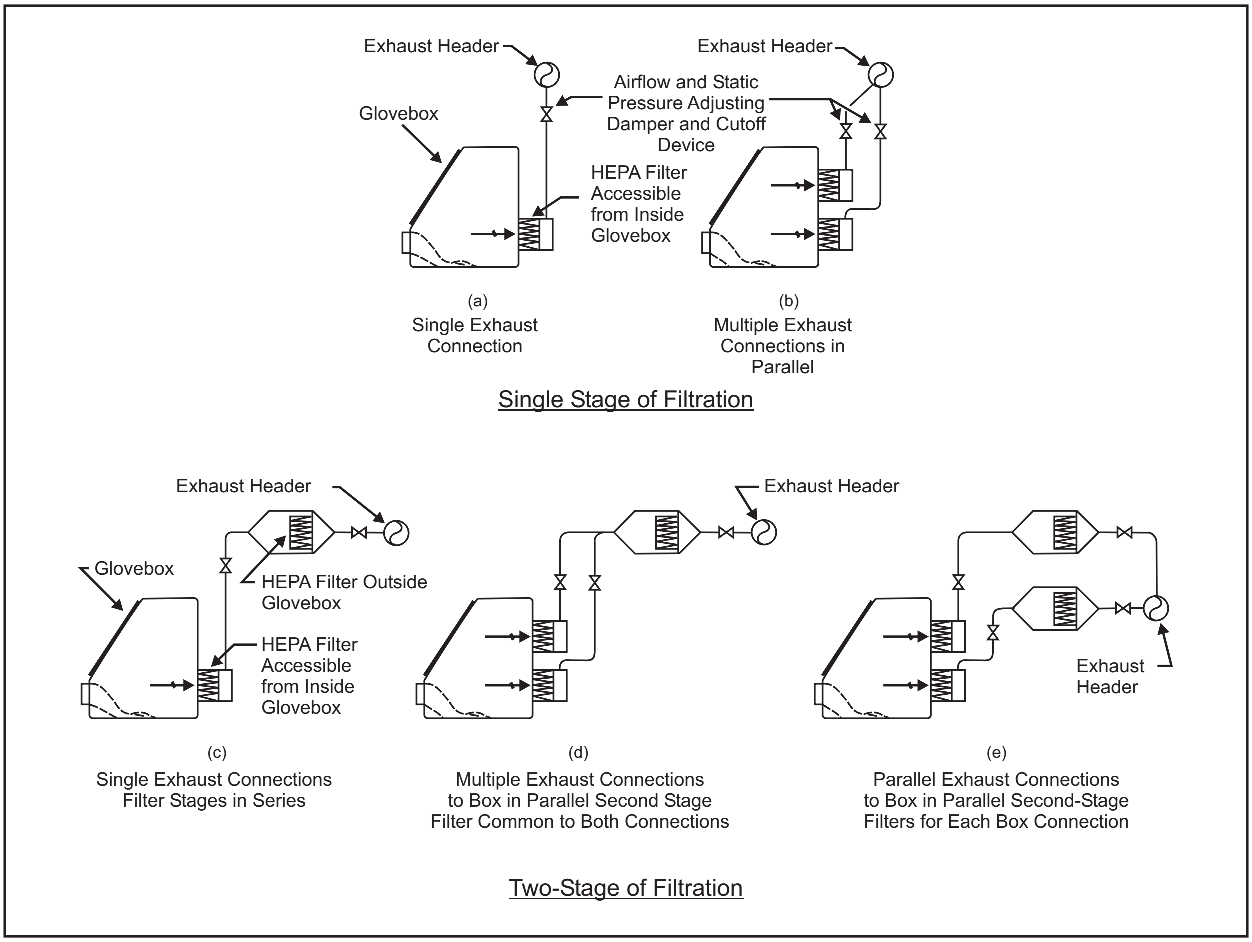


Figure 7.10 – Suggested Arrangements for Single- and Parallel-Filtered Exhaust Connections for Gloveboxes

7.3.2 HEPA Filter Selection Criteria

HEPA filters are available in many configurations for many applications. For most applications, glovebox HEPA filters are customized to meet industry needs. Not all the different filter housings described earlier are intended for nuclear service. These filter housings use different-sized filters with different types of seals. Filter selection should be based on airflow requirements and efficiency requirements. Airflows for protecting workers, venting fumes, and cooling are discussed in this section. The efficiency of HEPA filters is discussed in Chapter 3.

Another variable to application is efficiency. Selecting a more efficient filter for an application may be necessary to prevent particle bypass through a standard HEPA filter. The higher-efficiency filters are called Very Large-Scale Integrated (VLSI) filters. There are materials in use that have a greater amount of small particles below the MPPS for HEPA filters. These materials may pass through the HEPA filer unimpeded and migrate into the ductwork. Redundant filters can sometimes be used for these applications; however, this assumes that the area between the filters can be cleaned. [Note: VLSI filters are not approved for nuclear use and are referenced for nonnuclear applications).

Several of the characteristics listed below should be considered when selecting filters for use at nuclear sites.

- Uses a standard-size HEPA filter located in the back- or end-wall of the glovebox.
- Maximizes inside box space by partially recessing the filter in the wall.
- Provides adequate space to transfer the HEPA filter out of the glovebox (see **Table 7.1**).
- Has a simple clamping method with no removable pieces and is operable with a gloved hand by a simple, clean clamping mechanism.
- Has a retainer that serves as a face shield for the filter and permits attachment of a steel-cased prefilter by a flexible magnetic strip (accessible from the front); the filter remains in position after being unclamped because of the folded lip at the top.

Table 7.1 – Glovebox Bag-Out Port Sizes for Transfer of Standard Open-faced HEPA Filters

Filter Size	*Required Port Size (inches)*	
	Round (diameter)	*Rectangular*
8 × 8 × 2 1/16	9 3/4	8 ½ × 4 1/2
8 × 8 × 5 7/8	10 3/4	8 ½ × 6 1/2
12 × 12 × 5 7/8	14	12 ½ × 6 1/2
24 × 24 × 5 7/8	26	25 × 6 1/2
24 × 24 × 11 1/12	27 3/4	25 × 12

7.3.3 Prefilter Selection

Prefilters are used to extend the life of the more expensive HEPA filters located at the inlet and exhaust filter housings. These filters are disposable and should be routinely changed when they are loaded and affect the ventilation system. This can be determined by noting the sensitivity of glove movement and pressure recovery. In easily airborne powder applications where a significant amount of dust is airborne in a glovebox, removing the prefilter may be the only means to restore safety (negative pressure) to the glovebox during a powder mishap. Prefilters for gloveboxes come in a range of sizes and configurations. Some facilities use simple cut, in-place pads, and some use HEPA filters (not tested) to perform the prefilter function. This has been application-, site-specific-, and retrofit-driven. For some applications where air entering the glovebox is HEPA-filtered and there is little or no dust loading in the glovebox, an exhaust prefilter may not be needed. A prefilter should be considered on the inlet HEPA filter on the glovebox unless the glovebox resides in a cleanroom. Prefilters are manufactured from a fiberglass media similar to the HEPA filters. As a result, they are susceptible to the same chemicals, fumes, and heat damage. Some prefilters are manufactured with a beverage board (coated cardboard) frame, which should be avoided if fire is a concern.

Prefilters are typical of the type referenced in Chapter 3, Section 3.4, as Class I panel filters. The main advantage of these prefilters is cost, quick installation, and removal. There also is a distinctive ergonomic advantage. These filters are pushed into a channeled frame instead of tucked into and around a frame—a difficult operation when the exhaust filter is ceiling-mounted. Use of a separate removable frame is preferable in these applications. [Note: The ability to perform this operation should be based on either a mockup or an existing glovebox installation.]

Prefilter holding devices should be manufactured from the same material as the glovebox or a material that is resistant to the chemicals and fumes that will be present in the airstream. Retaining fasteners, when used, should be made of dissimilar materials that do not gall. It is better to dispose of a 302 stainless steel wing nut than to replace a 304-L stainless steel stud welded on a glovebox. The frame should be designed to minimize air bypass around the prefilter, yet allow enough clearance between the HEPA filter and prefilter to prevent media contact. An independent holding frame should be incorporated in the design to prevent disturbing another filter installation.

7.3.4 Inlet HEPA Filters

Work performed in gloveboxes frequently requires supply air that is free of airborne contaminants. Inlet HEPA filters help maintain clean conditions inside and, when chosen properly, also serve three other useful functions: (1) extending the service life of the exhaust filter by protecting them from atmospheric dirt loading, (2) preventing the spread of contamination from the glovebox to the room in the event of a glovebox pressure reversal, and (3) providing overpressure relief.

The design of the inlet filter installation is relatively simple for air-ventilated nonrecirculating gloveboxes. Since no duct connections are required, open-faced filters may be used with an installation and clamping method that leaves one face completely exposed. Typical methods of installation are shown in **Figures 7.11 and 7.12**. Because they are less likely to be contaminated, inlet air filters are easier to replace than exhaust filters; therefore, they provide fewer problems and less risk during changes. Whether mounted to the glovebox internally or externally (external mounting is preferred), the same high-quality mounting, clamping, and sealing are required.

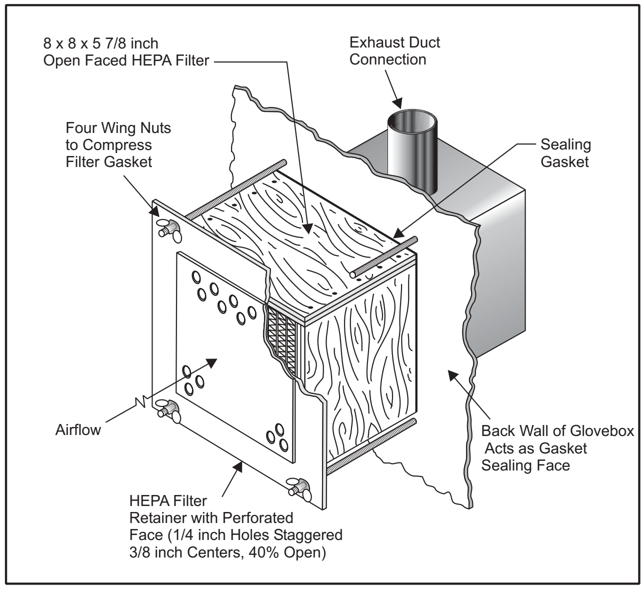


Figure 7.11 – Open-Face Filter Installation Method (a)

The open face of the filter must be protected from physical damage and fire. Plugging of the inlet filter by smoke is a secondary concern, however, since one recommendation for glovebox fire suppression is to reduce normal airflow. Locating the inlet connection (or an attached inlet duct) high in the box tends to reduce the amount of air drawn into the box during a fire because of the chimney effect.

7.3.5 HEPA Filter Selection

The number of types and sizes of HEPA filters used at an installation should be minimized for logistical and operating economy. All HEPA filters should be constructed of fire-resistant materials. HEPA filter sizes used in glovebox systems vary, with square 8- × 8- × 3 1/16-inch; 8- × 8- × 5 7/8-inch; and 12- × 12- × 5 7/8-inch sizes and nominal airflow capacities of 25, 50, and 125 cfm,

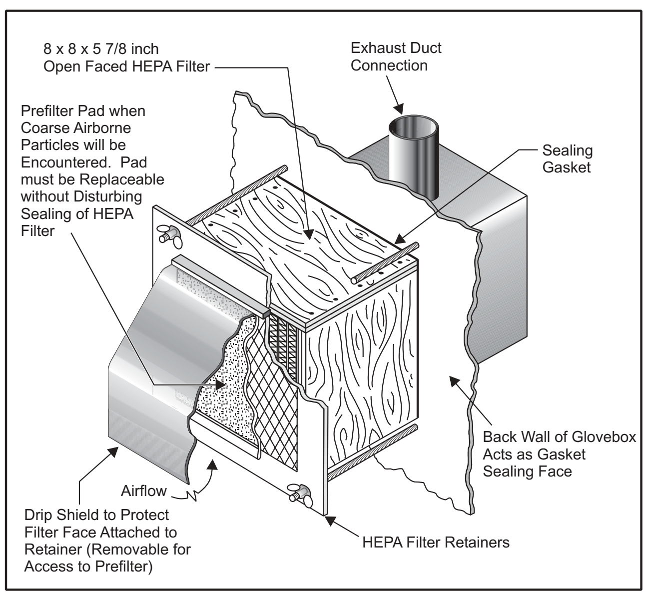


Figure 7.12 – Open-Face Filter Installation Method (b)

respectively. Glovebox filters should be operated at their design airflow. Wood-cased fire-resistant HEPA filters are less expensive and should be considered wherever the operating environment (temperature, humidity, etc.) permits. Most applications use 304 and 304-L stainless steel due to the robust nature of the casing and the chemical, fire, and humidity requirements. The “cartridge,” as noted in Figure 7.5, comes in a round configuration with an 8-inch diameter.

Disadvantages of Enclosed and Open-Faced HEPA Filters. Disadvantages of both enclosed and open-faced HEPA filters include:

- Capacities are insufficient for large amounts of dust.
- Chemical fumes such as caustic or hydrofluoric acid mist can destroy filter medium separators and adhesives.
- Sharp corners and edges of metal casings can damage protective bagging.
- In dry atmospheres (less than 2 percent RH) the plywood of wood-cased HEPA filters may shrink and delaminate, eventually causing failure of the filter. Extremely low moisture levels may cause a shrinkage problem for particleboard casings as well. This could be an acute problem in inert atmospheres where very low moisture levels [less than 50 parts per million (ppm)] have to be maintained. In such systems, steel-cased filters should be used.

Open-faced HEPA filters have the following additional deficits:

- They are vulnerable to damage during handling and storage.
- They lack a handle or gripping area for easy withdrawal from an enclosure.
- It is difficult to replace damaged face gaskets.

Enclosed HEPA filters also have additional deficits:

[Note: They are not recommended for nuclear applications stated in Chapter 3.]

- They lack Underwriters Laboratories (UL) certification.
- Reeding (induced vibration of separators caused by air motion) at high flow rates is worse than in open-faced filters because the entering air impinges on a smaller area of the filter pack.
- Their weight is greater than that of open-faced filters.
- They cost substantially more than open-faced filters.
- They have greater space requirements.
- There is an air leakage problem with steel cases, especially in inert-atmosphere and high-pressure applications.
- There are no visible means of detecting damage to the medium.

7.3.6 Prefilters

As in larger systems, prefilters may be used in both the inlet and exhaust airstreams to extend the life of the HEPA filters used in glovebox filtration systems. Prefilters are inexpensive items, and the decision to use them requires the designer to evaluate the advantage of longer HEPA filter life against frequent glovebox system problems associated with limited space. Prefilters attached directly to the face of the HEPA filter provide no fire protection for that HEPA filter. Glovebox prefilter service often requires filters to be subjected to periods of high temperature, moisture, dust, and corrosive agents that shorten their effective life and mounting.

Experience with prefilters in glovebox ventilation systems has shown that the use of metal media is impractical. Without viscous coatings, the filtering efficiency of metal-media prefilters is poor, and these filters are often almost impossible to clean and decontaminate. Adhesives and oil coatings that improve particle retention reduce in-box cleanness and fire resistance. Experience clearly indicates that using conventional types of prefilters that require cleaning or decontamination or both before reuse also is impractical. Throwaway filters with simple installation methods are preferred. After use, the units are discarded as contaminated waste unless collected materials must be reclaimed. Glass-fiber-media prefilters are preferred because they offer good serviceability, low costs, and only a small amount of combustible content.

Inlet airstreams with HEPA filters should be fitted with prefilters when using atmospheric air. However, there may be no need for a prefilter when: (1) the room air has been cleaned of the bulk of its airborne dust by building supply-air systems, (2) local room activities do not generate dust and lint that can be drawn into the box, and (3) airflow through the HEPA filter is less than 75 percent of its rated capacity.

A common method of prefiltering in older gloveboxes is to clip a thin (1/8- to 1/4-inch) fiberglass pad to both the inlet and exhaust HEPA filters, as shown in **Figure 7.13**. Neither plastic foam nor organic fiber should be used because both are flammable. The pad is cut to fit the face of the HEPA filter and is clipped to the filter retainer. This method of attachment permits easy removal of the prefilter pad without disturbing the seal of the HEPA filter. Normal usage generally requires frequent replacement of the prefilter pads, which do not have much dirt-holding capacity and can quickly become plugged by house dust and lint. Convenient methods of attaching the prefilter pads are essential to simplify the operations performed inside the glovebox. Frequent replacement of prefilter pads provides the following benefits:

- Air resistance (pressure drop) does not change rapidly, which allows airflow to remain more constant without frequent manipulation of airflow dampers.

- Accumulation of combustible dust in the exhaust path is lessened, thereby providing better fire protection for the HEPA filter downstream if the prefilter is not applied directly to the face of the HEPA filter.

- The exhaust path can pass a greater airflow when relieving an emergency condition.

Thin fiberglass pads (1/4-inch thick or less) can provide average atmospheric dust collection efficiency of up to 20 percent with low airflow resistance. Thin, clean fiberglass pads used at air velocities of 35 fpm will create an initial pressure drop in the range of 0.03 to 0.15 in.wg. For applications where long-term continuous processes hamper regular maintenance of in-box filters, the designer must include the following provisions:

- Greater suction pressure (well below the limit that would subject glove or box integrity to unsafe differential levels) controlled by the damper to allow longer use of prefilters;

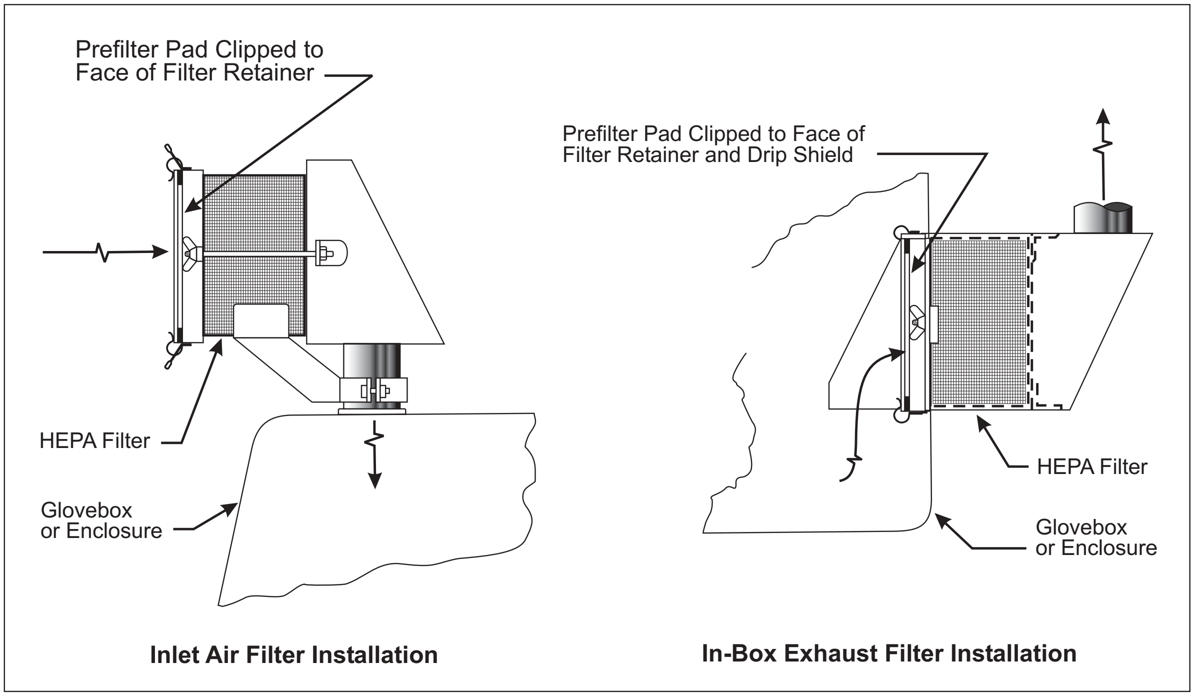


Figure 7.13 – Typical Installation of Prefilter Pads on Face of HEPA Filters

- Larger prefilters; and
- Selection of a prefilter with less initial resistance to permit longer use, even with lowered collection efficiency.

7.3.7 Roughing Filters

In some installations, it is desirable to recover material from the filters for either reprocessing or waste minimization. Roughing filters may be used for this purpose. The filter medium is typically less efficient than that of the HEPA filter. Construction materials may be suitable for the recovery process (Category 3 - combustion, acid dissolution, etc.), but must not present a hazard to the downstream prefilter and HEPA filters. Fire screens, etc., must be used to prevent roughing filters from impacting downstream prefilters or HEPA filters.

7.4 Filter Replacement

Safe replacement of a contaminated glovebox filter must be planned in the design phase to facilitate proper execution. The filter change method and other maintenance functions, if not site-specific, should be determined and planned. The designer should prepare a written preliminary filter change procedure along with the design documents. If the design is questionable due to an extreme custom nature, the glovebox should be mocked up so that an operational demonstration can be performed. [Note: In the past, special tools were used to perform filter and maintenance operations out of necessity and should be avoided, if possible.] In applications where controlled inert atmospheres are present, filter changes should be planned for times when other routine or special maintenance operations are taking place inside the box to reduce interruptions to operations and loss of inert gas, and to minimize the time required to reintroduce the inert gas into the box spaces.

The operational team directly involved in a filter change-out must wear appropriate respiratory protection, as specified by site-specific requirements. Filters installed inside the glovebox must be accessible via the gloves on the glovebox. When total contaminant activity is high, additional protective measures may be necessary to reduce worker exposure. One of the safest and most common methods for preventing the spread of contamination while maintaining confinement is bagging the filters in and out of the glovebox. The plastic bagging materials used are discussed in Chapter 6, Section 6.2.3. When inert-atmosphere or oxygen-free environments are used inside the glovebox, additional provisions may be required to prevent air leakage into the box.

Replacement of a HEPA filter inside an air-ventilated box involves many steps that must be performed sequentially. Standard Operating Procedures must be written, and the filter change team must be trained to perform the operations in a safe, controlled manner. Close coordination between maintenance and operating personnel is necessary to establish a mutually satisfactory date and time for the filter change, to identify the boxes and systems involved, to procure the necessary materials, and to schedule personnel. The health and safety requirements of the industrial hygienist, health physicist, and safety engineer must be established. One of these specialists should be designated the health and safety supervisor and should be available to monitor the operation and assist as necessary.

When the necessary materials and tools are ready and all personnel have been instructed in their specific duties, final permission must be secured from the responsible operator to alter the airflow and replace the filters. The flow path of the exhaust system should be thoroughly understood, and persons responsible for related exhaust systems that will be affected should be forewarned. For instance, if two glovebox exhaust systems manifold to the same blower, final filters, and stack, the removal of one system from service for a filter change will affect the system flow and pressure characteristics of the other system. Safety clothing and respiratory protection should be worn as directed by the health and safety supervisor. The following steps are suggested for changing a filter and placing a box back in service:

1. Cease all glovebox operations and contain unsafe materials in suitable containers.

2. Cut off gas flow to the glovebox affected, and adjust flow through the remaining branches to restore a safe negative pressure and flow rate in each.

3. Bag a clean replacement filter (and prefilter if used) in a small, clear plastic bag with sufficient tape to hold the spent filter and prefilter with all of the hand tools required, as shown in steps A, B, and C of **Figure 7.14**. It is recommended that the hand tools needed for filter changing be introduced the first time the filters are changed, and then left in the glovebox for subsequent use if space and environment permit. Decontamination is often more costly than tool replacement.

4. Using the glovebox gloves, remove the dirty filter and prefilter from their mounting frame.

5. Insert the dirty filter and prefilter into an empty plastic bag along with any residual materials, slowly expel excess air, and seal with tape.

6. Inspect the gasket sealing face or fluid seal knife-edge of the mounting frame and clean if necessary. Place the replacement filter in position and secure the clamping devices. Place the new prefilter in position and secure.

7. Remove the dirty filters and all debris from the glovebox and place the removed items in a container for contaminated waste disposal.

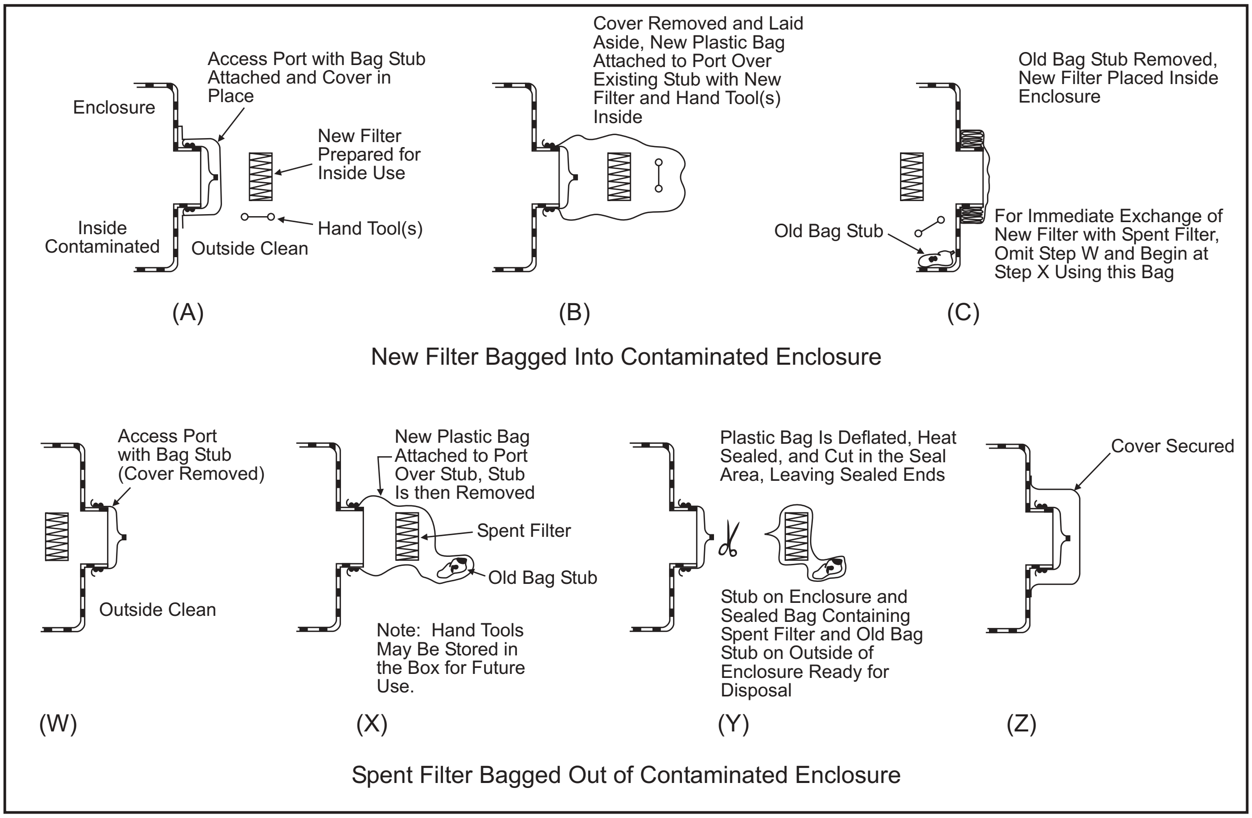


Figure 7.14 – Filter Changing Process

8. Restore airflow through the glovebox and adjust the flow and negative pressure throughout the system.

9. Before glovebox operations are resumed, test the newly installed HEPA filter with challenge agent, using the permanent test connections on the housing. If the test result is not satisfactory, stop the flow and inspect the filter for damage. If no damage is apparent, reposition the filter, restore the flow, and retest the filter. If the second filter challenge is unsatisfactory, the filter should be replaced and steps 3 through 9 should be repeated. Continued leakage suggests a mounting frame failure, filter damage, or a faulty test, and each possibility should be examined in detail until the fault is discovered and corrected.

10. Decontaminate the area.

11. After successful filter replacement, notify the responsible operator.

Filters located external to a glovebox (used in some older glovebox installations) require convenient access for changing, and it is usually necessary to interrupt airflow during the change. Since they are located outside the glovebox, highly contaminated filters must be bagged during the change. Different bagging techniques provide different degrees of protection. The technique shown in **Figure 7.15** is an old method of filter change, and is not recommended in new installations. This method seals both ends of the air ducts, and no flow can occur downstream while the filter is removed. When uninterrupted airflow through a box is required, this method of filter change necessitates the use of multiple exhaust connections on the box. An out-of-box filter in the process of being removed from a system by the procedure, illustrated in Figure 7.15 Step 3, is shown in **Figure 7.16**. [Note: This type of installation should not be used on future nuclear installations due to the potential for contamination release and cleanup. Further, note that flexible hose connections as shown in Figure 7.15 should never be used for new nuclear applications.]

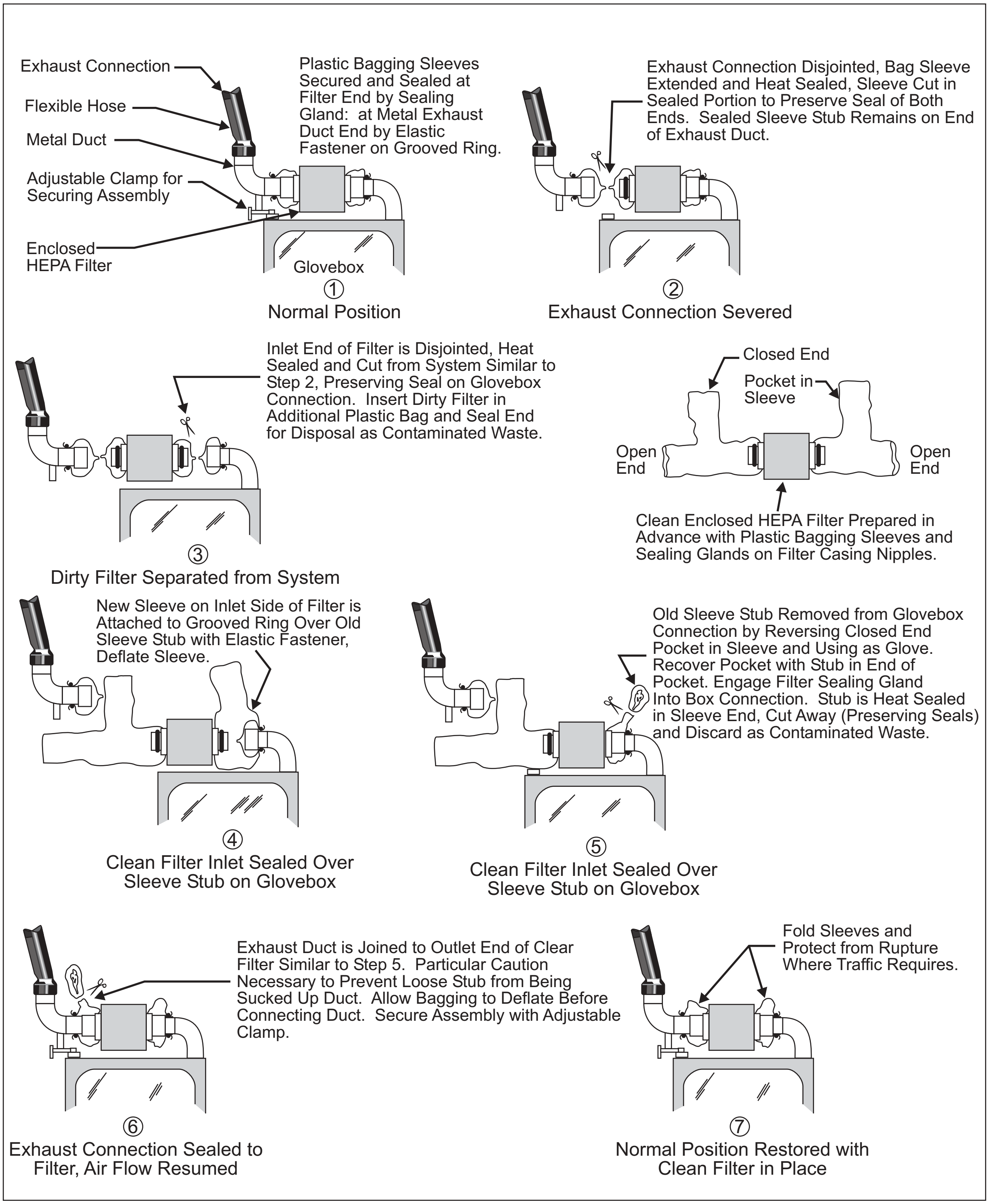


Figure 7.15 – An Older Method of Filter Change [Note: Not recommended for new installations, a bag-in/bag-out filter housing is recommended for new installations.]

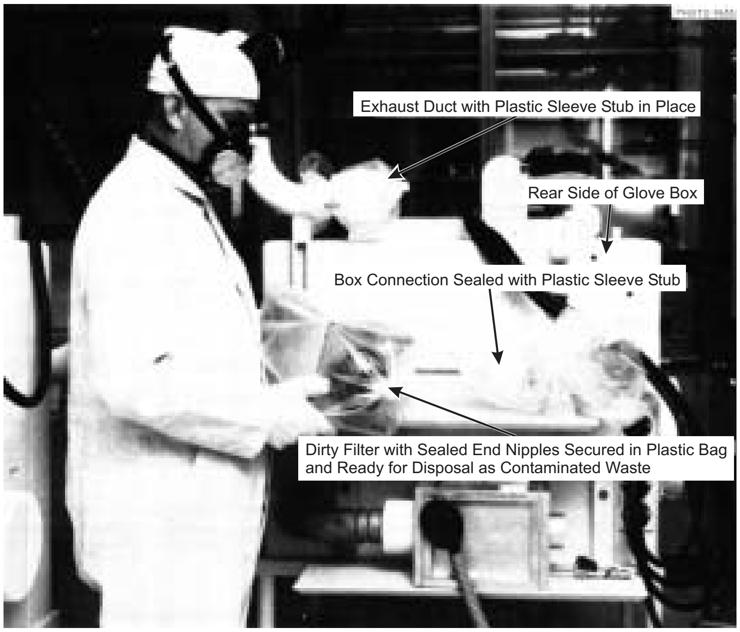


Figure 7.16 – Removal of an Out-of-box Filter

For other methods where bagging does not block the airflow path (e.g., using the housings represented by Figure 7.15), but merely encapsulates the filter being removed or replaced, there is a dependence on the damper in the duct to prevent blow-by (leakage) during a filter change. In other methods, isolation dampers or valves are used to isolate the filter during a filter change. The filter housing is still adjusted to the glovebox to remain slightly negative in pressure. The technique of bagging filters from housings (Figure 7.15) offers protection only for local personnel and the service area where the filter mounting device is located. The side of the system downstream of the filter is protected not by bagging, but by leak-proof dampers and flawless handling of the dirty filter. Because any dislodged particles will be swept downstream when airflow is restored, downstream HEPA filters should be provided to intercept these particles.

7.5 Glovebox Safety

The history of glovebox safety in the United States began with the use of very unsophisticated gloveboxes of simple design for simple operations. These were "sandblasting-style" gloveboxes with and without filters. Some early gloveboxes were actually manufactured from plywood. Glovebox use evolved from the need for safe working environments and reduced operator exposure. This evolution led to more complex gloveboxes and more complex problems. Most lessons learned were the result of accidental experiences. Simply put, many variables existed due to lack of experience with glovebox use. Through all of these experiences, much was learned about ergonomics, operator safety, the importance of training, and fire and explosion protection. Ergonomic problems related to handling material, performing service functions, and transfers were discovered early and are still a critical requirement in glovebox design. Operator safety has improved as a result of better glovebox designs with less operator intervention. Training has become a critical path from design through commissioning, operation, and decommissioning. Fire prevention is important enough that a chapter in DOE -STD-1066, *Fire Protection Design Criteria*,[3] was written specifically for gloveboxes.

7.5.1 Protection Against Fire and Explosion

The current guidance regarding fire and explosion is given in DOE-STD-1066[3] and DOE O 420.1, *Facility Safety*[6] which outlines the requirements for glovebox applications needing fire suppression (see Chapter 10 for more discussion of fire protection).

Fire Protection. Applications employing fire protection are guided by the following principles:

- Use nonflammable materials as much as possible in construction. Gloves and windows are the most susceptible to fire due to their construction materials. Laminated or tempered safety glass is the material of choice regarding fire. [Note: For applications where explosion, overpressure, or moving or rotating machinery are a concern, impact-resistant, fire-retardant polycarbonate should be used to protect the worker.] Some material hazards may also dictate the use of high-impact material due to the hazards to operating and maintenance personnel from a cracked or broken window. Some applications resolve this problem by placing a layer of glass inside the glovebox.

- Strictly adhere to acceptable housekeeping practices. Spontaneous combustion of certain materials can occur in a glovebox as well as in the secondary work area.
- Avoid the use of flammable materials within the box wherever possible and limit the amount of flammable material to the calculated air change (see Section 7.2) when no suitable nonhazardous substance can be substituted. Use containers for flammable substances that are approved for the planned operation.
- Maintain a current in-box material inventory. Gloveboxes should be used as designed. They are inappropriate for long-term storage, especially for chemicals.
- For inoperative gloveboxes, establish a safer, glovebox configuration and periodically check to ensure the gloveboxes are in a safe condition. Precautions include isolating boxes by closing fire stops, checking through-flow, checking port covers, disconnecting electrical equipment, and removing corrosives.
- Design the box with downdraft ventilation (high air inlet, low outlet) if possible to inhibit combustion while still purging the box. Generation of light flammable gases by the process may dictate exhausting from the top.
- Provide a protective atmosphere (see Section 7.5.2). This measure is listed last because those preceding it are applicable to all gloveboxes, whereas inerting is used only when there is too much risk involved in operating without a protective atmosphere. Assessing the degree of risk involved in an operation is often a subjective evaluation.

7.5.1.1 Detection

A glovebox fire detection system is recommended when there is a high risk of fire determined by a Fire Hazard Analysis (FHA). If flammable solvents, coolants, packaging materials, etc., must be present during operation, especially in unattended boxes, a heat detector should be installed on the glovebox. Fire detectors should be consistent with DOE-STD-1066.[3] Fire detectors are required in plutonium gloveboxes due to the pyrophoric nature of the material.

7.5.1.2 Suppression

Since a fire within a glovebox may be of paper, chemical, electrical, or pyrophoric metal origin, there is no single suppression method that is best for all gloveboxes. This is discussed thoroughly in detail in DOE-STD-1066.[3] However, when designing a glovebox, the designer should be aware of the materials, material quantities, process, and interfacing equipment that will be involved in the installation. At this point, the FHA should determine the proper suppression system for the installation. The fire suppression system must not cause a breach of the glovebox confinement that can spread contamination and increase the personnel exposure hazard to an unacceptable level.

There is no assurance that filters will remain functional during and following exposure to fire, smoke, or burning debris. Variable destructive effects on prefilters and HEPA filters include the temperature reached during a fire, the quantity and density of the smoke released, and the duration of the fire.

7.5.2 Inert Environments

Inerting a glovebox environment is done when working with materials that are pyrophoric, oxygen-sensitive, or moisture-sensitive, or when a process must be protected. Inert gases such as helium, argon, and nitrogen are metered into a gas-tight glovebox to displace the "air" volume. The characteristics of the gas (lighter than air, heavier than air) are applied using proper sampling sensors to obtain a true inerted glovebox. In pyrophoric and high-fire-potential applications, oxygen sensors are used to verify real-time concentrations. Inline filters should be installed to protect the oxygen monitor, or any monitor, from contamination. Monitors and sensors are available for many different types of gases and fumes. These should be selected when fire, explosion, and any associated risk to the process would result in danger to personnel and/or the facility. This should be determined by the facility risk and fire assessment groups. In most of these instances, the facility fire department should be directly connected to any alarms related to the event.

Gas-tight systems require quality construction of all components including gloveboxes, filters, and associated ducts. Any air ingress associated with the filter mounting or connecting duct will adversely affect the quality of the inert atmosphere that can be maintained in the glovebox and thus the cost of inert gas purification. Penetrations used to pass electrical input/output signals and power into the glovebox should be hermetically sealed for this purpose.

In fire protection applications, the preventive step of inerting is safer, though more expensive, than extinguishing a fire if it does occur. However, oxygen must be reduced below 1 percent before it fails to support the burning of some pyrophoric metal.[1] The use of dry air (RH less than 20 percent) reduces the hazard of pyrophoric metal fires, but does not eliminate it. Moisture in the presence of heated pyrophoric or reactive metals (e.g., finely divided plutonium) increases the possibility of explosion by generating hydrogen. The suitability and cost of an inert gas for the process are significant factors when selecting this type of fire control. The gas flow rate in most inert gas boxes is generally low. The flow must be consistent with required box-atmosphere purity levels, the scrubber, or the inert gas purification system that supports it. The inert gas may be purged on a once-through basis or recirculated through a purification unit. Purification, scrubbers, etc., should be protected with HEPA filters. Some of these systems are equipped with filters; however, it should be noted how the filter is safely changed while maintaining a level of confinement. Gloveboxes usually have filters installed for this purpose, the designer should assess the potential for equipment contamination and cleanup.

7.5.3 Control and Instrumentation

Glovebox instrumentation may range from simple indicators and alarms to sophisticated control systems. The type of control or instrument used will depend on the characteristics to be monitored, the relative hazards, and the method and time available to correct an upset condition. Operational characteristics to be measured and alarmed should always include the differential pressure between box and surroundings, the filter resistance, the gas flow rate through the box, and the box atmospheric temperature. An alarm should be available for any activity that could lead to degradation of or loss of confinement; fire; or any other safety concerns. In addition to instruments and sensors on the box, it may be necessary to indicate and provide for readouts and/or alarms at a central panel for oxygen content, liquid level, neutron flux, gamma flux, fire, and explosive gas mixture inside the box.

When a monitored characteristic requires annunciation for safety when the level of a monitored parameter passes some predetermined point, the alarm may be local. For example, an alarm may alert the operator to an upset condition (e.g., when the glovebox pressure differential becomes less negative than its design relative to the surroundings) or it may signal an annunciator panel in an adjoining "cold" area (e.g., by the entry door to the glovebox room, in a control room, or both). Standard operating procedures and sufficient information on the current contents of each box should be available to assist evaluation of the hazard area when an alarm sounds and to aid in planning corrective action.

Minimum instrumentation for a glovebox ventilation system should include devices to indicate the differential pressure between the box and its surroundings, exhaust filter resistance, total exhaust flow rate, and exhaust air temperature. **Figure 7.17** shows the arrangement of indicating devices in a glovebox ventilation system. The items shown above the double-dashed line indicate the types of instruments commonly used to supplement the minimum instrumentation necessary to improve safety for a particular operation or circumstance. For example, when box operators are not in full-time attendance for a continuous process, a sensor can be provided to monitor abnormal pressure, temperature, or almost any other critical process parameter and to actuate a remote alarm where an attendant is stationed. **Figure 7.18** shows an example of a local mounting for a differential pressure gauge (commonly referred to as a differential pressure gauge) on top of a glovebox. The instrument should be mounted near eye level, and the indicating face should be located so that the operator has a clear view while manipulating the gloves. The gauge display should make operating conditions easily discernible to the operator (e.g., a differential pressure gauge with a range of 1 in.wc with "0" at the top). Sensing lines should be short and should be sloped directly back to the glovebox so that moisture will not pocket in the tube. Inline HEPA filters either should be located inside or as close to the glovebox as possible to prevent contamination migration into the gauge lines and gauge. Tubing should be at least 3/16 inch-diameter to allow the instrument to respond quickly to rapid changes in pressure. Use of a three-way vent valve at the gauge permits easy calibration (zeroing) without disconnecting the sensing tube. Calibration of glovebox differential pressure gauges should be done routinely.

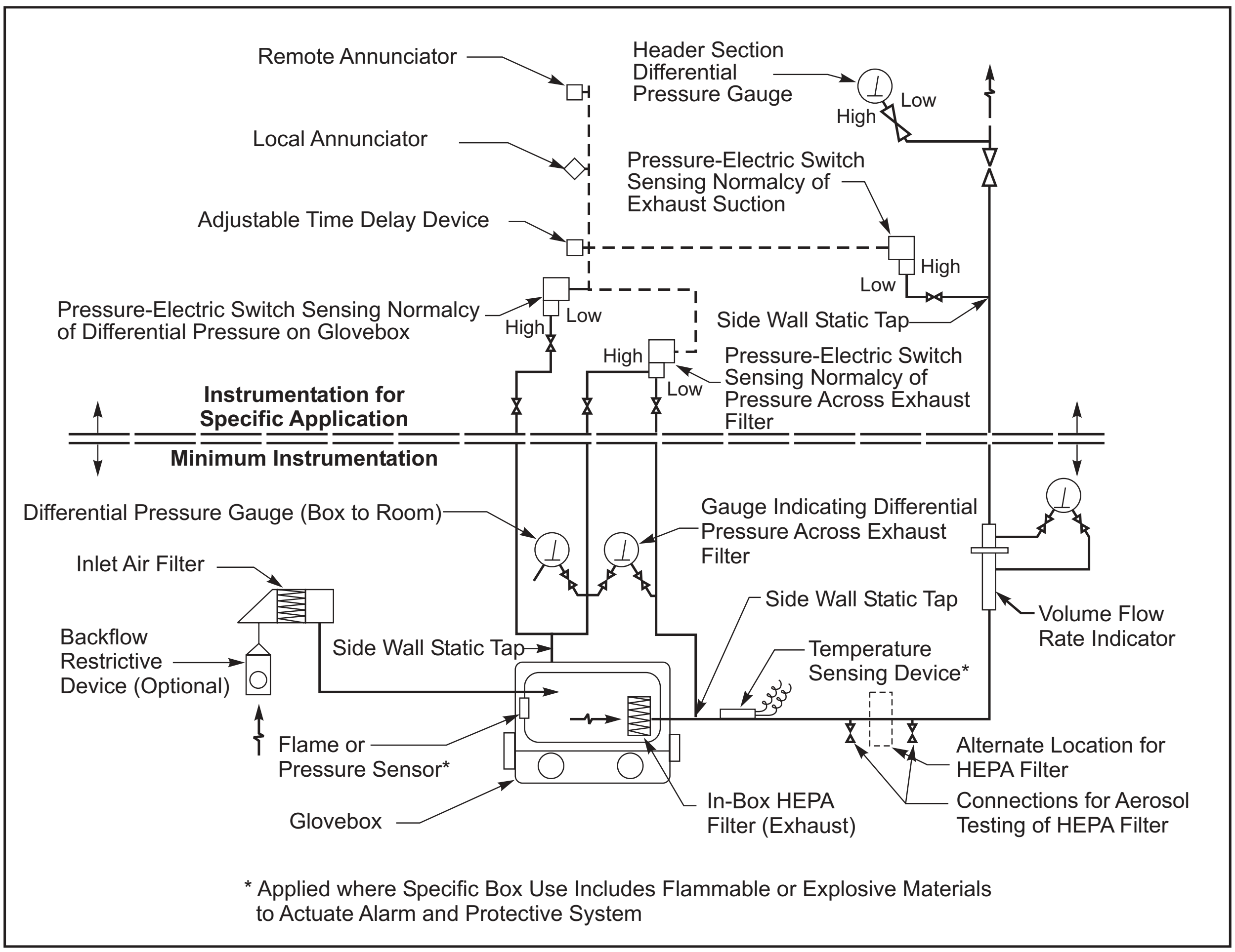


Figure 7.17 – Arrangement of Indicating Devices in Glovebox Ventilation System

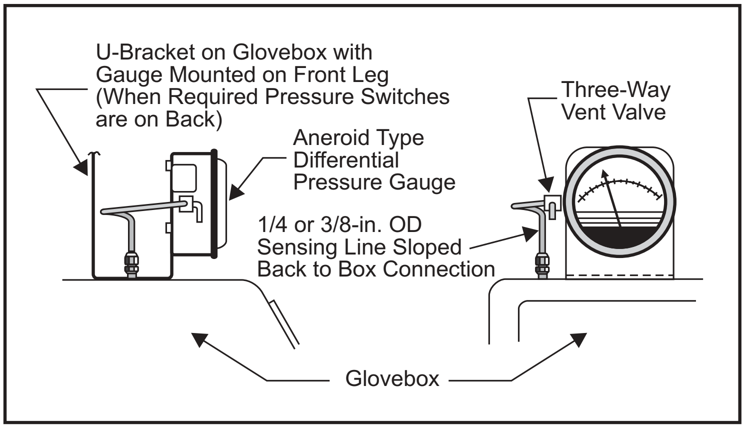


Figure 7.18 – Typical Local Mounting for Differential Pressure Gauge

Selection of a differential pressure gauge, differential pressure gauge with switch, or transducer should be determined by the application. One advantage of using a gauge is simplicity. A line is connected across the upstream and downstream plenums of a filter where the pressure drop can be measured. Most gauges and transducers install in this manner. A differential pressure gauge with switch has the addition of an alarm function. A transducer allows multiple readouts and greater accuracy, and can be used to automate the exhaust system. It is more costly, however, because it must have a power supply, readout, and transducer. The requirement for a gauge should be based on the actual system pressure. Exhaust filter pressure drops, for example, can vary up to 3 in.wg. If the inlet filter housing valve is closed, the device will see the full negative capacity of the blower. The gauge or transducer must have a proof pressure greater than the maximum system pressure (negative or positive) so that it will not be damaged by excessive pressure.

Devices that measure pressure have a problem with “drift.” This occurs on most devices because of continual pressure on the device. As a result, they must be recalibrated on a routine schedule. Liquid-filled devices (manometers) are not recommended for glovebox pressure indicators; however, they have been used to check the calibration of an existing device. Inlet filters on air-ventilated gloveboxes generally do not require differential pressure gauges. The pressure drop across the inlet filter is approximately the same as the box pressure.

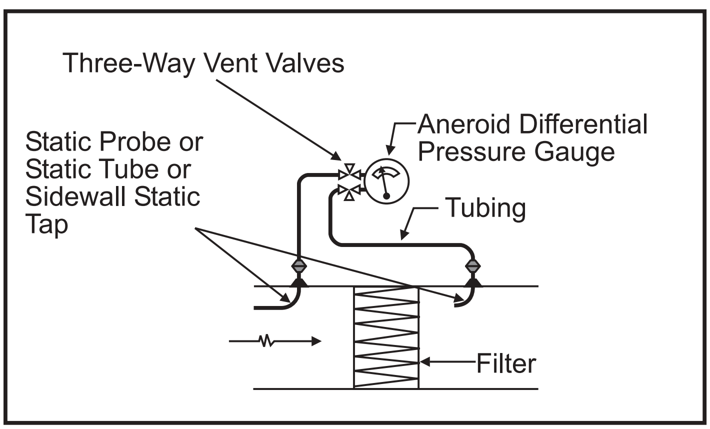


Figure 7.19 – Indicating Pressure Drop through a Filter

A differential pressure gauge should be provided for each exhaust HEPA filter stage to indicate filter resistance. Pressure-sensing connections can be provided to permit the use of portable instruments. Suitable alarms or controls that can function on small pressure differentials (equal to 0.25 in.wg) are difficult to keep calibrated and are often expensive. **Figure 7.19** shows a method for indicating pressure drop through a filter. Chapter 5, Section 5.6, gives some further information on differential pressure instrumentation.

Instruments used to measure airflow rates from gloveboxes include an orifice plate, venturi meter, flow nozzle, and calibrated Pitot tube. The important point is to use a simple, trouble-free device that gives reliable readings within an accuracy of ±15 percent. When free moisture is absent, a Pitot tube is the least expensive and most adaptable device for the small volume flow rates associated with glovebox ventilation. Velocity pressure measurements (corrected for Pitot-tube single centerline location) for airflows and duct sizes common in glovebox applications are given in **Figure 7.20**. The corrections shown are for air at 60 degrees Fahrenheit and 14.7 pounds per square inch absolute (psia), and neglect the Pitot-tube coefficient. Pitot tubes are available with coefficients of 1.00, but there is an advantage in using the more common commercial Pitot tube with a coefficient of 0.825 at low flow velocities. The equation for measuring velocity with a Pitot tube is shown below.

$$V = K\,(2gh)^{1/2}, \qquad (7.5)$$

where:

V = fluid velocity, ft/sec

K = coefficient of the pitot tube

g = acceleration of gravity, 37.17 ft/sec^2

h = velocity pressure (ft) of the air-gas stream

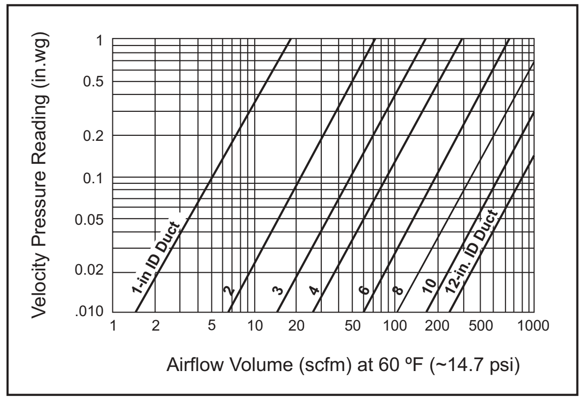


Figure 7.20 – Velocity Measurements

The following equation is used for air at standard conditions:

$$V = 4005\,K\,(hw)^{1/2} \qquad (7.6)$$

where:

V = fluid velocity, fpm

hw = velocity pressure, in.wg.

A Pitot tube with a coefficient of 0.825 has a velocity pressure reading that is 1.47 times the velocity pressure reading of the Pitot tube with a coefficient of 1.00 for the same fluid velocity. This pressure differential allows the low velocities often encountered in glovebox ventilation to be measured more easily.

Figure 7.21 shows the arrangement of a round orifice in a straight section of metal duct. Either method (Pitot tube or orifice) can be used to read the flow volume directly on a properly calibrated gauge. For a thin, sharp-edge, round, concentric orifice with the properties given in **Figure 7.22**, the flow rate can be determined with sufficient accuracy for glovebox applications by the following equation:

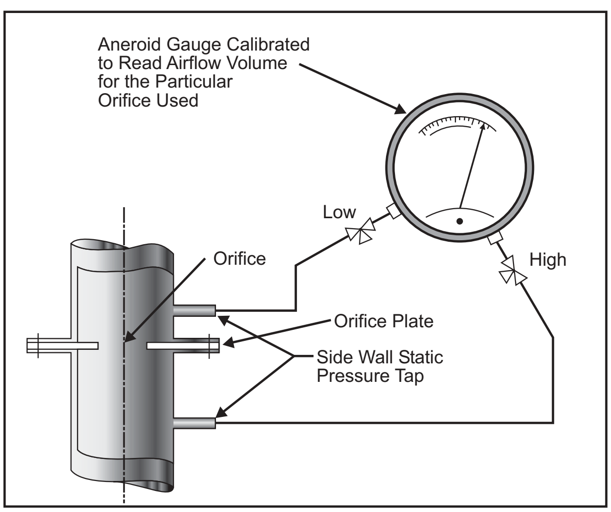


Figure 7.21 – Orifice Meter Method of Measuring Volume Flow Rate in Small Ducts

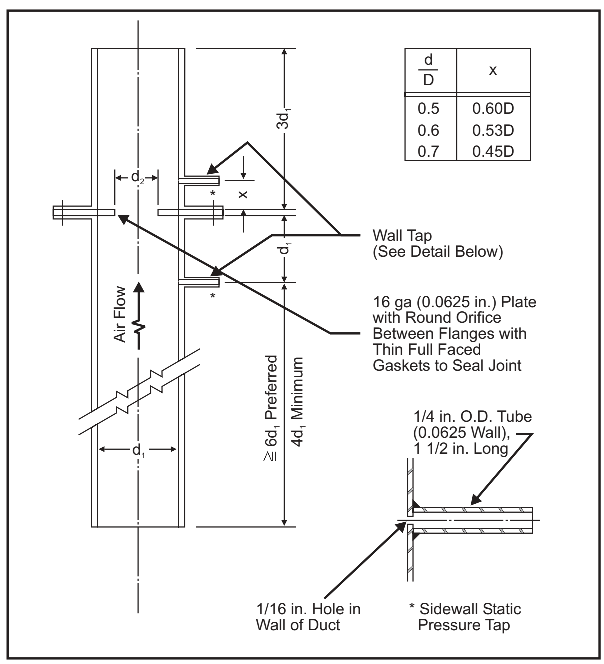


Figure 7.22 – Arrangement of Sharp-Edge Concentric Orifice in Small Duct

$$Q = 14\, d^2 h^{1/2} \qquad (7.7)$$

where:

Q = airflow, cfm

d = orifice diameter, inch

h = pressure drop across orifice, in.wg

Assumptions inherent in the constant 14 used in equation (7.7) include: (1) air at standard temperature and pressure, (2) flow coefficient for orifice = 0.65, and (3) ratio of orifice diameter to smooth-duct diameter, D, 0.2 = d/D = 0.7. The practical use of this formula can be shown by the following example.

Determine the orifice size necessary for a 20-cfm airflow rate that would give a reading near the center of scale on a 0- to 0.50-inch-range gauge.

$$Q = 20 \text{ cfm}$$
$$h = \frac{0.50}{2} = 0.25 \text{ in.wg}$$
$$d = \frac{Q}{14h^{1/2}} = \frac{20}{14(0.25)^{1/2}} \qquad (7.8)$$
$$d = 1.79 \text{ in.}$$

For 3-inch schedule 10 stainless steel pipe (3.260-inch-diameter), the d/D ratio is 1.79/3.26 = 0.55, which is within the acceptable range.

A shortcoming of the thin-plate orifice is loss of head of the air flowing through the device. **Table 7.2** gives the loss of head of concentric orifices for various d/D ratios.

Table 7.2 – Loss of Head for Various d/D Ratios

d/D ratio	*Fraction of Velocity Head Not Regained*
0.2	0.95
0.3	0.89
0.4	0.83
0.5	0.74
0.7	0.53

In the example above, 0.70 × 0.20 = 0.14 in.wg is the pressure loss when 20 cfm flows through the orifice of d/D = 0.55.

Immediately after installation and while filters are still clean, the measured pressure drop across the HEPA filter can be used to check airflow to a high degree of accuracy by proportioning the measured pressure drop to that stamped on the filter case at the time of predelivery testing. The pressure drop across the filter is no longer a dependable indication of gas flow rate after the filter has accumulated dust. After a filter has been in service for a period of time, it is necessary to measure both the pressure drop across the filter and the airflow through it to evaluate the filter's status and relationship to the whole ventilation system.

Written procedures for periodically testing each alarm, control, and emergency system serving the glovebox and its ventilation system are essential.

7.5.4 Challenge Aerosol Testing of Glovebox Filters

Testable HEPA filter installations must be tested immediately after installation and then again periodically to ensure that air cleanup capability and confinement integrity remain intact. The principles of challenge aerosol testing of HEPA filters are given in Chapter 8. The HEPA filters used in glovebox systems are often inconvenient to test because the challenge aerosol must be injected into the inlet duct or glovebox. The challenge aerosol cannot be fed into the inlet of the box to test the exhaust-side filters if high-efficiency filters are used in the inlet. Methods A and B (**Figure 7.23**) require the challenge aerosol to be drawn into the glovebox by the suction of the exhaust system. However, the challenge aerosol should not be injected into gloveboxes housing apparatus with open or exposed optical lenses or with highly polished surfaces, delicate balances, crystalline structures, sensitive conductors, or similar equipment or products. In such cases, the filter should be installed in the duct downstream of the glovebox so that the injected challenge aerosol will not back up into the glovebox proper. Method C (**Figure 7.24**) may then be used for challenge aerosol testing of the exhaust HEPA filter.

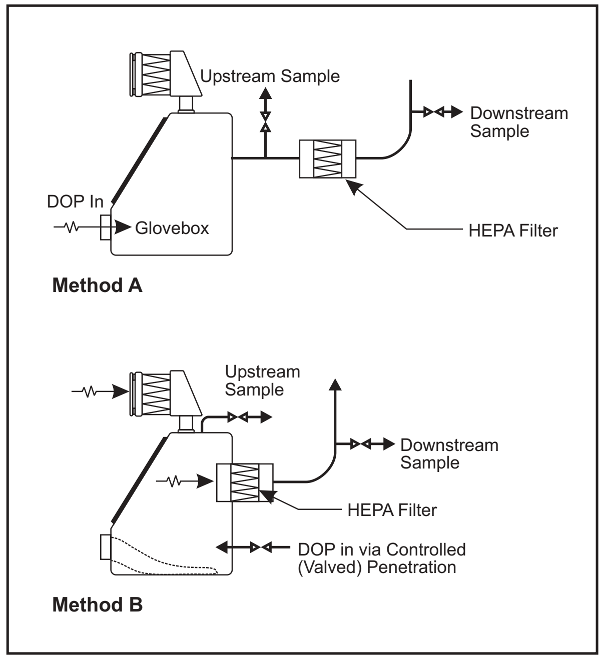


Figure 7.23 – Methods of Injecting Test Aerosol and Extracting Samples (Method A and B)

Where new or replacement exhaust filters are required to be tested before restarting the ventilation system, Method D (Figure 7.24) may be used. Note that in this method the exhaust path from the glovebox is closed and the challenge aerosol-air mixture for filter testing is drawn from a separate valved path. The side path is closed and sealed after testing is completed.

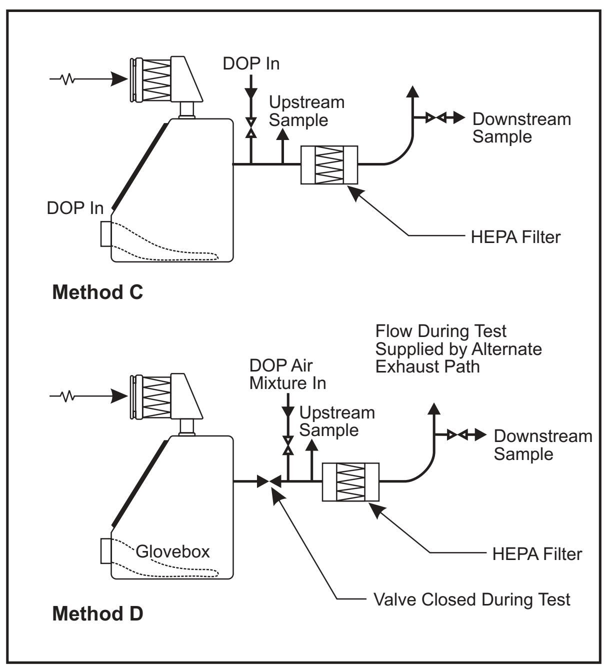


Figure 7.24 – Methods of Injecting Test Aerosol and Extracting Samples (Methods C and D)

Methods A and B (Figure 7.23) require injection of the challenge aerosol-air mixtures into the glovebox via some convenient opening. A gloveport can be used if confinement is not critical during testing. Otherwise, a connection can be prepared (**Figure 7.25**), or an alternate method can be devised. Methods C and D (Figure 7.24) do not require the introduction of a challenge aerosol into the glovebox. The challenge aerosol inlet connection must be sized to pass the challenge aerosol or challenge aerosol-air mixture. The connection for concentrated challenge aerosol in Method C must admit 2 to 5 cfm, while the connection in Method D must accommodate the total challenge aerosol-air mixture used for the test.

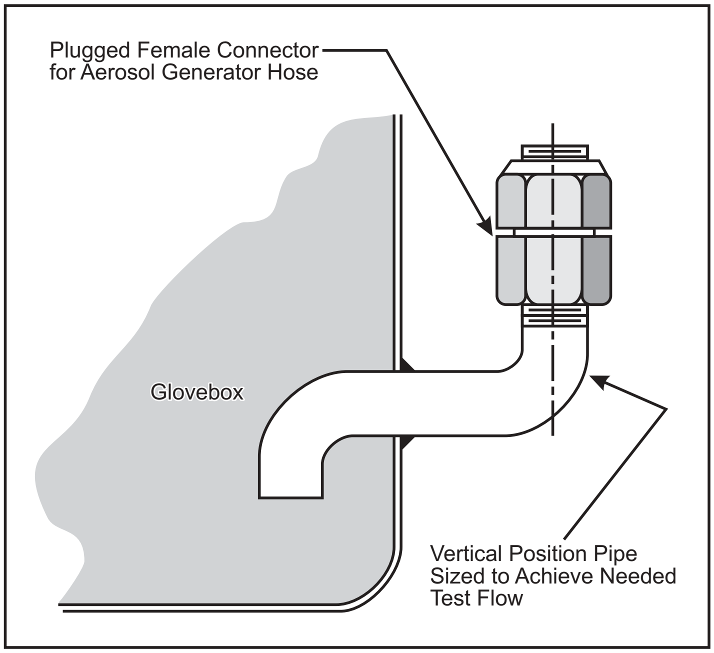


Figure 7.25 – Connection for Introducing Test Aerosol into Glovebox

7.5.5 Glovebox Shielding

Some gloveboxes may require gamma, beta, and neutron shielding because of the nuclides used and the amounts of material involved. Boxes handling kilogram quantities of plutonium can be shielded by providing lead-impregnated gloves, glovebox shielding (water or any other similar mass), lead glass over the windows, and lead-hinged plugs or covers over the ports. The operating, shielding, removal, and replacement requirements of the glovebox HEPA filter must also be considered when glovebox shielding is required. The thickness of the shielding affects the design of the filter housing used on this type of glovebox. The designer should account for this by extending the service fittings (pressure measurement) and any other glovebox pass-through used in the design. This practice is also mandated for bagging ports used to remove the primary HEPA filters and the cover doors. Ergonomic operations inside shielded gloveboxes should be given careful consideration because lead-lined gloves and dimensional differences make manipulations very difficult.

7.5.6 Seismic Design Considerations

By their very nature, gloveboxes are typically top heavy. This presents some unique challenges when designing the supports and holddowns for the systems during a postulated seismic event. Several facilities have had to redesign their support systems after the facility was operating. This led to many obstructions and interferences which could have been avoided at an earlier design stage. For seismic considerations in DOE facilities, see Chapter 9.

7.5.7 Criticality Considerations

When criticality is a potential concern for glovebox design, care must be taken in providing for the appropriate geometry control and water use restrictions. Drains, in particular, must be designed with great care. The buildup of fissile material on the HEPA filters must also be considered.

7.6 References

1. AGS (American Glovebox Society), 1998, *Guidelines for Gloveboxes*, AGS-G001 (Second Edition), Santa Rosa, CA.

2. ASME (American Society of Mechanical Engineers), 2003, *Code on Nuclear Air and Gas Treatment*, ASME AG-1, New York, NY.

3. DOE (U.S. Department of Energy), 1999, *Fire Protection Design Criteria*, DOE-STD-1066, Washington, DC, July.

4. ASHRAE (American Society of Heating, Refrigeration and Air Conditioning), 1973, *Handbook and Product Guide – Systems*, New York, NY.

5. ASME (American Society of Mechanical Engineers), 1989, *Testing of Nuclear Air Cleaning Systems*, ASME N510, New York, NY.

6. DOE (U.S. Department of Energy), 2000, *Facility Safety*, DOE Order 420.1, Washington, DC, November.

CHAPTER 8

TESTING

8.1 Introduction

The rationale behind high-efficiency particulate air (HEPA) filter specifications was developed by Humphrey Gilbert, a Manhattan Project safety engineer who coined the term, "HEPA filter." The heart of the filter is the media (paper), originally the same filter paper used in World War II (WWII)-era military gas mask canisters. As a result, the HEPA filter inherited many of the same specifications used for gas mask military standards, most of which were developed during WWII and have remained largely intact to the present. For example, HEPA filters are tested for efficiency using aerosols with a 0.3-micrometer (μm) particle size because academics in the 1940s calculated that a particle of that size would be the most difficult to capture or filter. Modern technology has proven this calculation relatively accurate.

The specifications of in-place testing, sampling and laboratory testing of adsorbents also evolved from the WWII-era of military gas mask canisters to application in the nuclear industry. Chapter 1 discusses the history and use of adsorbents for nuclear power reactors, radiochemical processing, fuel processing plants and noble gas control.

Testing of high-efficiency nuclear air cleaning systems is required to achieve and maintain high performance and continued safe operation of nuclear facilities. In nonreactor nuclear facilities throughout the U.S. Department of Energy (DOE) complex, HEPA filters in confinement ventilation systems can be constantly challenged with radioactive aerosols. Nonreactor nuclear facilities comprise the bulk of DOE nuclear facilities, and failure of their air cleaning system components can lead to uncontrolled release of radioactive aerosols. Thus, maintaining nuclear facility operability depends on the performance of these air cleaning components.

At the same time that HEPA filters and adsorbers were being developed for nuclear applications, methodologies were being developed to assure their performance. These methodologies eventually evolved into a performance assurance program with three major components: <u>(1) design qualification of individual components through destructive testing, (2) quality assurance (QA) of individual components through nondestructive testing, and (3) performance assurance of nuclear confinement ventilation systems through in-place testing.</u> This overall performance assurance program was designed to be hierarchical because components were built on a foundation laid down by preceding components. Design qualification assured that filters produced according to a manufacturer's design met specific performance criteria for normal and off-normal operation. Ideally, performance criteria were directly related to a facility's design basis. In fact, however, this often was not the case, making it difficult to impossible to crosswalk between facility operation requirements and material/design qualification test criteria.

Once a manufacturer's design was qualified, the filter model number was put on a qualified products list (QPL) maintained by the Department of the Army. It was mandated that only QPL-listed manufacturers could be used for HEPA filter procurement. The nuclear industry adapted the QPL for use in procuring HEPA filters. Standard test procedures and equipment available from the American Society for Testing and Materials (ASTM), the Technical Association of the Pulp and Paper Industry (TAPPI), and others were referenced in the documentation of QPL products. Numerous organizations have issued consensus standards incorporating major provisions of the military specification and qualification standards. Those holding the most interest for nuclear service applications are the publications prepared by a standards writing group sponsored by the American Society of Mechanical Engineers (ASME) Committee on Nuclear Air and Gas Treatment (CONAGT), with participation from DOE and the U.S. Nuclear Regulatory Commission (NRC). Upon withdrawal of the U.S. Department of Defense (DoD) Military Specifications MIL-51079, *Filter Medium, Fire Resistance, High Efficiency,* (1980)[1] and MIL-51068, *Filter Particulate, High Efficiency, Fire-Resistant,* (1981),[2] the MIL standard requirements were incorporated verbatim into ASME AG-1, *Code on Nuclear Air and Gas Treatment*, Section FC.[3] The Army no longer publishes the QPL.

HEPA filters for nuclear service now undergo four tests: (1) a design qualification test performed by a qualified laboratory, (2) quality control testing at the manufacturer, (3) a DOE-required acceptance test, and (4) and a system leak test at the facility where the filter will be used. Manufacturers submit prototype filters for design qualification testing. This testing examines areas such as media penetration and resistance to airflow, rough handling, pressure, heated air, and spot flame. The filter medium receives the most rigorous and extensive control and evaluation**.** At present, the U.S. Army's Edgewood Arsenal in Maryland is the only facility available to perform this qualification testing. This testing is required to be repeated every 5 years. Manufacturers receive a letter stating whether their filter designs passed the qualification tests.

After qualification of a filter design, manufacturers are eligible to sell their HEPA filters for use in nuclear applications. Before the filters are supplied to DOE, however, ASME AG-1[3] requires manufacturers to perform quality control testing including penetration testing and resistance to airflow.

DOE-STD-3020[4] requires further acceptance testing of HEPA filters that will be used in DOE nuclear facilities. This testing must be performed at a DOE Filter Test Facility (FTF). Manufacturers are required to submit their HEPA filters to the DOE FTF. This 40-year-old requirement was reestablished by the Secretary of Energy in a letter dated June 4, 2001, and reconfirmed in a letter dated July 11, 2003[5]. At the FTF, filters must pass a rigorous visual inspection by trained inspector personnel and various flow tests (penetration, resistance to flow, etc.). Filters that fail a visual inspection are not subjected to flow tests. There has been a 40-year history that suggests a failure rate of 3 to 5 percent for visual inspections and approximately 2 percent for performance. This persistent failure rate forms the basis for performing both the manufacturers' tests and having them independently verified at the FTF in order to obtain a HEPA filter with an efficiency of at least 99.97 percent. The FTF tests and the manufacturers' tests are based on: (1) uniform aerosol concentration, (2) uniform flow, (3) qualified sample locations, (4) capability for 100 percent and 20 percent flow, and (5) a challenge aerosol of 0.3 µm. This particle size represents the size of maximum penetration through the filter. Only filters that pass the FTF tests are forwarded to a DOE nuclear facility. Filters that fail are returned to the manufacturer, typically without cost to the buyer.

After being installed at a DOE nuclear facility, an in-place leak test is done to ensure the performance of the confinement ventilation system. Unlike bench tests for new filters that are designed to determine filter quality via a penetration test utilizing an aerosol containing a substantial fraction of particles in the range of the minimum filterable size, in-place tests are designed to reveal the presence of defects in the filter unit that result from such things as rough handling during transportation, paper and gasket damage during installation, inadequate pressure against intact gaskets, and penetrations through the housing to which the filter units are attached. Aerosol penetration during an in-place test in excess of established limits is assumed to indicate defective installation and/or filter damage. Procedures are conducted to locate and correct the defects. Such procedures include increasing gasket compression; examining gaskets for breaks and tears; replacing broken filters (repairs are not permitted for nuclear service in the United States); and welding closed any unauthorized penetrations, cracks, and open seams in the filter house and mounting frames (patching with caulking compounds is not permitted for nuclear service in the United States). Following each repair, the system must be retested until it meets the established criteria for leak tightness.

The performance of the periodic/surveillance in-place test cannot be overemphasized. The in-place leak test described by ASME N-510 is used to conduct a periodic surveillance to reconfirm the performance of the filter system. The in-place leaks test confirms the safety basis assumptions "system efficiency." The final result is a measure of efficiency that forms the basis for removal efficiency assumed in the safety bases. The in-place test results may also be credited by the RadCon and air emission permits for removal of respirable particles. Unlike the filter penetration test which validates the filter design assumption using a mono-disperse aerosol test, the in-place leak tests uses a poly-dispersed (0.7 mean diameter) and determines the system efficiency where the system components (i.e., gaskets, frame, housing, etc.) are challenged. The test is performed under actual conditions and at operational airflow. The criteria for the in-place leaks tests are typically provided by the safety basis or other operating licenses/permits. The test results may also be used as a service life indicator.

Each of the components of this vigorous performance assurance program is described in this chapter.

8.2 Proof of Design – HEPA Filter Design Qualification Testing for Nuclear Service

As discussed previously, the U.S. Army's Edgewood Arsenal tests prototype HEPA filters to qualify the designs for use in DOE nuclear facilities (this testing is required to be repeated every 5 years). ASME AG-1, Section FC,[3] requires quality product qualification testing for efficiency, airflow resistance, rough handling, overpressure, heated air, and spot flame. The following subsections discuss each design qualification test and associated acceptance criteria.

8.2.1 Penetration (Efficiency)

The performance of a HEPA filter may be expressed either as a particulate collection efficiency (percent of particulate concentration stopped by the filter) or as a penetration. Penetration where the total aerosol penetration through the filter medium, frame, and gasket of a filter that has been encapsulated shall be no greater than 0.03 percent of the upstream concentration at rated airflow and at 20 percent of rated airflow. The reason for the 20 percent flow test is to increase sensitivity for pinhole determination. Concentration may be given by particle count per unit air volume (emphasizing the smallest particles present), particle weight per unit air volume (emphasizing the largest particles present), ionizing radiation intensity per unit volume of air (particle size effect is indeterminate), or light-scattering intensity per unit air volume (emphasizing small particle sizes). Sometimes filter penetration is expressed as a decontamination factor (DF), the ratio of the untreated air concentration to the treated air concentration (e.g., 99 percent collection efficiency is the same as a DF of 100 and is equal to a penetration of 1.0 percent). The DF descriptor is used most frequently when ionizing radiation is the concentration descriptor.

8.2.2 Airflow Resistance

The resistance of a filter to airflow, often called "pressure drop" and "back pressure," is usually given as the height of a water column (measured in in.wg) that exerts an equal pressure. The characteristic flow regime through HEPA filter media is aerodynamically described as laminar. For this reason, the airflow resistance of these filters changes in direct proportion to changes in air volume even though the air approaching the filter may be turbulent. Resistance to airflow at the rated airflow of the filter shall be no greater than 1.0 in.wg for filter sizes 4 and 5, and 1.3 in.wg for filter sizes 1, 2, 3, 6, 7, 8, and 9. See ASME AG-1, Section FC[3] for filter definitions.

The test protocols used to qualify HEPA filters for nuclear service are described below. Bench testing of all new filters intended for U.S. nuclear service is conducted with a test aerosol in a tester called a Q107 aerosol penetrometer (**Figure 8.1**). This device was designed by the U.S. Army Chemical Corps during the 1950s, and its construction and operation are described in MIL-STD-282 *Military Standard Filter Units, Protective Clothing, Gas Mask Components, and Related Products: Performance/Text Methods*,[6] Method 102.9. The complete penetrometer consists of a monodisperse test aerosol generator, an instrument that measures the size and uniformity of the particles formed, a clamping device to seal the filter under test into the test fixture, a total scattering photometer to measure test aerosol penetration, and a manometer to measure filter resistance at rated airflow rate.

8.2.3 Test Aerosol Test

The basic apparatus and procedure is described in detail in Military Standard MIL-STD-282[6] and DOE-STD-3025.[7] Room air is drawn through filters and split into three streams. One stream of 85 cubic feet per

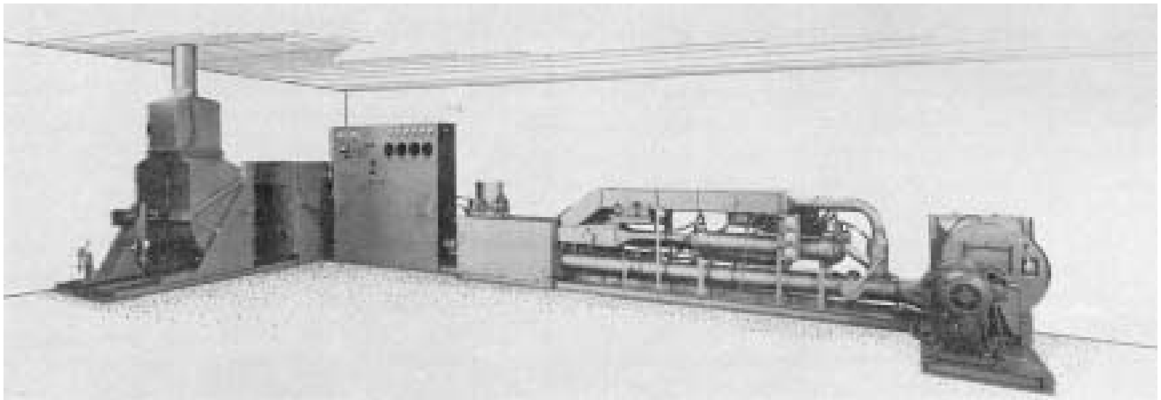


Figure 8.1 – Q107 Penetrometer for Efficiency Testing of HEPA Filters (Equipment contains a thermal DOP generator capable of producing a monodispersed aerosol)
(Photo provided by ATI)

minute (cfm) is heated to 365 degrees Fahrenheit and is passed over liquid test aerosol heated to 390 ± 20 degrees Fahrenheit. As the heated air passes over the surface of the hot test aerosol, it becomes saturated with aerosol vapor. Traditionally the test aerosol of choice was dioxytl phithalate (DOP). When the test-aerosol-saturated air contacts the second airstream (265 cfm held at approximately 71 degrees Fahrenheit), the condensation aerosol is formed. The third stream of diluent air (850 cfm) is introduced in a mixing chamber to dilute and disperse the aerosol-laden air. A forward light-scattering photometer is used to measure test aerosol penetration, and a manometer is used to measure filter resistance at rated airflow rate. Modern penetrometers that use jet impactors to obtain the same aerosol without heating the test aerosol liquid are commercially available.

The size of the test aerosol is determined by passing a sample through an optical particle-sizing instrument called an OWL[8] and noting the degree of polarization of a light beam. A polarization angle of 29 degrees indicates a particle diameter of 0.3 µm when the aerosol is monodispersed. The brightness and number of red bands produced when the beam is rotated 360 degrees indicates the uniformity of the particles. However, when the aerosol is not precisely monodispersed, the polarization angle read by the OWL represents an average diameter that is not the same as for a precisely monodispersed aerosol.[9] For example, a test aerosol with a count median diameter of 0.232 µm and a geometric standard deviation of 1.15 (perfect uniformity is a geometric standard deviation of 1.0) would give a polarization angle of 29 degrees, whereas a 0.3-µm aerosol with the same degree of size dispersion would give a polarization angle of 45 degrees.[9]

In the early 1980s, DOE issued a contract to the Los Alamos National Laboratory (LANL) to review HEPA testing practices. In the subsequent study, LANL highlighted the pros and cons of the MIL-STD-282[6] testing methodology, and recommended looking at modern technology to develop an alternative. This alternative system became known as the High Flow Alternative Test System (HFATS) and is currently used by some HEPA filter manufacturers and the DOE FTF located in Oak Ridge, Tennessee.

The HFATS uses the MIL-STD-282 Q-107 aerosol penetrometer blower, ducting, filter holding fixture (chuck) and some of the controls as a platform. The thermal monodispersed aerosol-generating components were disabled and replaced with the LANL-designed aerosol generator incorporating the standard Laskin nozzles and impactors. This combination generates a polydispersed aerosol that allows for penetration determinations at the particle size of maximum penetration (≅ 0.2 µm diameter) and at the traditional particle size of 0.3 µm diameter. The Q-107 aerosol monitoring and aerosol efficiency measuring instrumentation was disabled and replaced with a laser aerosol spectrometer, an upstream sample diluter, and a computer. A final report covering all the details is in LANL publication LA-10748[10] available from National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

In summary, the HFATS eliminated several problems inherent with the MIL-STD-282 system and took advantage of state-of-the-art aerosol sizing instruments, which are capable of providing more detailed information regarding filter performance. It also allowed the use of liquids other than DOP and at a much lower concentration to test the filter. When using any test aerosol, consideration must be given to the flammability of the material.

8.2.4 Resistance to Rough Handling Qualification Test

The rough handling tester (**Figure 8.2**) was designed by the U.S. Army Chemical Center (Edgewood Arsenal) to subject a carbon filter to vibration to determine whether carbon channeling would occur during shipping and handling. If channeling occurred, then toxic gases would have a bypass path around the carbon, allowing penetration of the filter. The HEPA filter inherited this test to determine its capability of being transported across country by commercial carriers. It was quickly determined that transportation by rail led to unacceptable failure rate. [Note: This test does not actually test the HEPA filter according to the way it is shipped; a commercial vibrating machine designed for this purpose should be used to test the filter. In addition, the filter should be tested in its packaging exactly as it will be shipped, not laid down horizontally and bolted to a table.]

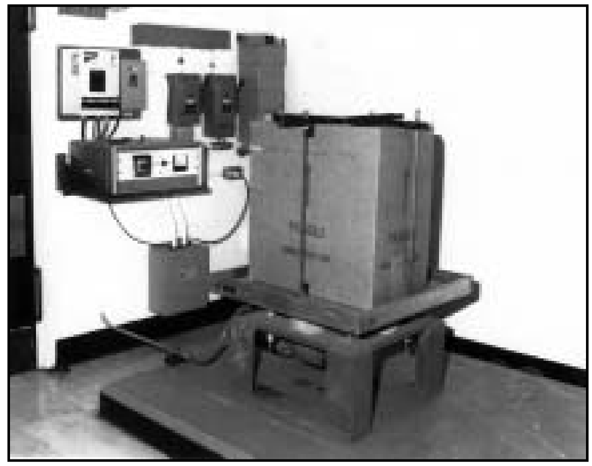


Figure 8.2 – Rough Handling Machine

In accordance with Method 105.9 of MIL-STD-282,[6] new, unused test filters (at least 2 of the size and design to be qualified) must undergo rough handling for 15 minutes at a total amplitude of 0.75 inches (using sharp cut-off cams that result in both a slow and an instantaneous 0.75-inch drop) and a frequency of 200 Hertz (Hz), with pleats and filter faces in vertical orientation. The filters must withstand this treatment without visible damage (cracked or warped frames, loose corners or joints, cracked adhesive, loose or deformed medium) or a decrease in filtration efficiency from 99.97 percent, as determined with nominal 0.3 μm test aerosol at full and 20 percent flows.

8.2.5 Moisture and Overpressure Resistance Qualification Test

The overpressurization tester (**Figure 8.3**), which tests HEPA filters at high humidity and at 10 in.wg, also came from a military standard for testing carbon filters that was applied to the HEPA filter. At least four new, unused filters of the type to be qualified must be aged a minimum of 24 hours under static conditions at 95 ± 5 degrees Fahrenheit and 95 ± 5 percent Relative Humidity (RH), after which they must be installed in a wind tunnel that has been modified to permit the introduction of water spray. After conditioning, the filters must withstand a spray of 1.25 pounds per 1,000 cfm, adjusted to produce a 10-in.wg pressure drop across the filter, and a flow environment of 95 degrees Fahrenheit. The minimum test duration under these specified conditions is 1 hour. After the test and the filters are dried out, there must be no visible evidence of failure. Within 15 minutes after completion of the pressure test and while still wet, the 0.3-μm test aerosol efficiency at full and 20 percent rated flow

Figure 8.3 – Overpressure Resistance Tester

must be a minimum of 99.97 percent. By indirect reference, this qualification test is a requirement of all U.S. nuclear application specifications (see ASME AG-1, Section FC).[3] This is the most stringent test an assembled HEPA filter will undergo and is limited to a 10-in.wg pressure drop. Some new HEPA filters have had difficulty meeting this requirement. For this reason, HEPA filters should never be rated for services at greater than 10 in.wg and should never be used above half this value.

8.2.6 Fire and Hot Air Resistance Qualification Test

The high-temperature test came from the nuclear industry as a result of a catastrophic fire at the Rocky Flats site. Related research work also was done at Lawrence Livermore National Laboratory (LLNL). The 700 ± 50 degrees Fahrenheit point of the test was selected in laboratory experiments. Since industry consensus standards did not come into vogue until the late 1950s and early 1960s, the HEPA filter inherited many then-current military standards and specifications.

New, unused filters must be exposed to heated air in a wind tunnel at 700 ± 50 degrees Fahrenheit for 5 minutes **(Figure 8.4)**. After exposure to heat, the filters must be cooled down and tested in-place, with the filter remaining in the heated air tester. An aerosol generator and photometer may be used for the aerosol test. The penetration at equal to or greater than 40 percent of rated flow must be less than 3 percent. By indirect reference, this test is a requirement of all U.S. nuclear application specifications (see ASME AG-1, Section FC).[3]

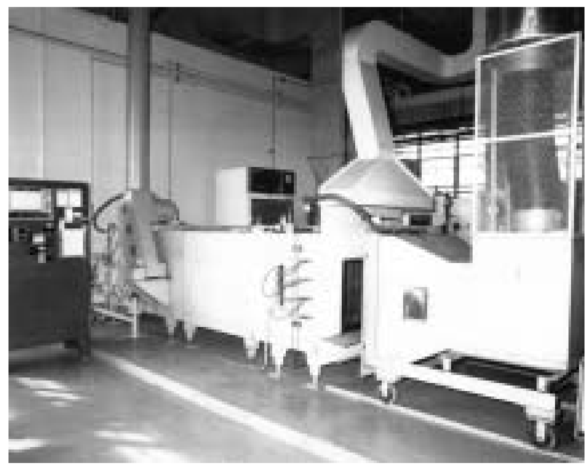


Figure 8.4 – Heated Air Tester

8.2.7 Spot Flame Resistance

New, unused filters must be tested for spot flame resistance. In this test, the HEPA filter is inverted in a test duct and operated at its rated airflow. A gas flame from a Bunsen burner is directed against the upstream face of the HEPA filter. The Bunsen burner is adjusted to produce a flame with a blue cone 2.5 inches long with a tip temperature of 1750 ± 50 degrees Fahrenheit. The tip of this flame is applied so that it is not less than 2 inches from the filter face. The flame is applied for 5 minutes at each of 3 separate locations on the filter face. The Bunsen burner flame then is directed into the top corner of the filter unit so that the tip of the blue flame cone contacts the frame, filter pack, and pack sealant. The flame is applied for a period of 5 minutes. After the removal of the test flame at each point of application, there must be no sustained flaming (burning) on the downstream face of the unit. By indirect reference, this test is a requirement of all U.S. nuclear application specifications (see ASME AG-1, Section FC).[3]

8.3 Manufacturer's Quality Control - Inspection and Testing of HEPA Filters

The manufacturer's qualification procedure involves two distinct phases: (1) a quality assurance/quality control (QA/QC) routine intended to ensure careful manufacture of a quality product, and (2) a series of tests to verify filter compliance with preset standards concerning the properties of components and the physical characteristics of the assembled filter, as well as a set of performance criteria related to collection efficiency and resistance to airflow. When all of these factors are within the tolerance limits set by the applicable standards, the manufacturer certifies that each delivered filter unit meets all acceptance criteria. The manufacturers required tests for HEPA filters are prescribed in ASME AG-1, Section FC.[3]

8.4 Filter Test Facility Acceptance Testing of HEPA Filters

HEPA filters are critical to the safety of workers and the public in the event of an accident at a nuclear facility. The greatest care is taken to ensure these filters perform both as designed and as assumed in the facility safety analysis. The U.S. Atomic Energy Commission (AEC) identified the need for QA testing of HEPA filters between 1957 and 1958. During this period, the AEC randomly selected filters from stock, and a significant number were found defective. In 1959, the AEC initiated QA testing at the Hanford and Edgewood Arsenal sites. Operations at the Oak Ridge FTF (ORFTF) and Rocky Flats FTF (RFFTF) followed in January 1963 and 1974, respectively. Historically, these FTFs have provided over 40 years of progressive QA testing and delivery of critical quality components. The ORFTF is the last of the three DOE HEPA FTFs remaining. DOE continues to perform 100 percent QA receipt inspection and efficiency-pressure drop testing on certain HEPA ventilation filters produced for use in DOE nuclear facilities. This is done to ensure that filtration efficiency reliably meets DOE specification requirements and that the last barriers of protection against the release of particulate radioactivity to the environment at DOE nuclear facilities are performing as they should. Historically, the rejection rate continues to fluctuate, as shown in **Table 8.1** below, with a high of 18.7 percent in 1996 decreasing to 1.6 percent in 1999, then increasing to 9.8 percent and 8.1 percent in 2000 and 2001, respectively. These significant reported rejection rates indicate that vendor testing alone is not sufficient to reliably produce a HEPA filter of at least 99.97 percent efficiency.[11]

Table 8.1 – Oak Ridge Filter Test Facility Testing Activities (Fiscal Year 1996 to 2003)

Fiscal Year	*Number Received*	*Number Accepted*	*Number Rejected*	*Resistance*	*Penetration*	*Manufact-uring Defects*	*Does Not Meet PO and/or Spec*	*Shipping Damage*	*Percent Rejection Rate*
1996	2,643	2,150	493	371	70	35	17	0	18.7
1997	2,916	2,814	102	59	20	7	16	0	3.5
1998	2,305	2,237	68	1	28	3	34	2	3.0
1999	2,362	2,325	37	0	31	6	0	0	1.6
2000	3,597	3,241	356	0	44	36	270	6	9.9
2001	2,722	2,505	217	1	39	46	123	8	8.0
2002	2,110	2,008	102	0	20	42	32	8	4.8
2003	2,772	2,621	151	0	26	93	27	5	5.4
Total	21,427	19,901	1,526	432	278	268	519	29	7.1

The operating policy of DOE's filter testing program, contained in DOE -STD- 3022-98, *DOE HEPA Filter Test Program*, [12] calls for testing all HEPA filters intended for environmental protection at a DOE-operated FTF (ORFTF). Delivery of certain HEPA filters to the FTF for QA review is mandatory for all DOE facilities. This service is also available to the public on a fee basis. The FTF test results are added to the information on the filter case. The test procedures at the FTF call for "penetration and resistance tests," "visual inspection for damage and visible defects," and other "visually verifiable requirements." Except for filters rated at less than 125 cfm, penetration tests are to be conducted at 100 percent and 20 percent of rated airflow capacity, and the maximum penetration of 0.3-μm particles at both airflow rates is 0.03 percent, in accordance with DOE-STD-3025-99.[7] Penetration tests may be conducted using a monodisperse aerosol and a total light-scattering photometer or a polydisperse aerosol with a single particle counting and sizing instrument. A QA program for the DOE FTF is contained in DOE -STD-3026-99, *Filter Test Facility Quality Program Plan*.[13] Specifications for HEPA filters to be used by DOE contractors are contained in DOE -STD-3020-97, *Specifications for HEPA Filters Used by DOE Contractors*.[4]

Visual Inspection

Immediately prior to installing new HEPA filters in a system they should be thoroughly inspected visually by a trained inspector for any damage to the filter frame, filter pack, and gaskets or fluid seal.

Visual inspection is an integral and vital part of every acceptance or surveillance test. A careful visual examination should be made of each internal and external component prior to installation to verify that the items have been received in satisfactory and serviceable condition. After installation, the system should be checked as part of the acceptance test procedure to make sure that all required items have been properly installed. A suggested checklist is provided in Section 5 of ASME N510,[14] which may be used to verify that system design and construction are in accordance with ASME N509.[15] ASME AG-1 also provides guidance for visual inspection in Section 5.0 and Appendix 1 of Section AA.[3] Preparation of the proper visual checklist is the most important part of the test procedure. The checklist should cover all major potential problems without further testing, including the relevant items identified in Section 5.0 of ASME N510,[14] and also should incorporate the field observation checklist items listed in Appendix C of ASME N509[15] where applicable. Certain items listed in the recommended checklist in ASME N510[14] are only observable prior to installing the components. Experienced field test personnel should be, and have been, able to find bank leak paths of a few tenths of a percent by visual examination, as well as many other potential problems not identified by the actual leak test procedures. Appendix B of this Handbook provides guidance and a sample checklist for HEPA filters used at DOE facilities that must meet DOE-STD-3020.[4]

8.5 In-Place Component Tests and Criteria

System tests fall in two broad categories: (1) prestartup acceptance tests to verify that components have been installed properly and without damage and that the system can operate as intended, and (2) surveillance tests made periodically after the system has been placed in operation to demonstrate its ability to continue performing its intended air cleaning function. Surveillance tests are leak tests of the HEPA filter and adsorber installations. To provide guidance for the preparation of test procedures, details of acceptance and surveillance tests are given in ASME N510,[14] and ASME AG-1.[3] In all cases, tests should be preceded by careful visual inspection, as previously discussed in Section 8.4.

8.5.1 Component Acceptance Testing

Acceptance tests also fall into two broad categories: (1) those that relate to the permanent elements of the system, ducts, housing, mounting frames, and location of test ports, and (2) those that verify the installation and condition of the primary air cleaning components (HEPA filters and adsorbers). Acceptance tests of HEPA filter and adsorber installations are identical to the surveillance tests of those elements and are covered in Section 8.6. Tests in the first category include leak tests of ducts, housings, and primary-component mounting frames; airflow capacity and distribution tests; gas residence time tests for systems containing adsorbers; duct-heater tests for systems containing heaters; and air-test aerosol mixing-uniformity tests. The acceptance test program for a particular system may contain any or all of these tests, depending on the nature of the system and its importance (i.e., the potential consequence of a failure of, leakage from, or release from the system).

NRC Regulatory Guides recommend the full battery of acceptance tests for engineered safety feature (ESF) systems, and the requirements for testing safety-related nuclear air treatment system components are covered by NRC Regulatory Guide 1.52.[16] In addition, requirements for testing of non-safety-related nuclear air treatment system components are covered by NRC Regulatory Guide 1.140.[17] Neither the ASME N510[14] standard nor the two regulatory guides are consistent in their requirements, and a coordinated version and further clarification are long overdue. The new 2001 revisions of both regulatory guides incorporate references to AG-1[3] in an attempt at consistency. While not perfect, they are a big improvement over the previous versions. Lesser systems may not warrant such stringent testing. On the other hand, these tests, which are conducted only once when a new or rebuilt system is accepted, provide an assurance of system reliability that cannot be obtained in any other way. The ASME CONAGT (responsible for ASME N510[14]) recommends that these tests be considered for any high-reliability system.

The original standard for nuclear air cleaning component testing was developed by the American National Standards Committee's N45.8.3 ad hoc group which was incorporated into the first version of *Testing of*

Nuclear Air Cleaning Systems, (ANSI N510-1975)[14] was later revised to ANSI/ASME N510-1980,[14] then ASME N510-1989.[14] This standard was updated by the ASME CONAGT Group, and a final version for acceptance testing was issued as ASME AG-1,[3] Section TA, "Field Testing of Air Treatment Systems." (Note: Section TA of AG-1 addresses the acceptance field testing of the system and its components. The standard for routine field surveillances is still under development. The seventh draft revision of the standard is entitled, ASME N511-2003, *Standard for In-Service Testing of Nuclear Air Treatment, Heating, Ventilating, and Air Conditioning Systems*. The basic precepts of ASME N510[14] and ASME AG-1,[3] Section TA, are listed below).

- All components (prefilters, mist eliminators, HEPA filters, adsorbers, etc.) are qualified and tested as individual components. Their original efficiency is established, and "as-installed" tests do not require further "efficiency testing." Only the in-place test is conducted to ensure the integrity of components is maintained and that no bypass exists.
- The housing is of the desired strength and integrity, which can be measured by isolating the unit envelope housing and leak testing under the specified pressure differential conditions.
- The framework integrity (framework holding critical components such as HEPA filters and adsorbers) can be measured by using blank off plates and pressure differential leak tests.
- When critical components are installed, the in-place leak test measures only the quality of the installation of the components.

The standard writers assumed that the components are well designed and that pyramiding of the four above-listed precepts will realistically measure the adequacy of the installed operating air cleaning unit.

For clarity, it must be reiterated that the definition of the "Air Cleaning Unit" is an assembly of components that together comprise a single subdivision of a complete air cleaning system, including all the components necessary to achieve the air cleaning function of that subdivision. A unit includes a single housing, with the internal components (filters, adsorbers, heaters, instruments, etc.) installed in or on that housing.

Acceptance tests are outlined in Table 1 of ASME N510[14] and in ASME AG-1,[3] Section TA. Before assembly, personnel should assure that all components meet the specified criteria. Typical QA acceptance only assures that paperwork is available. This paperwork should be checked both for original supply and for replacement parts. Before installing components, personnel should perform the following tests:

- Visual Inspection,
- Duct Leak Test,
- Housing Leak Test, and
- Mounting Frame Leak Test.

During and immediately after installation of components, personnel should perform the following tests:

- Visual Inspection,
- Airflow Capacity and Distribution Test,
- Air/Aerosol Mixing Uniformity Test,
- In-Place Leak Test HEPA Stage,
- Remove Adsorbent and Perform Laboratory Testing (to establish baseline carbon efficiency),
- In-Place Leak Test Adsorber Stage, and
- Duct Damper Bypass Leak Test (if required).

The tests listed in ASME N510,[14] Table 1, include:

- Visual Inspection – Section 5 (to ensure that components are properly installed and are not damaged);
- Duct and Housing Leak and Structural Capability Test – Section 6 (to ensure the installed housing has leakage and structural integrity);
- Mounting Frame Pressure Leak Test – Section 7 (to ensure that no bypasses exist at welds, etc.);
- Airflow Capacity and Distribution Tests – Section 8 (to ensure that desired flows can be achieved with clean and dirty filters, and also that velocities through components are in the narrow range where the components were qualified individually;
- Air Aerosol Mixing Uniformity Test – Section 9 (to ensure the test aerosol injection and sampling ports are located properly to perform testing of the HEPA filter bank or adsorbent stage);
- HEPA Filter Bank In-Place Test – Section 10 (to establish that the HEPA filters are properly installed and were not damaged before or during installation);
- Adsorber Bank In-Place Test – Section 11 (to establish that the adsorbers were properly installed and that there is no major settling and/or channeling of the adsorbent);
- Duct Damper Bypass Test – Section 12 (to qualitatively assess leakage through bypass dampers in the system);
- System Bypass Test – Section 13 (to ensure that all filter banks and potential bypass leakage paths are assessed in the leakage test). All negatively pressurized portions to the flow discharge can be important and are frequently overlooked, e.g., fan shaft seals, damper control linkage, sample ports. The importance of the amount of bypass leakage is increased as the credit for removal of the contaminant increases in the system;[18]
- Air Heater Performance Test – Section 14 (to ensure that the heaters used for humidity control are capable of achieving the desired RH); and
- Laboratory Testing of Adsorbent – Section 15 (to quantify the efficiency of the carbon media for its ability to adsorb radioiodines).

Two critical items have to be understood in the use of ASME N510.[14] First, the standard is considered a test method for air cleaning systems designed according to ASME N509.[15] However, ASME N510[14] was initially issued in 1975, and ASME N509[15] in 1976, years when a large number of U.S. power reactors were already designed, and even many later, facilities were designed with only with limited adherence to common sense engineering practices or the requirements of ASME N509.[15] The second critical item is the potential for misinterpreting the Scope section of ASME N510,[14] which states that it is a “basis for the development of the test programs and detailed acceptance and surveillance test procedures,” and "that it be rigorously applied only to systems designed and built to ASME N509.”[15]

In spite of this rather clear scope definition, many facilities established their test methodology by either generally claiming that, “testing shall be in accordance with ASME N510,”[14] even when their systems were not designed for it (or according to NRC Regulatory Guide 1.52[16] or 1.140,[17] which refer to ASME N509[15] and N510[14] requirements). Some never developed a specific test program for each unit and system to modify the basic N510[14] procedures to ensure achievement and maintenance of the desired result (complete system integrity). The treatment of issues related to air cleaning unit and system testing here is based on ASME N510.[14]

If all of the referenced tests are performed sequentially every time and the airflows are well balanced from a specified intake point to a specified discharge point, then the test series may be considered a system test. However, if only parts of it are performed, it is not a system test—only an installed component section test (i.e., a HEPA filter bank or adsorber stage bank test).

8.5.2 Duct and Housing Leak Test

The level of duct and housing leaktightness (and therefore the acceptance criterion for the test) is based on the type of construction and the potential hazard (consequence) of a leak. Recommended maximum permissible leak rates for various duct and housing constructions are given in AG-1, Section TA.[3] The designer may specify tighter requirements based on the confinement requirements of the system.

Duct leak tests may be conducted by testing the entire ductwork system at one time or by testing one section at a time and blanking off the ends of the section under test. The second method is more practical for larger systems. When segmented, the permissible leak rate for the individual sections is based on the proportionate volume of that section. The apparatus and procedure for leak testing levels 1 and 2 ducts are described in the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) *HVAC – Duct Design*.[19] Using the described procedures outlined in ASME N510,[14] duct leak tests can also be developed with some modifications. The ASME N510 standard offers two test methods for housing leak test: the Pressure Decay Method (the most convenient for larger duct and housing systems) and the Constant Pressure Method (the most effective for smaller volumes).

Test methods for level 3, 4, and 5 ducts and for housings are described in Section 6 of ASME N510.[14] If the specified leak tightness cannot be met, leaks are located, repaired, and retested by one of the methods described in Section 6 of ASME N510.[14]

When performing the unit housing leak test, it is important to follow the normal procedures (door closing, etc.) and thereby avoid creating a once-in-a-lifetime condition that does not resemble normal operating procedures and conditions. The test is supposed to demonstrate that the unit housing will maintain the specified leaktightness during its operating life. Based on experience, this is an unrealistic expectation. There is always some deterioration of door gaskets, or occurrence of sprung doors, damaged threads on closures, and leaks due to maintenance work on the unit. To ensure the leak integrity of the housing is maintained, personnel should perform periodic retesting (every 10 years). However, the risk of spreading contamination does not warrant this test on ventilation systems that are in continual use in contaminated or potentially contaminated applications. Surrogate methods such as acoustical monitoring or tracer gas monitoring may be appropriate when entry into the housing is precluded.

8.5.3 Mounting Frame Pressure Leak Test

This test is performed to ensure the installed HEPA filter/adsorber mounting frame is installed with no leak paths through the structure. This is considered an optional test because the same evaluation is done after the filters are installed, and an in-place leak test is performed on the bank. However, this test may be useful for determining gross leakage prior to filter installation. Any repairs required must be done before installation of any HEPA filter/adsorber. This test is also the first check for any other leak paths through conduits, drains, etc., which communicate between the upstream and downstream side of a single bank of HEPA filters or adsorber banks. Realistic test performance requires the unit housing leak test to be performed and the specified leak criterion to be met. The acceptance value set in the specifications should always be realistic.

These tests are conducted to verify there are no leaks through the HEPA filter and adsorber mounting frames or through the seal between the mounting frames and the housing. The tests also verify there is no bypassing of the mounting frames through electrical conduits, drains, compressed air connections, and common anterooms of the housing, or other inadvertent leak paths. Familiar sources of leaks are weld cracks and incomplete welds. A properly designed mounting frame should have no penetrations (via conduits, piping, or ducts), and lighting, drain, and other ancillary systems should be designed so that no bypassing of the HEPA filters and adsorbers can occur. Nevertheless, unauthorized modifications are often made in the field. The purpose of this test is to disclose such occurrences, as well as any leaks caused by poor workmanship or shipping damage. The test is recommended for any installation, whether duct and housing leak tests are performed or not, but it is particularly necessary when subsequent in-place tests of the HEPA filter and adsorber stages will be performed using a shrouded method.

This test is conducted by first blanking off all openings for filters and adsorbers and closing or blanking off all openings in the housing, then conducting a soap-bubble or spray test aerosol leak test around all welds and other potential leak paths (as described in Section 7 of ASME N510).[14] After all leaks have been repaired, individual chambers of the housing should be checked by a pressure leak rate test to verify there are no bypasses that were not disclosed by the leak detection check. It is unnecessary to perform these tests from the upstream side of the mounting frame, and it is quite acceptable to test two mounting frames simultaneously by blanking off the openings of both and pressurizing the space between. Because the mounting frame pressure leak test is a chamber-by-chamber test of the housing, it can replace the need for a housing leak test.

8.5.4 Airflow Capacity And Distribution Test

This test is used: (1) to verify that the specified volume flow rate of the air can be achieved with the installed fan under actual field conditions at maximum and minimum filter pressure drop, and (2) to verify that the airflow distribution across each HEPA filter or adsorber stage is within the specified uniformity at the designed volumetric flow rates. ASME N509[15] and N510[14] require an airflow capacity of ±10 percent maximum deviation from design flow. This value is not well correlated to the assumption of NRC Regulatory Guide 1.52[16] and the radioiodine test methods specified in ASTM D3803.[20] The variation of ±10 percent in velocity through the adsorbent bed results in a very high variation of the methyl iodide-131 removal efficiency. Recent parametric testing for radioiodine removal efficiency showed that even the ±4 percent flow variation permitted in ASTM D3803[20] is too high to obtain good reproducibility. To ensure proper correlation of the results used to justify the potential performance of the adsorber stage, the volumetric flow through the adsorber stage should result in not less than a 0.25-sec residence time (for a 2-in.-thick bed). Therefore, a design flow of +0, -20 percent is much more realistic than the design of ±10 percent permitted by ASME N509[15] and N510.[14] Similarly, ASTM D3803[20] should require a velocity corresponding to 0.25-sec residence time and +4, -0 percent to achieve adequate reproducibility and to err on the conservative side. The procedure for airflow capacity testing recommends making pitot tube traverses of the ducts. However, the following values must also be considered.

Duct Size	***Number of Readings***	***Precision of Measurements***
<150 mm	1	±20 percent
400 < 150 mm	4	±12 percent
950 < 400 mm	8	±10 percent
>950 mm	12	±5 percent

mm = millimeter

ASME N510[14] is unclear about how the precision of the measurement should be used to achieve the ±10 percent specified flow capacity. Due to the convoluted design of the air cleaning system inlet and outlet ducts, it is often impossible to find an adequate duct location that is, as required by the American Conference of Governmental Industrial Hygienists (ACGIH) *Industrial Ventilation – A Manual of Recommended Practices*,[21] 10 duct diameters downstream and 5 duct diameters upstream of points where turbulence is induced in the airflow (e.g., elbows and junctions), which further subtracts from the precision of the velocity measurements. The location where the acceptance airflow capacity test was performed should be tagged (indicating the date, method used, etc.) to ensure that future tests are made at the identical location. For example, LLNL places test fittings at the locations used. The test fittings are about an inch in diameter to permit turning equipment 90 degrees after insertion and are capped. This makes them both durable and easier to find. ASME N510,[14] Table 1, requires this measurement to be an acceptance and surveillance test. However, experience shows that changes in airflow capacity occur in intervals as short as 18 months due to damper adjustments, pressure conditions at inlet points, duct disassembly and reassembly either upstream or downstream of the unit, etc. Therefore, this measurement should be a routine surveillance test item each time a unit or system surveillance test is made.

The actual text of ASME N510,[14] Section 8, indicates via a note that only the air distribution test is an acceptance test (presuming the airflow capacity is both an acceptance and a surveillance test, as it should be). The unit should be operated for 15 minutes prior to the test to achieve steady-state conditions. The airflow distribution test leaving the HEPA filter banks is required by ASME N510.[14] In many existing units, there is inadequate space to perform the test downstream of the banks. Any test performed on the entry side of these banks must be more conservative for the HEPA filter banks because of the flow-straightening characteristics of HEPA filters. Therefore, if such a test meets the criteria, it should be acceptable. [Note: The currently permissible separate airflow distribution uniformity of ±20 percent on top of a ±10 percent airflow capacity and a potential test error of ±10 percent results in permissible residence times in the adsorber section might be less than that presumed for the iodine-131 DF used to establish the authorization basis of the facility.]

8.5.5 Air-Aerosol Mixing Uniformity Test

The purpose of this test is to verify that the aerosol or challenge gas is introduced in order to provide uniform mixing in the airstream approaching the HEPA filter bank or adsorber stage to be tested. No safety credit should be claimed for HEPA filters or adsorbers that are not tested regularly to verify they continue to meet performance requirements. Although individual filter units and adsorber cells are tested by the manufacturer, in-place testing after installation is essential because of the damage and deterioration that can take place during shipping, handling, installation, and service. Therefore, an important phase of acceptance testing is verification that HEPA filter and adsorber installations can be tested satisfactorily. The design of many older systems permitted an acceptance test of the HEPA filters, but made testing after the system began operation nearly impossible. Some systems were designed to be so cramped that quantitative testing of the kind specified in ASME N510[14] was impossible due to poor airflow distribution or ducts that had unreachable portions of cross-sectional area. Such designs are not acceptable in high-reliability applications.

The test method described here includes tests to establish the adequacy of the test aerosol injection and upstream sampling port locations, but does not generate data reflecting the adequacy of the downstream sampling port location. Undoubtedly, the test should be a prerequisite for performance of any in-place test of a HEPA filter bank and adsorber bank stage. The verified locations of injection and upstream sample ports should be documented, and the locations should be tagged to indicate the date, method used, etc., as well as the tests to be conducted. All other ports found to be unsatisfactory should be tagged to prevent later accidental use of incorrect injection or sampling ports.

The aerosol/vapor injection point for the first HEPA bank and the adsorber stage should always be ahead of any unit or system bypass line, and the downstream sampling point for the second stage HEPA filter bank and for challenge aerosol/vapor should always be downstream of the return of the bypass line into the main duct.

Good testability requires provision of permanent test aerosol injection and sample ports or other planned and pre-established means for injecting the test aerosol and for taking reliable, well-mixed samples. Details of the air-aerosol mixing test are described in Section 9 of ANSI N510.[14] It is essential that the air and test agents mixture challenge to the filters (adsorbers) is thoroughly mixed so that the concentrations entering all points of the filters, including the upstream and downstream sample points, are essentially uniform. Adequate mixing upstream usually can be obtained by introducing the test aerosol at least ten duct diameters upstream of the filters or adsorbers, or by introducing it upstream of the baffles or turning vanes in the duct. When neither of these methods is practical, a Stairmand disk located four to six duct diameters upstream will provide satisfactory mixing. A Stairmand disk is a plate with the same geometric shape as the duct section that blocks the central half of the duct area. Air flowing past the disk creates vortices on the leeward side that compel turbulent and thorough mixing. The disk is placed into the duct for testing. At other times it is either removed, swung out of the way, or turned on a pivot so the long axis is parallel to the direction of flow. When duct arrangement makes it necessary to introduce the test aerosol directly into the filter housing, a design such as that discussed under multistage housings (Section 8.7) may be required. Extraction of the downstream sample at a point several duct diameters downstream of the fan will usually provide a well-mixed sample. Fan-shaft leakage should be considered in sampling downstream of the fan. Since leakage at the shaft will be in-leakage, sufficient air to dilute the downstream sample can be drawn in if the shaft annulus is large (yielding a low downstream concentration reading), or dust may be drawn into the fan to provide a high downstream reading (which may be particularly prevalent during construction). Application of a shaft seal, or at least a temporary seal, is recommended during testing. If this is not practical, a photometer leak reading should be taken with and without the aerosol generator "on" to establish shaft seal leakage.

The second aspect of testability—access—requires space for personnel and equipment; space to manipulate equipment without damaging filters or creating hazards for personnel; passages for getting personnel and equipment where they are needed; means of providing power (electrical, compressed air) to the equipment; access to both faces of the filters and adsorbers; adequate lighting; viewports; and other features that facilitate safe testing. Space also will be needed later during filter replacement for: (1) temporary storage of removed filters/adsorbers and their replacements, (2) crew movements required to effect the change (such as bagging in/out), (3) placement of tools, and (4) personnel, including both the filter technicians and any associated safety staff or radiation monitoring technicians. Consideration should be given to making the area easy to decontaminate if necessary by making the floor and area as free of cracks, crevices, and hard to clean/reach places as practical.

8.5.6 Duct Damper Bypass Test

Section 12 of ASME N510[14] requires testing of potential bypass leakage paths, through closed dampers or valves, to ensure that radioactive gases or particulates do not escape treatment through the HEPA and/or adsorber banks. This test allows testing of the potential leak path during the test aerosol or Halide test on the HEPA/adsorber banks, assuming the injection sample ports are located such that the potential bypass is included in the test envelope. Otherwise, the bypass (damper) may be tested using conventional pressure-testing techniques.

8.5.7 System Bypass Test

Section 13 of ASME N510[14] requires challenging of all potential bypass leakage paths and all portions of the nuclear air treatment system (including the housing stages) during the test sequence, which could potentially defeat the purpose of high efficiency nuclear air treatment components. All potential bypass leakage paths around the HEPA/adsorber banks must be included as a single overall leak test of the sum of the individual tests on the separate banks. In dealing with a series of HEPA or adsorber banks, each bank must be tested individually to ensure that contaminated air does not bypass the filter banks or escape treatment. Small system bypass leakage may be very significant for systems that have multiple HEPA banks with greater than 99.8 percent assigned efficiency per bank[18] (per the authorization basis).

8.5.8 Duct Heater Performance Test

Section 14 of ASME N510[14] requires the humidity control system for the carbon adsorber bank (which prevents water buildup on the carbon) to be tested to ensure satisfactory performance. For example, the voltage always has to be checked to make ammeter readings meaningful. The temperature should be checked sufficiently upstream and downstream of the heater to ensure an adequate rise in air temperature. The readings obtained also should be evaluated by a cognizant individual to ensure the desired RH can be achieved with the potential minimum and maximum environmental temperatures in the inlet stream.

8.6 Surveillance Testing

There are three types of surveillance tests: (1) in-place leak tests of HEPA filter banks using an accepted test aerosol, (2) in-place leak tests of adsorber stages using a slightly adsorbable gas such as the fluorocarbon Refrigerant-11, and (3) laboratory tests of samples of adsorbent withdrawn from the system to establish its remaining adsorption capacity. These tests are also employed as part of the acceptance procedure for new installations, with the exception that laboratory tests are made on samples of adsorbent taken from batch material as furnished.

Surveillance tests of HEPA filter and adsorber systems should be made at regular intervals after installation to detect deterioration and leaks that may develop under service conditions. Regular in-place testing of standby systems is necessary because deterioration can take place even when the systems are not being operated. Aside from component damage, frequently discovered causes of failure to meet in-place test requirements include loose clamping bolts; inadequate clamping devices such as C-clamps; foreign material trapped between gaskets and mounting frames, rough or warped mounting frame surfaces; cracked welds; unwelded joints in mounting frames; incorrectly installed components (e.g., HEPA filters installed with horizontal pleats); inadequate seals between mounting frames and housings; poorly designed mounting frames; and bypasses through or around conduits, ducts, or pipes that penetrate or bypass the mounting frames.

In-place tests should be made by introducing a test aerosol upstream of the bank to be tested. [Note: The upstream aerosol introduction should never be swapped to the downstream side. This actually occurred at one DOE facility where upstream introduction was a physical impossibility.] The concentrations of test aerosol upstream and downstream (upstream concentration is considered 100 percent) should then be determined, and penetration should be calculated from the ratio of concentrations. The reliability of this test is determined by: (1) the ability to properly introduce the test aerosol and obtain representative samples, and (2) the availability of physical access to the banks being tested. The first can be verified by an air-aerosol mixing test. This test should be made once, at the time of acceptance testing, and its satisfactory completion is required before both acceptance and future surveillance in-place testing of HEPA filters and adsorbers.

8.6.1 In-Place System Leak Test, HEPA Filter Banks

Section 8 and 9 of ASME N510[14] are prerequisites for the HEPA filter in-place system leak test. In cases where there are multiple series or parallel HEPA banks and associated bypass leakage paths, the guidance outlined in Section 13 of ASME N510,[14] "System Bypass Test," should be followed. The proper procedure to be used with dual HEPA filter banks is to introduce a test aerosol at the predetermined qualified location (the test port) upstream of the first bank, and then determine a downstream reading of the first filter bank between the first and second filter bank. If this determination is satisfactory, then while injecting at a point (or through a manifold) upstream of the second HEPA filter bank (between the banks), readings should be taken downstream of the second HEPA filter bank, preferably downstream of the fan.

There are three major types of in-place system testing methods. The first test method uses a light-scattering photometer with a polydispersed aerosol. The second method uses a shroud and/or scanning test technique, and the third uses a laser spectrometer in lieu of the forward light-scattering photometer. Due to differences in the designs of HEPA filter plenums throughout the DOE complex, as well as corresponding differences in testing techniques, the Defense Nuclear Facilities Safety Board recognized a need to standardize methods for in-place system testing at DOE sites. To address this need, a conference was held at the DOE Savannah River Site (SRS) to exchange information about the sharing of in place system testing technology among DOE contractors.[22] The conference concluded that all DOE sites basically used the same type of penetrometer, with the exception of LANL, which uses the laser spectrometer. In-place system tests of HEPA filter installations are made with a polydispersed test aerosol consisting of droplets with a light-scattering number mean diameter (NMD) of 0.7 µm and a size range of approximately 0.1 to 3.0 µm.[14] This range should be compared to the test aerosol used for efficiency testing by manufacturers and DOE's Filter Test Facility (ORFTF) which is a monodispersed aerosol with a light-scattering NMD of 0.3 ± 0.03 µm. The in-place system test is made by challenging the upstream side of the filter or filter bank with test aerosol smoke, then measuring and comparing (using a light-scattering photometer) the test aerosol concentration in samples of downstream (filtered) and upstream (unfiltered) air (**Figure 8.5**). If the system exceeds the specified maximum permissible penetration value, the downstream faces of the filters and mounting frame can be scanned with the photometer probe to locate localized high concentrations of test aerosol, indicating leaks. Figure 8.5 illustrates the basic equipment and a schematic of a standard test arrangement. [Note: Figure 8.5 is not intended to depict an actual system.] The instrument shown is a forward-light-scattering photometer with a threshold sensitivity of at least 10^{-3} µg/L for 0.2- to 1.0-µm particles, and a sampling rate of at least 1.0 cfm is recommended.[4] The instrument should be capable of measuring concentrations

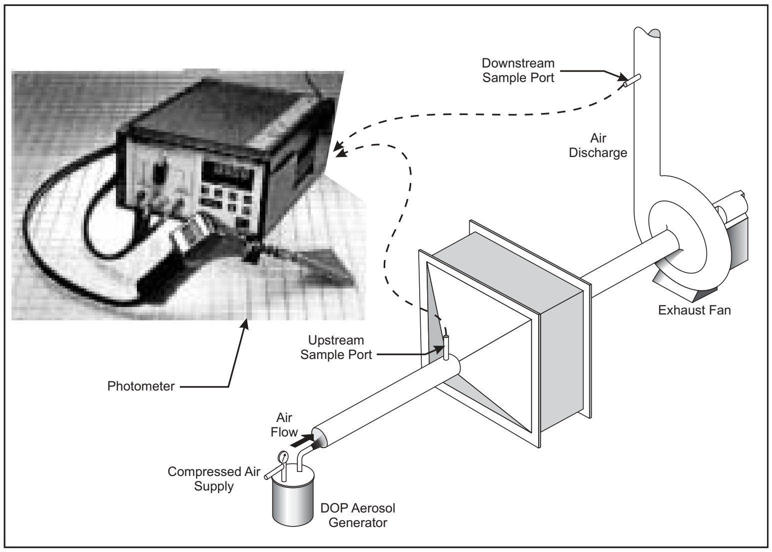


Figure 8.5 – Equipment Arrangement, In-place Testing of HEPA Filters

10^5 times the lower detection limit. An upstream concentration of 20 to 100 µg/L is desirable. Compact self-contained instrument packages are commercially available (**Figure 8.6**). Polydispersed aerosol may be generated thermally or by compressed air. Compressed-air generators are widely used for testing small systems. They are commercially available or can be "homemade" in sizes from 1 to 24 nozzles, as shown in **Figure 8.7**. Care must be taken in selecting the aerosol test agent, as some replacements for DOP have made a flame-throwing device out of the generator (see Chapter 10.6.2.1). A rule of thumb for determining generator capacity is not to exceed one Laskin nozzle per 500 cfm of installed filter capacity. Compressed-air generators are suitable for systems up to about 3,000 cfm; above this size they become cumbersome. Although gas-thermal generators are generally used for testing systems of 6,500 cfm installed capacity and larger, they have too much output for small systems (Figure 8.7). The engineer must not confuse this type of generator with the mono-dispersed test equipment used by filter manufacturers or the DOE ORFTF for determining the particulate efficiency of HEPA filters. The gas-thermal generator produces a polydispersed aerosol of about the same NMD and size range as the compressed-air generator. It is also small and can generally produce enough aerosol at a concentration of 40 to 50 µg of test aerosol/L to test banks up to 30,000 cfm installed capacity. Nitrogen must be used with some thermal systems to avoid a potential fire hazard.

Figure 8.6 – Commercially Available Packaged Forward-light Scattering Photometer for HEPA Filter In-place Testing

A detailed description of the procedure for conducting an in-place test of HEPA filters is given in Section 10 of ASME N510[14] and in ASME AG-1, Appendix TA.[3] A prerequisite of the test is a demonstrated ability to achieve good mixing of the test aerosol and air at the upstream and downstream sample points (Section 9, ASME N510).[14] For systems in which good mixing cannot be achieved, multipoint sampling and averaging may be used, in accordance with Section 11 of ANSI N510.[20]

An acceptance criteria of 0.05 percent maximum leakage for the in-place system test is recommended for systems that are designed in accordance with this handbook.

For the shroud/scan in-place test method (**Figure 8.8**), ASME N510 (1980),[14] the photometer, generator, and test aerosol are the same as those used in the standard test method described above.

A manifold is installed in the upstream and downstream shroud. The upstream shroud must be placed over a filter, and the generator turned on. It is important to verify that the aerosol mist is filling the shroud using an upstream sample/challenge manifold located in the shroud. When the 100 percent upstream concentration is obtained, the meter is set to 0 and the downstream reading is taken. If the downstream shroud method is used, the sample tube must be connected to the downstream shroud manifold, and the downstream shroud must be placed against the frame of the filter to be tested for a minimum of 15 ± 5 seconds as determined by the photometer operator. If the downstream scan method of testing is used, each filter and gasket must be probed. The photometer is then read, and the highest leak rate reading is recorded "as found." The final leak rate readings are recorded.

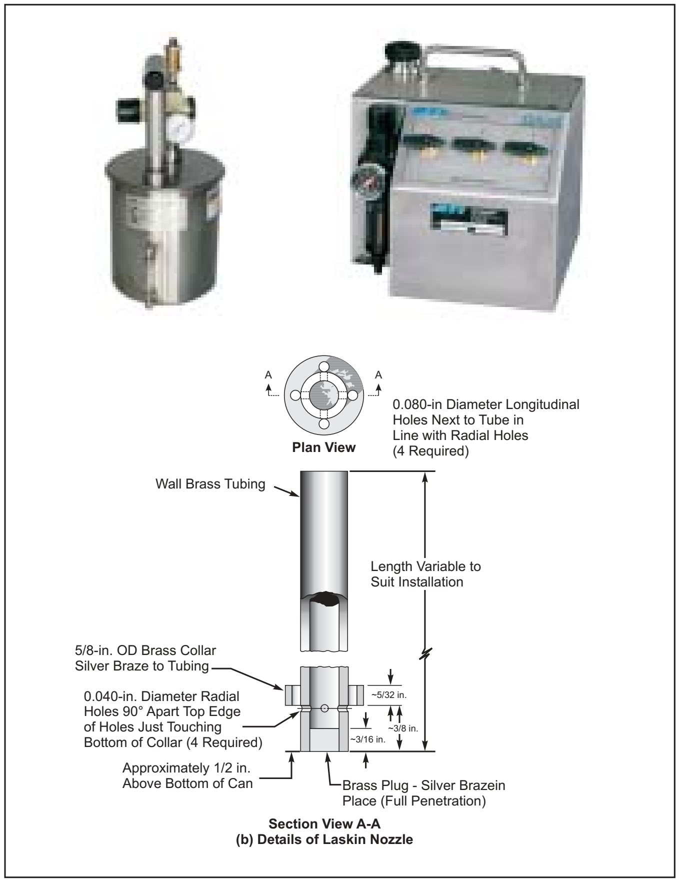


Figure 8.7 – Compressed Air-Operated Aerosol Generator

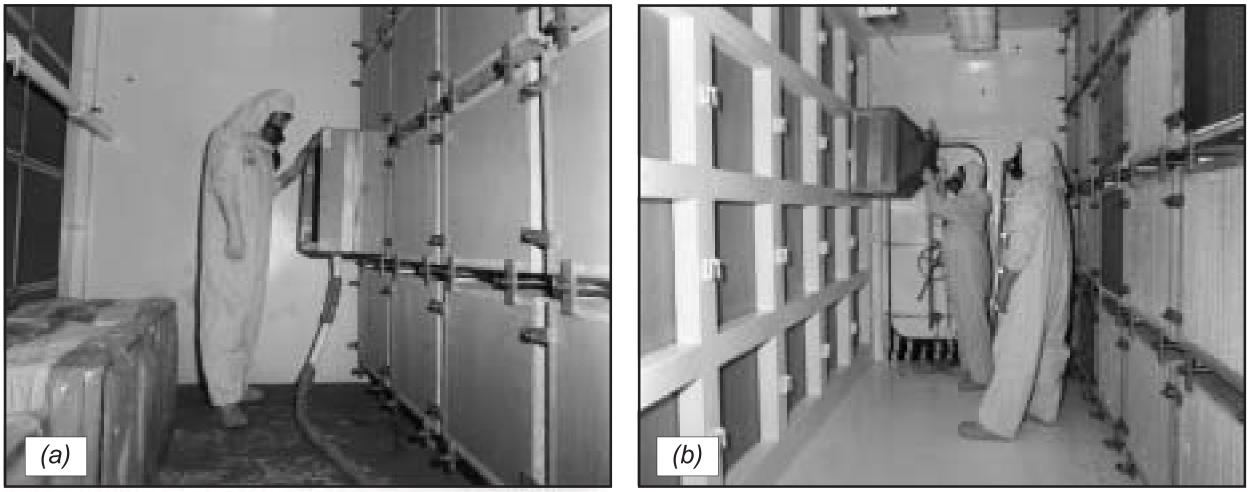
To calculate leak rates, the leak rate readings from the data are added together and the sum is recorded. This total is then divided by the number of filters in the filter stage, and the result is recorded, as expressed below.

$$\frac{Sum\,(As\ Found\ or\ Final)}{Total\ Number\ of\ \ Filters} = Overall\,(As\ Found\ or\ Final)\ Leak\ Rate$$

Overall efficiency is determined by subtracting the overall leak rates ("as found" and "final") are subtracted from 100 percent and recording the result, as expressed below.

100 percent – Overall ("As Found" or "Final") Leak Rates = Overall (As Found or Final) Efficiency

A third test method, the single-particle particle-size spectrometer, was implemented at LANL using the guidelines of NE F 3-41T.[24] This modified procedure uses a laser particle size spectrometer with the capability of counting single particles downstream of two filter stages where DF of the first stage and overall system effectiveness are established. DF measurements as high as 10 were obtained,[25] indicating a high level of sensitivity that can be used on single-stage filters. The advantage of the single-particle particle-size spectrometer method is that it provides information on system performance relative to the most penetrating particle size of the filer system being tested. The downside is that the instrument is prone to malfunction, being a laboratory-type instrument, and is heavy, cumbersome, and expensive.



Upstream Aerosol Generation Downstream Sampling

Figure 8.8 – Shroud Test

8.6.2 In-place Testing for Adsorbers

The in-place leak test of the adsorber bank (stage) measures bypass (mechanical) leakage around or through the installed adsorber bank. This test may be performed: (1) as an acceptance test to verify system design function following initial field installation; (2) after an abnormal incident, replacement, repair, or modification that may affect design function; or (3) as a periodical in-service (surveillance) test to monitor system condition and operational readiness.

Bypass leakage around the adsorber bank (stage) may result from mounting frame weld degradation, damaged or poorly compressed gaskets, common drains between housing compartments, common electrical conduits between housing compartments, and inadequately dampered bypass ducts. Bypass leakage through the adsorbent media may be due to poor adsorbent filling technique and subsequent settling from system vibration and air or gas pulsation.

Since the in-place leak test only provides a measure of bypass leakage, this test is often performed in conjunction with the laboratory test of the adsorbent media. Assuring that the adsorber bank meets bypass leakage acceptance criteria and the adsorbent media itself performs adequately provides the necessary information required to determine whether the adsorber bank is performing as designed.

There are two methods commonly used for in-place leak testing of the adsorber bank stage. One uses a fluorocarbon refrigerant gas or an alternative tracer gas. The other uses a radioactive tracer gas (iodine or methyl iodide). The first method, developed by Savannah River Laboratory,[25] is the most frequently used, particularly in commercial applications. The second method involves the use of radioactive isotopes and personnel licensed to handle them. This test should not be confused with a laboratory test of adsorbent media. Radioiodine tracer methods were developed primarily for DOE installations.[26, 27] Both in-place tests are leak tests designed to measure bypass leakage, and they must be supplemented with laboratory tests of samples taken from the adsorbers at the time of the in-place test to determine system leak tightness and the radioiodine removal efficiency of the adsorbent media. For commercial nuclear power plants, typical bypass leakage acceptance criteria for the adsorber bank (stage) range from 1.0 percent to 0.05 percent, depending on specific plant license bases. The current NRC Regulatory Guide 1.52 [16] requires that in-place leak testing for adsorbers be performed: (1) initially; (2) at least once each 24 months; (3) following the removal of an adsorber sample for laboratory testing if the integrity of the adsorber section is affected; (4) after each partial or complete replacement of a carbon adsorber in an adsorber section; (5) following detection or evidence of penetration or intrusion of water or other material into any portion of an ESF atmosphere cleanup system that may have an adverse effect on the functional capability of the adsorber; and (6) following painting, fire, or chemical release in any ventilation zone communicating with the system that may have an adverse effect on the functional capability of the system. The Regulatory Guide further specifies that the in-place leak test should be performed in accordance with Section 11 of ASME N510-1989[14] and the in-place leak test should confirm a combined penetration and bypass leakage quantity around or through the adsorber of 0.05 percent or less of the test gas at system rated flow of ± 10 percent.

8.6.2.1 Nonradioactive Tracer Gas Test

The first test, commonly referred to as the Freon™ test, is made by challenging the upstream side of the adsorber with a slightly adsorbable and readily desorbed fluorocarbon gas [usually Refrigerant-11, trichloro mono fluoromethane], then determining the concentrations immediately upstream of the adsorber bank and at a point downstream of the adsorber bank where satisfactory mixing with air occurs. Bypass leakage is calculated from the ratio of downstream-to-upstream reading, as follows.

$$\text{Percentage Bypass} = \text{Reading Downstream} / \text{Leakage Reading Upstream}$$

Since it is the *ratio* of concentrations that matter, the units may be expressed in terms of peak height or some other measure directly related to tracer concentration, although the measure may not necessarily reflect the actual volumetric or mass tracer concentration.

Refrigerant-112 was originally used, but is no longer produced. Refrigerant-112 was more strongly adsorbed by the adsorbent bed than Refrigerant-11 and allowed testing of banks under conditions of high RH or elevated adsorbent moisture content. With the introduction of ASME AG-1,[3] alternative, substitute tracer gases are allowed (permitting tracer gases with stronger adsorption potentials than Refrigerant-11), providing the selection is made in accordance with the AG-1,[3] Appendix TA-C, selection criteria. Noncommercial installations have successfully used alternative tracer gases.[28] When the carbon beds nondestructive test was developed, testing equipment consisted of a pump to draw upstream and downstream air samples from the adsorber system, two identical gas chromatographs with electron-capture detectors for measuring refrigerant gas concentrations, a timer, and several rotameters for determining sample dilution factors. The chromatographs had a linear range of about 1 to 100 parts per billion (ppb) (by volume) for detection of the refrigerant gas. Since the upstream concentration exceeded the linear range of the instrument, the sample was diluted with a known volume of air to bring it within the detection range of the chromotograph. Calibrated rotameters were used to determine the dilution factors. Currently, two types of equipment are used to perform this test. Traditional, noncontinuous chromatographs have been developed specifically for in-place leak testing, eliminating the need for rotameter dilution and providing microprocessor-based leak rate calculation. Modern chromatograph-based equipment used for the adsorbent in-place leak tests is shown in **Figure 8.9**. Continuously monitoring detectors are also used as shown in **Figure 8.10**. **Figure 8.11** shows a schematic of the test setup. Prefilters and HEPA filters in housings have no effect on the nonradioactive

Figure 8.9 – Modern Chromatograph-Based Equipment

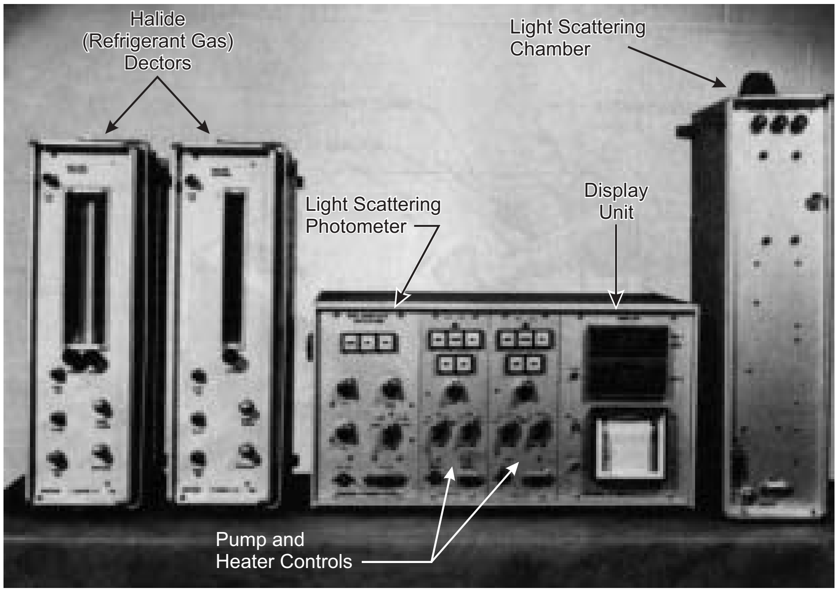


Figure 8.10 – Continuous Monitoring Charcoal Testing Equipment

tracer gas test. The test should be performed by experienced, trained personnel, and should be conducted in accordance with prescribed procedures (ASME N510,[14] Section 11). Use of the mixer shown in Figure 8.11 is not necessary if samples can be taken from an area that assures good mixing, e.g., downstream of the fan or downstream of duct bends or transitions that introduce turbulence into the airstream. Where good mixing cannot be achieved, temporary or permanently installed sampling manifolds constructed in accordance with ASME N509,[15] Appendix D, may sometimes be used.

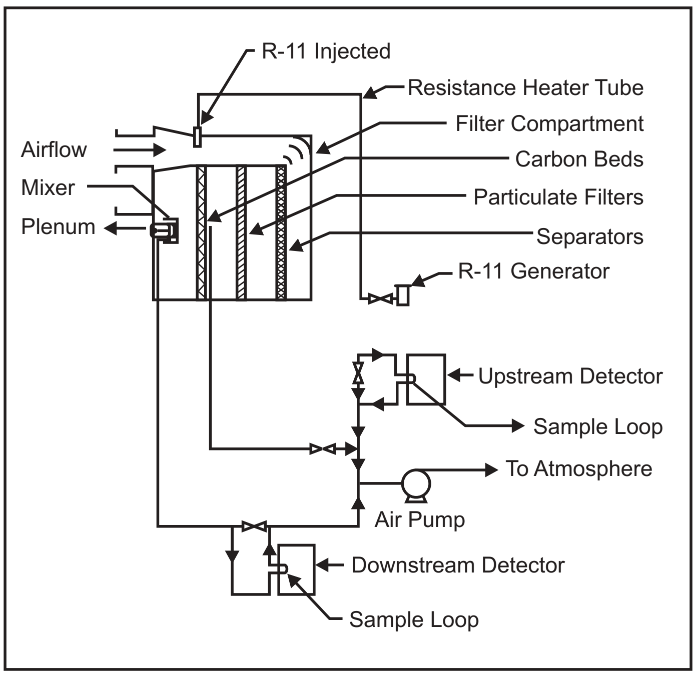


Figure 8.11 – Schematic of Charcoal Testing Setup

8.6.2.2 Radioactive Iodine Tests

These tests are currently used for routine adsorber-bank testing at Oak Ridge National Laboratory (ORNL) and the Hanford (Richland, Washington) facilities of DOE. Two tests are used, one with radioactively traced elemental iodine, and the second with radioactively traced methyl iodide. Equipment requirements for controlling the injection and sampling flows during elemental iodine testing include an iodine injection tube (**Figure 8.12**), two sampling units (**Figure 8.13**), a sample extraction pump, and two calibrated flowmeters. The sampling units are filled with charcoal of known efficiency for elemental iodine. The test gas is iodide-127 containing the iodide-131 tracer. A combination of injected radioactivity (in microcuries), sampling rate, and counting technique (usually dictated by the kind of counting equipment available) must be developed to give the required test precision. At ORNL, a combination of sampling and injection rates is selected which, with available counting equipment, will produce an upstream sampler radioactivity count between 8 x 10^5 and 5 x 10^6 counts per minute. These are not rigid limits, but are instead convenient target values with considerable latitude. Satisfactory tests have been made with sampling rates as low as 0.03 percent of the system flow rate, but sampling rates of about 1.0 cfm per 1,000 cfm (0.1 percent) of rated adsorber capacity are recommended.

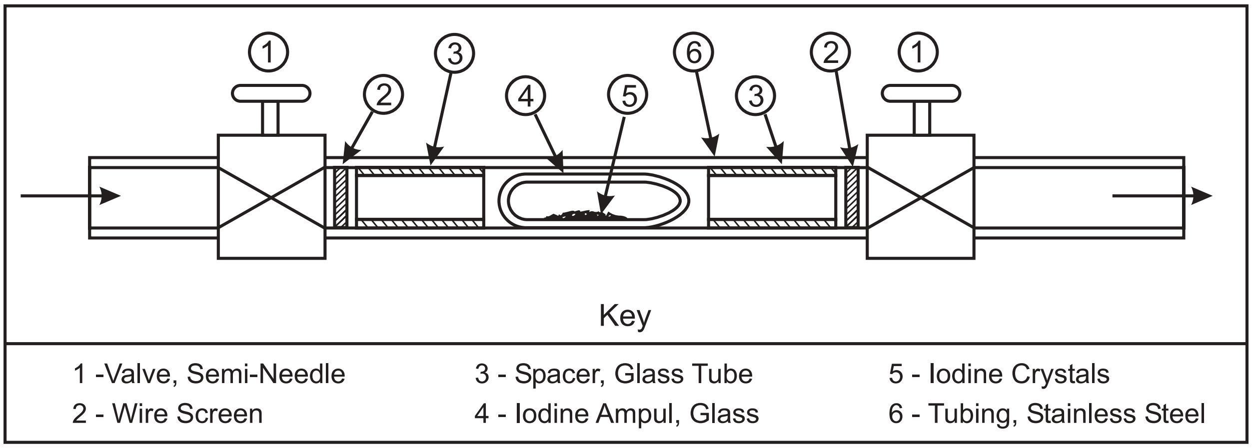


Figure 8.12 – Injector Tube for Radioactive Tracer Test

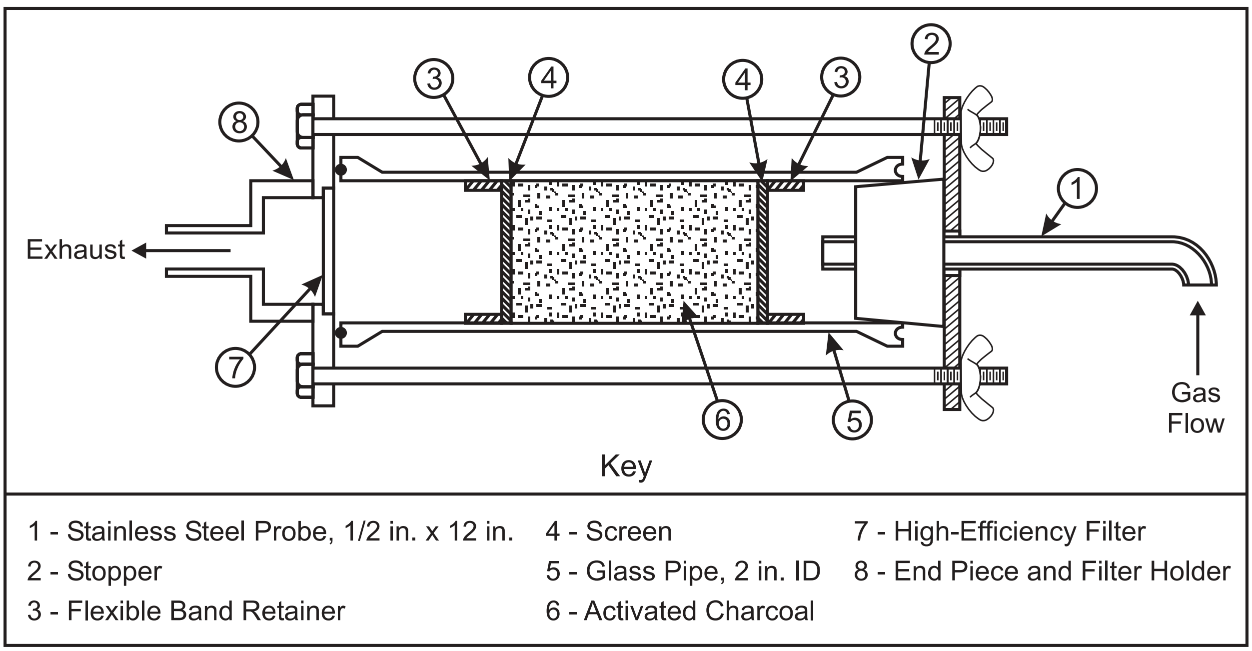


Figure 8.13 – Sampling Elements for Radioactive Tracer Test

The amount of iodine required and the size of the injector tube are not critical. The amount of iodide-127 is invariably 100 mg in the ORNL tests, although this amount may be doubled if excessive plateout in the upstream duct or housing occurs. The amount of iodide-131 tracer must be adjusted to give the radioactivity count noted above. The radioactive iodine source is prepared by mixing the required quantities of iodide-127 and iodide-131 as sodium iodine, precipitating the iodine fraction of palladium iodide by treatment with acidified palladium chloride, then decomposing the palladium-iodide under vacuum. The liberated iodide-127 and iodide-131 is collected in a liquid-nitrogen-cooled U-tube and transferred to a glass ampule that is installed in the injector (Figure 8.13). Preparation of the iodine and loading of the injector must be carried out in a laboratory equipped for handling radioactive materials. To inject iodine during the test, the injector tube is crushed, breaking the ampule and releasing the iodine vapor. Heat may be applied to the injector tube prior to its being crushed and also during the test to assist in vaporizing the iodine source. Compressed air is passed through the tube at a carefully controlled rate for 2 hours.

Figure 8.14 shows a typical in-place radioiodine-tracer test setup. After system flow and background radioactivity levels are established, iodine is injected far enough upstream to ensure adequate mixing with the main airstream, and samples are withdrawn simultaneously through the upstream and downstream sampling units. Injection of iodine is continued for approximately 2 hours, but system airflow and downstream sampling are continued for another 2 hours to catch any iodine that may desorb from the beds, in addition to that which penetrates immediately. Exhaust air from the sampling units is usually dumped back into the upstream side of the main system. The iodine content of the carbon in the samplers is determined by direct gamma spectroscopy, and the bypass leakage is determined from the following equation.

$$E = \left(1 - \frac{C_d}{C_u - B} \right) \tag{8.1}$$

Where

E = efficient, percent

Cd = iodine content of downstream unit, dis/min

Cu = iodine content of upstream unit, dis/min

B = background due to impurity iodine is charcoal, dis/min

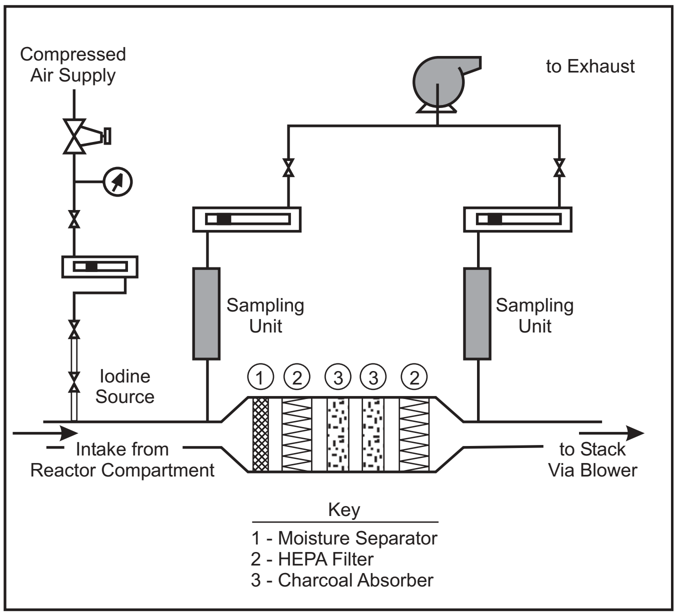


Figure 8.14 – Test Setup for Radioiodine Tracer Tests

The methyl iodide test for determining the efficiency of adsorbers for organic radioiodine compounds is similar to the test for elemental iodine and uses the same equipment, except for the injector. The injector used for the methyl iodide test is a U-tube and a vapor expansion chamber. Sampling and analytical procedures are the same as those for the elemental iodine test. The test vapor is methyl iodide-127 containing methyl iodide-131 tracer. Because the methyl iodine test determines a different property of the adsorbent and depends on a different sorption mechanism, it cannot be used in place of the elemental iodine test. Therefore, both tests are required for a complete evaluation of impregnated charcoal adsorbers. Both of these tests suffer from the limitations of using radioactive tracers in the field and from the number of variables that must be controlled to achieve reliable results.

8.6.3 Test Sequence and Frequency

The recommended test sequences and frequencies in both ASME N510[14] and NRC Regulatory Guides 1.52[16] and 1.140[17] are inadequate to ensure that an air cleaning system is maintained in an acceptable operational condition. ASME AG-1,[3] Section TA, provides updated guidance on testing sequence and frequency.

Surveillance Tests are outlined in Table 1 of ASME N510,[14] and are repeated in **Table 8.2**.

Additionally, due to the potential for unauthorized flow adjustment and duct damage, all air cleaning system airflows should be rebalanced at least every 5 years. Regularly scheduled testing and air balancing properly verifies the safe, effective operation of air cleaning systems and ensures that design parameters are being met and systems are operating within specified acceptance criteria. ASHRAE STD 111, *Practices for Measurement, Testing, Adjusting and Balancing of Building Heating, Ventilating, Air Conditioning and Refrigeration Systems*[29] should be followed.

Table 8.2 – Surveillance Tests

Test	Recommended Frequency [a]
Visual Inspection	Before each test series [b]
Duct Leak Test	Acceptance [c]
Structural Capability Test	Acceptance [c]
Housing Leak Test	Acceptance and at least once every 10 years [c]
Mounting Frame Pressure	Optional Leak Test [d]
Airflow Capacity/Distribution	Acceptance [c] Surveillance [e]
Air-aerosol Mixing Uniformity	Acceptance [c] Test
In-place System Leak Test - HEPA	Acceptance after each HEPA filter replacement and at least once each operating cycle (every 12 months for DOE sites as a basis or more/less frequency, as determined by a technical evaluation) [c, f]
In-place System Leak Test - Adsorbers	Acceptance after each adsorber replacement and at least once each operating cycle [c, f]
Duct Damper Bypass Test	Acceptance and at least once each operating cycle [c, f]
System Bypass Test	Acceptance and at least once each operating cycle (See HEPA above) [c, f]
Air Heater Performance Test	Acceptance and at least once each operating cycle [c]
Laboratory Test of Adsorbent	Acceptance before each adsorber replacement, and at least once each operating cycle [c, g, h]

Notes:

[a] Field test of motors, valve and damper actuators, and fire protective systems are not covered in ASME N510.[14]

[b] The frequency of verifying loop seals and traps must be evaluated by the owner to assure integrity at all times.

[c] Acceptance tests must be made after completion of initial construction and after any major system modification or repair.

[d] The mounting frame leak test is a recommended, but optional, test that identifies the mounting frame leakage that would be included as a part of total bank leakage during HEPA filter bank and adsorber bank in-place leak tests. In many cases, a thorough visual inspection of the mounting frame ensures the mounting frame leakage component of total bank leakage will be minimal (significant leak paths can be visually located). It is left up to the owner to determine whether a mounting frame leak test is warranted based on the visual examination.

[e] Airflow capacity checks for surveillance purposes must be performed prior to any in-place leak test.

[f] Periodic in-place leak tests of systems located within reactor confinements and used only for recirculation are not recommended by the NRC.

[g] Adsorbents must be tested before installation or replacement to establish efficiency. Samples for laboratory testing should be taken before routine in-place testing of the installed system to verify the condition of the adsorbent.

[h] Adsorbent must be sampled and laboratory tests must be conducted to confirm performance at intervals not exceeding 720 hours of system operation for any system immediately following inadvertent exposure to solvent, paints, or other organic fumes or vapors that could degrade the performance of the adsorbent. The 720-hour requirement may be modified based on laboratory test history.

8.7 In-Place Testing for Multistage Systems

HEPA filters are sometimes used in series to increase system reliability or to reduce the effluent air concentrations released from transuranic materials-handling operations. Two questions of importance arise when HEPA filters are employed in series: (1) how can they be tested in place, and (2) what will be the ultimate DF?

With a lower size detection limit at 0.1 µm and excellent analytical characteristics, laser spectrometer counting and sizing instruments have been proposed as a feasible and satisfactory method for testing two or more HEPA filters in series when it is not possible to test each individually. Some uncertainties, however, remain. To have an adequate number of particles downstream for a statistically reliable penetration measurement, high upstream particle concentrations are required; this, in turn, calls for an accurate aerosol dilution device to reduce the particle concentration entering the laser spectrometer to a point where coincidence counting becomes insignificant. This often calls for a reducing concentration by 2 to 4 orders of magnitude, a difficult procedure. In addition, overall tests fail to indicate the status of individual filters in the series. This is important because there are no agreed-upon criteria for permissible penetration through two or more filters in series.

Systems that contain two or more HEPA filter stages and/or two or more adsorber stages in series in the same housing give special problems because of the difficulty of obtaining a representative single-point sample downstream of the first bank and the difficulty of introducing the second-stage test aerosol at a point where good mixing can be achieved. Some series banks are too close, so neither of these objectives can be achieved in the normal manner. Because of the high collection efficiency of the first-stage elements, sufficient test aerosol cannot be introduced upstream of the first stage to permit effective testing of the second stage. It has been shown that accepted test aerosols have no adverse effect on activated carbon or other adsorbents when used for testing nuclear air cleaning systems, and the refrigerant gases used to date have no adverse effect on HEPA filters.

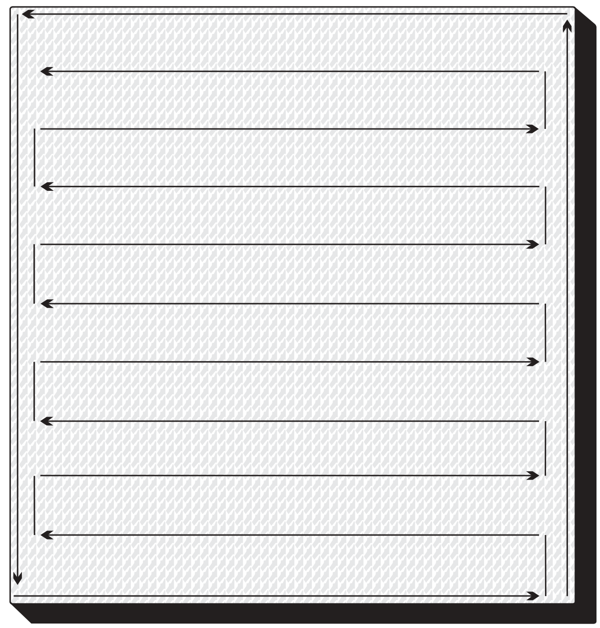


Figure 8.15 – Recommended Scanning Pattern

8.7.1 First-stage Downstream Sample

The first-stage downstream sample can be obtained by using a multiple sampling technique. For testing multistage HEPA filter banks, scanning the downstream face of the stage to be tested is an approved technique, in accordance with the procedure outlined in Section 4 of Institute of Environmental Sciences and Technology (IEST) RP-34.1.[30] The recommended scanning pattern for each filter in the bank is shown in **Figure 8.15**. Prior to starting scanning, the upstream side of the stage is challenged with test aerosol and the photometer is adjusted to read 100 percent. A high concentration will always exist directly downstream of a leak. During the downstream scan, the relative magnitude of each leak is determined by turning the scale shift knob of the instrument until a reading about halfway between half and full scale is obtained. The reading is recorded, and the leak flow for that point is calculated from the following equation.

$$\frac{Leak - probe\,meter\ reading\ (percent)}{Upstream\,concentration\ (percent)} \times probe\ \ flow\,rate = leak\ \ flow \qquad (8.2)$$

where probe flow is the airflow capacity of the instrument.

The percent penetration of the total bank is calculated from this equation.

$$penetration = \frac{\sum n\,leak\ \ flows}{total\ \ flow} \qquad (8.3)$$

Defective filters must be replaced and installation deficiencies must be corrected before the final test is conducted. This method is considered more sensitive than the usual method of HEPA filter testing, and is recommended for multistage systems with plutonium or transuranic element source terms.[31]

8.7.2 In-Place Testing for Multistage Adsorber Systems

Systems containing two or more adsorber stages in series in the same housing pose the same problems as multistage HEPA filters. The same techniques can be used for gas injection and testing as used in the aerosol HEPA filter systems described above. Additionally, since any tracer gas injected upstream of the adsorber bank is only temporarily adsorbed, additional difficulty with desorption interference may be encountered when attempting to test subsequent adsorber stages. Normally, it is advantageous to start with the downstream bank when testing series adsorber banks to minimize desorption interferences. It may be possible to perform individual bank leak testing of series adsorber banks by using temporary or permanently installed sampling manifolds or by providing a temporary jumper duct to bypass airflow around the second stage to either the system fan or to a temporary auxiliary fan.

8.7.3 Test Aerosol/Gas Injection, throughout Second-Stage Upstream Sample

When the test aerosol/gas is introduced through an auxiliary duct, the upstream sample can be taken any place in the auxiliary duct (upstream of the bank to be tested), assuming the auxiliary duct is long enough to ensure good mixing and prefilters are not installed. When using an auxiliary blower, a downstream sample can be taken downstream of the blower. Another method of ensuring proper mixing of the test aerosol/gas with air is to shroud adjacent filters (adsorbers) and introduce the agent to each filter element (adsorber cell) individually by using a multiple discharge distributor, as shown in **Figure 8.16**. The upstream sample is taken downstream of the perforated distribution plate. The downstream sample is taken with a multipoint sampling probe (**Figure 8.17**). The penetrations of the individual filters (adsorbers) are averaged to find the gross bank penetration. This method requires that a mounting frame pressure leak test be made, usually at the time of acceptance testing,[32] and that the air-containing test gas be passed through a unit (filter or adsorber cell) or group of units one at a time. This method has the advantage of substantially reducing the total quantity of test aerosol/gas introduced to the system if scanning is required to locate leaks; however, it requires more time than the usual method of taking single-point upstream and downstream samples. The vapor test gases have no adverse effect on HEPA filters, and it is possible to inject the gas upstream of the HEPA filters when testing adsorbers. [Note: Shroud testing is rarely performed in the commercial nuclear plant environment.]

Figure 8.16 – Adsorber Tray Mounting Frame. "X" Cross Units Are for Test Gas Injection

Modern air cleaning systems should be designed to eliminate back-to-back series adsorber elements within a single housing. Gasketless deep-bed adsorbers or series adsorbers contained in separate, testable housings may be used when the design requires bed depths in excess of the standard two inches.

8.7.4 Adsorbent Sampling and Laboratory Testing

8.7.4.1 Sampling

The effectiveness of the adsorbent may be impaired due to aging, weathering, and/or poisoning by chemical contaminants. The charcoal ages as a result of oxidation of the adsorptive sites at the adsorbent surface.[33] Aging may occur in the drum (static) or in the operating air cleaning system (dynamic). Weathering typically occurs during system operation when the adsorbent is exposed to normal atmospheric, low-level contaminants in the airstream, e.g., oxides of nitrogen and sulfur and outgases from plant materials and equipment. Poisoning generally refers to an acute exposure of the adsorbent to chemical compounds that temporarily or permanently impair its ability to remove radioiodine and radioiodides. Periodic sampling of the adsorbent provides a means of providing a representative sample of adsorbent for radioiodine testing. The radioiodine laboratory test, together with the in-place adsorber leak test, provides a means of assessing overall adsorber system health.

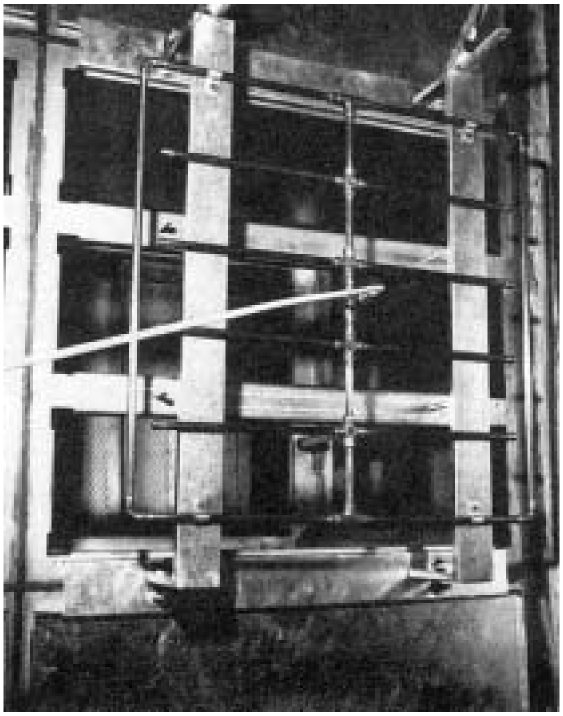


Figure 8.17 – Multiple Point Sample Probe

Figure 8.18 –Multicell System

Flow-through cartridges must be provided and installed in an area of the bank where air will flow through them, and not in obvious low-flow areas such as the outside edge of the mounting frame. If sample cartridges are not provided, other means of sampling are necessary. In a multicell system such as that shown in **Figure 8.18**, samples can be obtained by removing and emptying a cell, taking a sample of the loose adsorbent, refilling the cell (using a qualified filling procedure), and reinstalling it in the bank. For some adsorber systems, it may be possible to take a "grain thief" sample.[34] In small adsorber installations, when considering the cost of the tests and labor involved in obtaining the sample, it may be beneficial to simply replace the adsorbers or adsorbent. Some users have found it more economical to replace the adsorbent at the stipulated sampling frequency rather than making surveillance sample tests.

NRC Regulatory Guide 1.52,[16] Revision 3, currently requires that sampling and analysis be performed: (1) after each 720 hours of system operation, or at least once every 24 months, whichever comes first; (2) following painting, fire, or chemical release in any ventilation zone in communication with the system that may have adversely affect the functional capability of the carbon media; and (3) following detection of, or evidence of, penetration or intrusion of water or other material into any portion of an ESF atmosphere cleanup system that may have adversely affect the functional capability of the carbon media.[3]

When using a "grain thief" for sampling Type II (cartridge) or Type III (deep bed) adsorbers, multiple samples should be taken from all sections of the adsorber bank. For deep bed adsorbers, it is important to sample from below the tops of screens so that carbon from the overfill is not commingled with the service carbon. In filters with a bed thickness greater than two inches (50.8 mm), samples should be taken from the center of the bed. Samples taken from the inlet side of a carbon bank will show more radioiodine penetration than samples taken from the exit side. Therefore, samples should be taken symmetrically from the exit screen side, the entrance screen side, and the middle of the bed. After using a grain thief to sample a Type II adsorber, the tray should be "topped off" with new carbon (assuming the tray is to be reused), and then marked as "Not Representative for Future Sampling."

When sampling Type II adsorber trays, the entire tray should be emptied and the contents mixed to yield a homogeneous composite sample. A smaller, grab sample may be taken from the tray contents for laboratory testing. If the bank is not being replaced, a new tray must be installed in the bank and marked as "Not Representative for Future Sampling."

Sample canisters may be used to take a representative carbon sample from the adsorber bank. Sample cartridges must be provided in sufficient numbers to permit taking samples at specified intervals for the life of the adsorbent. Sample cartridges must be designed so that bed depth, airflow, and pressure drop across the cartridges are the same as for the adsorber stage. For this reason, the zero-flow hang-on cartridges shown in **Figure 8.19** are not acceptable. Properly designed sampling canisters should have a minimum diameter of 2 inches (50.8 mm) and should have the same bed depth as the main bank. Sampling canisters should be mounted vertically so that any bed settling within the canisters will not create a mechanical bypass of the carbon media.

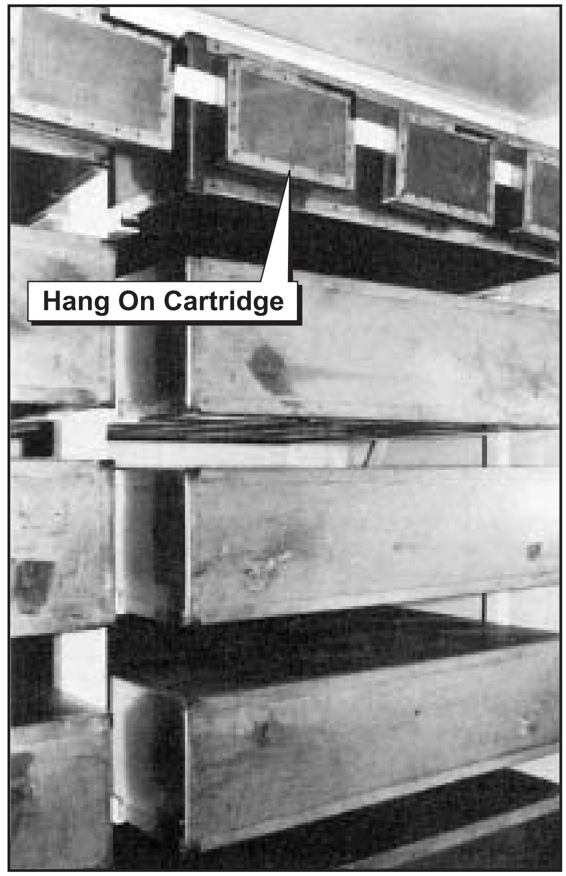


Figure 8.19 – Zero Flow Hang on Cartridges

All samples taken from an adsorber bank must be representative of the main bank. Any method used for sampling (grain thief, sample canister, dumping) must yield representative composite samples. One method of confirming that a sampling procedure is acceptable is to compare the radioiodine testing results from the sampling procedure with the radioiodine testing results from a representative sample of the main bank taken after the carbon is removed from the system. After a bank has been emptied, all of the carbon is accessible for sampling, allowing a true representative to be taken. If the test results obtained from a homogenized sample taken when the entire bed has been emptied are consistent with the results from in-situ sampling, then the sampling procedure is acceptable.

Carbon samples taken from the adsorber bank should be thoroughly mixed and packed into vapor-tight containers such as a plastic bottle. At least 125 ml of carbon for each two inches of bed thickness are required for the laboratory test. All samples that are to be sent to a testing laboratory must be marked with the following minimum information:

- Utility/Company,
- System Identity,
- Sample Date,
- Purchase Order Number,
- Test Standard (ASTM D3803-1989),[20]
- Test Temperature,
- Test Humidity,
- Face Velocity,
- Adsorbate (methyl iodide),
- Pressure,
- Bed Thickness, and
- Contact Person/Telephone Number.

Test results for samples sent to a laboratory for radioiodine penetration analyses must be available within 30 days of their sampling date.

8.7.4.2 Laboratory Testing

Most radioiodine laboratory testing on activated carbon samples taken from safety-related filtration systems installed in U.S. commercial nuclear power plants are conducted in accordance with ASTM D3803-1989.[20] This requirement was made mandatory by NRC Generic Letter 99-02,[31] issued in 1999. Other test standards that can be used for non-safety-related systems include ASTM D3803-1979[20] and 1986,[20] as well as RDT-M16-1T 1973.[34]

Table 8.3 Standard ASTM D3803-1989 [21] Testing Conditions

Temperature	54 degrees Fahrenheit
Humidity	95 percent
Face Velocity	12.2 m/min (40 fpm)
Pressure	29.91 in. Hg.
Methyl Iodide	1.75 mg/m3 Concentration
Equilibration Time	120 minutes
Pre-equilibrations	16 hours
Loading Time	60 minutes
Post Sweep	60 minutes
Bed Thickness	50 millimeters

Radioiodine penetration analysis is conducted in the laboratory using the ASTM D3803-1989[20] standard test method. Testing is conducted in sophisticated environmental chambers that are capable of precisely controlling the temperature and humidity. The activated carbon sample is loaded into stainless steel testing canisters, one canister for each two inches of adsorber bank bed depth. Along with two more canisters containing new carbon, the canisters with the activated carbon sample are assembled into a canister stack for testing. The canister stack is placed into the environmental chamber and plumbed into the testing system. The system environment is adjusted to the required temperature and humidity, normally 86 degrees Fahrenheit and 95 percent RH. All test parameters are monitored by a computer monitoring system for the duration of the test. After an initial thermal equilibration period, humid airflow is started through the carbon beds for the duration of the pre-equilibration and equilibration periods. The loading period begins with the introduction of methyl iodide into the airstream. The methyl iodide is fed into the system for a period of 60 minutes, called the loading period. After completion of the loading period, the injection of methyl iodide is stopped, and the humid air continues for an additional 60 minutes. This is called the “post sweep.” The carbon canisters are then disassembled and carbon from them is loaded into plastic counting canisters for analysis. Each carbon sample is counted in a gamma spectrometer to determine the amount of radioactivity contained in each carbon canister. Knowing the amount of radioiodine present in each carbon canister allows calculation of the radioiodine penetration in percent penetration.

Detailed descriptions of the penetration measurement may be found in ASTM D3803-1989.[20] Radioiodine laboratory testing on activated carbon samples taken from safety-related filtration systems installed in U.S. commercial nuclear power plants are conducted in accordance with ASTM D3803-1989.[20] Previous versions of ASTM D3803 (1979 and 1986) and RDT M16-1T-1973[34] are still specified for non-safety-related adsorber systems. However, for future licensees, currently applicable documents include NRC Regulatory Guide 1.52,[16] Revision 3, (safety-related) and 1.140,[17] Revision 3, (non-safety-related). Both of these Regulatory Guides now reference ASTM D-3803-89.[20]

Acceptance criteria for radioiodine penetration are described in the facility technical specifications for safety-related systems. For other systems, pertinent information related to system design performance may be found in vendor design documentation or the facility Final Safety Analysis Report.

8.7.4.3 Frequency of Testing

The following test schedule (**Table 8.4**) is suggested for both continuous and intermittent online adsorber systems designed in accordance with this Handbook.

Table 8.4 – Test Schedule for Adsorbers

Application	***Frequency***
All systems.	Before system startup, following any major system repair or modification, and following each filter (adsorber) replacement.
Radiochemical plants, fuel reprocessing plants, and laboratory fume hoods.	Semiannually or quarterly where high moisture loadings or high temperatures are involved. In some systems, frequent (even monthly) testing is often specified where the environment is particularly severe. The frequency may be reduced if experience indicates a lesser frequency is satisfactory.
Reactor post-accident cleanup systems and post-accident cleanup systems of fuel reprocessing plants.	Annually or 720 hrs of system operation, whichever comes first (as specified in NRC Regulatory Guide 1.52).[16]
Zone III or tertiary confinement [a] areas of facilities that handle radioactive materials.	Annually.
Zone II or secondary confinement [a] areas of plants and laboratories that handle radioactive materials.	Annually.
Zone I or primary confinement[a] areas (glovebox lines, hot cell exhaust, etc.) of laboratories and plants that directly handle moderate to large quantities of radioactive materials.	Semiannually unless experience indicates that annual testing is sufficient. If filters (adsorbers) are replaced at short (less than 6-month) intervals to limit exposure of personnel to radiation during a filter (adsorber) change, or to permit contact maintenance of the system by limiting the amount of radiation that can be collected in the filters (adsorbers), systems should be in-place [i.e., leak-tested following each filter (adsorber) change]. Laboratory testing of adsorbents may not be necessary if the adsorbent is replaced frequently.
Systems that are continually on standby, but are operated occasionally during plant maintenance to ventilate the system.	At least biannually.

[a] Zones and confinements are found in Chapter 2, Section 2.2.9.1.

8.8 Testing of Deep Bed Sand Filters

Deep bed sand filters are not true HEPA filters, although their efficiency approaches that of a true HEPA filter when tested for aerosol penetration using the test method described in Chapter 8 of this Handbook; a physical description is found in Chapter 9. This method, which is the same method used to leak test HEPA filter systems, uses a poly-dispersed aerosol with a light scattering mean diameter of 0.7 micron. Many experts believe this method of testing sand filters tends to over rate the filtration calculated efficiency, so it may be prudent to use another method of testing to confirm test data. One method of doing this is to measure the quantity of radioactive particulate in the airstream before and after it passes through the sand filter and compare them to the aerosol test result.

Aerosol should be injected into the system as far upstream of the sand filter as possible for good mixing. An Air-Aerosol Mixing Uniformity Test, as described in ASME N 510,[14] should be performed to determine the best injection point and sample points. A perforated dip tube designed and installed per ANSI N 13.1[32] should be used upstream and downstream of the sand filter to further ensure a representative sample of the aerosol concentration is used. The upstream and downstream concentration of background aerosols (dust test) that may interfere with the test results should be performed prior to the introduction of aerosol into the system. The background test is performed by setting the aerosol photometer's internal calibration feature to reference the instrument to a concentration equivalent of 100 micrograms of aerosol per liter of air. The background concentration is then measured upstream and downstream (upstream first) and recorded. The background levels should be stable and allow for detection of aerosol penetration smaller than the maximum allowable penetration. The aerosol should be injected into the sand filter for a period of 15 to 30 minutes, depending on the size and cfm of the sand filter, prior to the test sampling to allow time for distribution of the challenge aerosol throughout the sand filter.

8.9 Areas for Continuous Improvement

8.9.1 Qualified Products List

The QPL for qualification of HEPA filters, which was once maintained by the military, needs to be re-established and maintained. With the military's elimination of the QPL for HEPA filters, ASME Code AG-1[3] specifies that qualification may be performed by independent laboratories. The problem is that, with the exception of Edgewood Arsenal, no laboratories have the equipment or inclination to qualify filters. Review and updating of the qualification test protocol is required. Changes may be needed in the heated air, moisture overpressure, environment cycle, or rough handling tests. Additional tests may be needed.

8.9.2 Suggested Improvements and Testing Standardization

Improved field-testing methods and equipment require the adoption of testing standards to ensure consistent testing and results. Although commercial nuclear applications apply the ASME N510[14] and ASME AG-1[3] standards, DOE contractors require clarification of the applicable parts of these referenced standards. An in-place testing conference held at the DOE SRS recognized that standardization of DOE contractors' in-place testing procedures for DOE applications was in order. The group also identified the following areas for improvement:[23]

- Referencing ASME N510[14] for testing of DOE filter systems results in auditing confusion and problems in demonstrating compliance with the referenced requirements.
- Filter specification (ASME/DOE) clarification is needed.
- Improvements are needed in the areas of standards, procedures, training requirements, and certification for filter test technicians.
- A DOE guidance document or standard for testing unique filter systems at DOE sites should be developed.
- Guidance on filter service life should be developed.
- The challenge test aerosol used by DOE contractors should be standardized.
- Mandatory/optional requirements for the in-place test procedure should be standardized.
- More stringent receiving inspection/QA requirements need to be developed and more training of personnel in this area is needed.
- QPL requirements for cylindrical filters should be developed.
- A decision is needed concerning whether FTF QA testing will continue, and which facility will perform the qualification tests.
- A decision is also needed to establish the testing protocol for HEPA filter vacuums and portable ventilation units.

8.10 Review of In-Place Filter Testing at Selected DOE Sites

In 1992 and 1993, LANL performed a 2-year review[35] of the HEPA filtration systems at seven different DOE sites:

- Paducah Gaseous Diffusion Plant;
- Portsmouth Gaseous Diffusion Plant;
- LANL, Area 200 of FP4, Technical Area 55;
- Plutonium Fuel Fabrication Facility and Plutonium Experiment Facility at SRS;
- High Flux Beam reactor and Medical Research Reactor at Brookhaven National Laboratory;
- Buildings 38 and 50 at Mound Plant (Mound); and
- ORNL, High Flux Isotope Reactor, Radiochemical Engineering Development Center and Isotope Enrichment Facility.

Although significant differences among the sites were found, there were also several issues common to all seven. The observations were divided into four areas:

Policy Development. (Includes filter shelf life, filter service life, role of HEPA acceptance and in-place filter testing and system oversight.) The goal should be to provide a technical basis for setting maximum storage and service times after which filters must be discarded or replaced.

Testing Multi-stage Systems. (Includes overall system and individual stage testing.) Requirements in this area include clarification for the use of acceptance-testing filters, the need to test intermediate stages of multiple stage systems, appropriate requirements for testing filters used with gloveboxes, and the types and degree of administrative oversight and record-keeping necessary when HEPA filers are part of exhaust and air emission control systems.

Guidance on In-place Filter Testing and System Supervision. Includes testing practices, test equipment maintenance and calibration, special concerns of older systems, measurement uncertainty, pass/fail decisions, frequency of routine testing, analysis and reporting of testing results, and technical support and training of testing personnel.

Uncertainty in In-place Filter Testing Results. The issue of how such results are affected by measurement methods, system characteristics, and system abnormalities needs to be studied.

Two principal conclusions emerged from these reviews. First, there was an immediate need to develop information on how filter mechanical integrity decreases with time, and to use this information to establish limits on filter service life. Second, there was a general need to ensure the validity of in-place filter testing results and to improve testing practices. A mathematical framework for describing the effects of abnormal system features on testing results was proposed as an aid in understanding the uncertainty in in-place filter testing results.[37]

8.11 Testing Portable HEPA Filtration Systems

8.11.1 General Testing and Periodic Maintenance Considerations

Problems with operating portable HEPA filtration systems (PHFS), i.e., systems that can move and are often not visually observable or detectable by onboard instrumentation. Therefore, filter replacement and testing are important to the continued safe operation of the unit. In-place testing is designed not only to validate the HEPA filter, but also to verify the integrity of associated seals, gasketing, ducting, and housings regarding leakage.

All HEPA filters used in the system should be tested by the DOE FTF before initial use. In addition, the device should be leak-tested after installation at the site and prior to operation. Most importantly, a thorough leak test should be conducted anytime the unit is jarred, bumped, or moved. Leak tests are conducted by first injecting an aerosol challenge into the inlet of the PHFS and measuring the aerosol challenge concentration at the inlet to establish a 100 percent baseline. Then the detector samples particle free air to establish a 0.000 percent baseline. With these two baselines, created samples of the PHFS outlet can be sampled to measure any aerosol leakage.

Any entry into a PHFS must be consistent with local radiological controls, which is normally controlled by a radiological work permit. Radiation and contamination surveys should be performed periodically for PHFS in use, and the labels on these units should be updated. The frequency of radiation surveys should depend on the specific use of the unit.

PHFS tend to be overlooked when it comes to maintenance and testing. Many standards and procedures address maintenance and testing of permanent Heating, Ventilating, and Air Conditioning (HVAC) HEPA filtration systems. However, no national standards and procedures are available for PHFS. Worse, because of their size and portability, personnel assume they are functioning correctly. Ironically, these units are capable of discharging contamination over the specific areas of the work site they are supposed to be protecting if filter bypass leakage is occurring.

These units by their very nature are prone to leakage. This is mainly because they are small and portable, and thus are transported from workplace to workplace in the back of trucks and are subjected to substantial rough handling by workers. This action creates leaks in units that were previously tested, giving personnel a false sense of security. For this reason, these units should be tested <u>anytime</u> they are transported to another workplace. When testing PHFS, test personnel should apply the same rigorous procedures outlined in ASME N510[14] and ASME AG-1[3] for the permanent HVAC HEPA filtration systems. After all, PHFS perform the same functions and have essentially the same components as the permanent HVAC systems.

8.11.2 Reasons For Testing PHFS

- Poor PHFS design.
- Poor workmanship and inadequate quality control by the PHFS manufacturer.
- Leaks in the filter media itself.
- Leaks due to failure of the adhesive bond between the filter media and its frame.
- Leaks between the filter frame and cabinet sealing frame seals.
- Leaks between the cabinet main frame and the cabinet housing.
- Leaks in the cabinet or housing due to damage in transit or handling.
- Leaks from misalignment or misassembled components of the PHFS.
- Leaks resulting from incorrect or inadequate maintenance.
- Leaks resulting from improper installation and operation of the PHFS at the work site.

[Note: Many of the above items <u>may not be applicable</u> to units constructed and certified to ASME AG-1[3] criteria.]

8.11.3 Portable Filtration Systems Testing Applications

There are two basic designs for these systems: those that “pull” air through the HEPA filter and those that “push” air through it. Therefore, some units locate the HEPA filter upstream of the motor/blower assembly, and others place the HEPA filter downstream of the motor/blower. The advantages and disadvantages of each design concept are summarized in **Table 8.6**.

Table 8.6 – Downstream/Upstream HEPA Filter Locations in PHFS

(+) Advantages	*(-) Disadvantages*
Type A DOWNSTREAM HEPA	Type B UPSTREAM HEPA
(+) Easier access to HEPA filter for scanning or leak testing	(-) Difficult access to HEPA filter for scanning or leak testing
(+) May not require mixing chamber to assure uniform mixing of test aerosol	(-) Requires mixing chamber to assure uniform mixing of test aerosol
(-) Motor/blower may become contaminated	(+) Motor/blower should stay uncontaminated unless filter leaks
(-) Cabinet interior may become contaminated	(+) Cabinet should stay uncontaminated unless filter leaks

Design, materials, specifications, and quality of construction vary widely among PHFS. These variables have a tremendous impact on overall performance and effectiveness. In particular, the cabinet material must remain rigid and undistorted during shipping, handling, and the rigors of daily operation to prevent the contaminated air from bypassing the HEPA filter. The type and gauge of metal fabrication methods, braces, holes, cracks, fasteners, welds, gaskets, and seals must be designed, specified, and assembled with potential leakage, durability in service, and maintenance in mind. [Note: Many of the above items may not be applicable to units constructed and certified to ASME AG-1[3] criteria.]

8.11.4 Testing Problems and Special Considerations

Some of the designers and manufacturers of PHFS have not put much thought or effort into creating units with integrity leak tests in mind. Not only do they unintentionally "design in" leaks, but they also often overlook the inclusion of features that allow access to areas that are critical for leakage testing. Access to the downstream face of the HEPA filter for the purpose of scanning is virtually impossible in most units where the blower is downstream of the HEPA filter. A mixing chamber with baffles is necessary at the inlet of this type of unit to provide adequate challenge aerosol mixing. Downstream measurements of the exhaust airstream can be subject to error due to channeling—the opposite of mixing. The aerosol from a specific leak may simply remain concentrated in a segment of the exhaust airstream. Therefore, sampling must be done at various points across the face of the exhaust air outlet, in effect a "scanning" of the opening. A single-point sample is usually not representative of what is in the exhaust airstream because the leak becomes diluted with the particle free air. The same considerations are included in making air velocity measurements across the exhaust opening or duct in accordance with ANSI/ASTM 41-2 (1987).[36] A single-point reading is not representative as discussed in ACGIH *Industrial Ventilation – A Manual of Recommended Practice*.[22]

8.12 Testing HEPA Filter Vacuum Cleaners

HEPA filtered vacuum cleaners (HEPA-Vacs) are most commonly used to control particulate before it becomes airborne. They are also used to control airborne particles and liquids in and around work areas and to provide localized control of loose debris when work operations could potentially spread contamination. When used in the nuclear industry, HEPA-Vacs are commonly referred to as nuclear or radiological vacuum cleaners.

8.12.1 Description of Radiological Vacuum Cleaners

Radiological vacuum cleaners are generally well-constructed, well-sealed devices with a HEPA filter on the exhaust. They are normally mounted on a cart with a comfortable handle and lockable, steerable wheels for portability and control during use. The power module consists of a blower powered by an electric motor and controlled by an onboard switch. The filter module consists of a positively mounted and sealed HEPA filter protected by a prefilter. All units should have a positive plenum (tank)-to-vacuum head seal. Vacuums that have latches but provide a loose tank-to-head seal that depends on the vacuum force to provide a positive seal (as in many commercially available shop vacuums) should not be used.

Some vacuum cleaners are equipped with controllers that allow the worker to regulate the flow. This works well in providing negative ventilation in small glove bags. Using HEPA filtered vacuum cleaners can significantly improve how contamination is controlled.

An inline HEPA filter can be installed in the suction hose to collect radioactive material before it reaches the vacuum cleaner. Fittings can be made to connect the vacuum cleaner hose to the HEPA filter. As debris is sucked into the hose, it is deposited on the inline HEPA filter instead of the HEPA filter inside the vacuum cleaner. Temporary shielding should be installed around the inline filter before operation, as the filter becomes highly radioactive.

If a large amount of debris will be collected, installation of a waste drum in the suction hose should be considered to ensure the debris collects in a waste drum and not the vacuum cleaner. Commercial systems are available, or one can be made by welding two pipes into a spare drum lid. As each drum is filled, the lid can be installed on a new drum and a regular lid can be installed on the full drum. Personnel doses are reduced because the debris is collected directly into the waste drum instead of the vacuum cleaner.

Vacuum cleaners should be constructed of a material that is easily decontaminated without damage to components. Units that use silicone-based material to prevent leakage should not be used. All hose connections should provide positive seals and should be constructed of a material that will not be damaged by repeated use or rough handling.

HEPA filters should have a positive seal and pass in-place leak testing. The filter holddown clamps should provide the required force (20 pounds per square inch) to seal the filter and prevent dislodging during rough handling and repeated use. They should be constructed of a material that will not warp or bend with repeated use.

The HEPA filter replacement method should be both simple and achievable in minimum time to reduce exposure and the chance of radioactive contamination. The vacuum cleaners should be designed to ensure HEPA filter integrity under all conditions of use and to prevent unauthorized or accidental access to the inner surfaces of the vacuum. Units should be constructed with no sharp edges or burrs that could injure personnel or damage protective clothing.

HEPA filters used in HEPA-Vacs should meet the efficiency and construction requirements for HEPA filters listed in DOE -STD- 3025[7] and ASME AG-1.[3] The maximum flow rate of the device should not exceed the flow rate at which the HEPA filter was efficiency-tested. The HEPA filters should be certified at the DOE FTF.

8.12.2 Operation

HEPA-Vacs are used to cleanup radioactive debris. Improper use of HEPA-Vacs may result in generation of airborne radioactivity, loose surface contamination, or high dose rates. HEPA-Vacs used for radioactive material should be marked, “For Radioactive Service Only.” A nuclear safety review must be performed and documented prior to use of a HEPA-Vac for fissile material.

HEPA-Vacs must be appropriate for the type and amount of radioactive material involved. The health physicist is responsible for determining the levels of filtration required on the exhaust. Programmatic organizations are responsible for the following items:

- Maintaining control of HEPA-Vacs.
- Ensuring that HEPA-Vacs are tested semi-annually. (HEPA-Vacs must be retested if the integrity of the filter media or the sealing surface of the HEPA filter is compromised, if the HEPA filter is exposed to water or high levels of water vapor, or if the HEPA-Vac is transported to another area or site.)

- Ensuring that HEPA-Vacs are properly labeled, controlled to avoid improper use, and serviced or emptied only by individuals trained to do so, and also that the health physicist is contacted before they are opened.

HEPA-Vacs used in contaminated areas should be equipped with HEPA-filtered exhausts or with exhausts that are directed to installed systems that are equipped with HEPA filters. Such provisions may not be necessary when these systems are used in areas where only tritium or radioactive noble gases are present or when the material to be vacuumed is wet enough to prevent the generation of airborne radioactive material or removable surface contamination. Extended use of air handling equipment may cause a significant buildup of radioactive material in the ductwork and filters. Periodic sampling of the exhausted air and surveys of the accessible surfaces of the equipment should be performed to assess the radiological impact of equipment operation. While use of the devices discussed above has been proven effective in reducing contamination spread and associated decontamination costs, these benefits must be weighed against the potential costs. Use of engineering controls may require expenditure of worker doses to set up, work in, maintain, and remove the device. There may be financial costs associated with device purchase or manufacture, worker training, possible reduced productivity, and device or component maintenance and disposal.

8.12.3 General Testing and Periodic Maintenance Considerations

HEPA-Vacs operational problems are very similar to portable HEPA filtration systems discussed in Section 8.11.1. It is worthwhile to repeat those observations here. Problems with operating HEPA-Vacs are often not visually observable or detectable by onboard instrumentation. Therefore, filter replacement and testing are important to the continued safe operation of the unit. In-place testing is designed not only to validate the HEPA filter, but also to verify the integrity of associated seals, gasketing, ducting, and housings to leakage.

All HEPA filters used in HEPA-Vacs should be tested by the DOE FTF before initial use. In addition, the device should be leak-tested prior to initial use when units have been opened and/or transported to another site, as well as semi-annually. Leak tests are conducted by first injecting an aerosol challenge into the inlet of the HEPA-Vac and measuring the aerosol challenge concentration at the inlet to establish a 100 percent baseline. Then the detector samples particle-free air to establish a 0.000 percent baseline. With these two baselines accomplished, samples of the HEPA-Vac outlet can be taken to measure any aerosol leakage.

Any entry into a HEPA-Vac must be consistent with local radiological controls, and normally would be controlled by a radiological work permit. Radiation and contamination surveys should be performed periodically for HEPA-Vacs in use and the labels on these units should be updated. The frequency of radiation surveys should depend on the specific use of the unit.

HEPA-Vacs tend to be overlooked when it comes to maintenance and testing. Many standards and procedures address maintenance and testing of permanent HVAC HEPA filtration systems. However, for HEPA-Vacs, no national standards and procedures are available. To make matters worse, because of their size and portability, personnel assume that they are functioning correctly. Ironically, these units are capable of discharging contamination over large areas of the work site if filter bypass leakage is occurring.

These units are prone to leakage by their very nature—mainly because they are small and portable, and thus are transported from workplace to workplace in the back of trucks, and are subjected to substantial rough handling by workers. This action creates leaks in units that were previously tested, giving personnel a false sense of security. For this reason, these units should be tested anytime they are transported to another workplace. When testing these HEPA-Vacs, test personnel should apply the same rigorous procedures outlined in ASME N-510[14] and ASME AG-1[3] for the permanent HVAC HEPA filtration systems. After all, HEPA-Vacs perform the same functions and have essentially the same components as the permanent HVAC systems.

8.12.4 HEPA Filter Vacuum Cleaner Tests

Numerous suppliers manufacture HEPA-Vacs, and each supplier has several models available. This leads to unique characteristics that must be considered when performing in-place testing. As in the permanent HVAC systems, a thorough visual inspection by trained personnel of the unit to be tested should be performed before conducting the test. This inspection should be done using a checklist tailored to the specific make and model to be tested. These units should also be tested for proper flow and suction capabilities. Generally, a 4- to 6-in.-diameter duct or flex hose 8 to 10 feet long is used to introduce the challenge aerosol to the input of the HEPA-Vacs under test. An upstream probe can be fitted close to the end of the hose for transition to the inlet connector on the unit under test. The output of the aerosol generator should be directed to the other end of this hose. This configuration usually allows adequate aerosol-air mixing of the aerosol challenge.

The greatest challenge to testing HEPA-Vacs is obtaining a representative downstream reading. For most HEPA-Vacs, downstream air is discharged radially in all directions rather than through a duct (as in permanent HVAC systems). To accomplish this, test personnel usually fabricate a collection hood to collect all of the downstream air discharged from the unit under test and connect a duct or hose to the hood. The hose or duct can be fitted with a downstream probe located at least 10 diameters downstream of the hood. After the upstream/one hundred percent baseline and the 0 percent baselines have been established, a downstream reading should be taken both with and without the aerosol generator operating. This is done to verify whether there is a background leakage reading. Some HEPA-Vacs generate significant amounts of particles due to their design configuration. If a background reading is detected, it should be recorded and deducted from the downstream reading obtained with the aerosol generator operating.

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CHAPTER 9

SPECIAL APPLICATION REQUIREMENTS

9.1 Introduction

Preceding chapters of this handbook have discussed the general requirements of high-efficiency air cleaning systems as they pertain to relatively common applications. This chapter discusses some special requirements that may have to be considered for certain applications, including:

1. Designing to survive natural phenomena such as a tornado or earthquake,
2. High-capacity sand filters.

9.2 Natural Phenomena

The ability of a system to survive and function during and/or following a natural disaster such as an earthquake or tornado must be taken into consideration in the design of air cleaning systems. By definition, such systems serve to control and limit the consequences of releases of energy and radioactivity in the event of occurrences.

9.2.1 Natural Phenomena Hazards

The natural phenomena hazards (NPH) of interest at a site include earthquakes, winds/tornadoes, floods, and lightning. Earthquakes and winds/tornadoes can lead directly to a release of hazardous materials. Floods and lightning, on the other hand, usually are not directly responsible for the release of hazardous materials, but can initiate other events such as fires or spills that lead to releases. These last two events should be discussed without specific details (unless deemed necessary for a specific site). U.S. Department of Energy (DOE) Order 420.1A, *Facility Safety*,[1] and DOE Guidance 420.1-2, *Guide for the Mitigation of Natural Phenomena Hazards for DOE Nuclear Facilities and Nonnuclear Facilities*,[2] establishes the policy and requirements for NPH mitigation for DOE sites and facilities. DOE Order 420.1A[1] utilizes a graded approach to provide for the health and safety of facility occupants; the public; and the environment, to protect against property losses, and to preserve production and research objectives. This graded approach in design, evaluation, and construction of structures, systems, and components (SSCs) varies in conservatism and rigor, ranging from normal-use buildings to nuclear power plant structures. DOE Order 420.1A[1] specifies that consistent NPH requirements in a graded approach are implemented by the use of target probabilistic performance goals. Performance goals are expressed as the annual probability of exceeding acceptable behavior limits beyond which an SSC may not perform its function or maintain structural integrity. Performance goals are targeted by specifying probabilistic NPH estimates and deterministic design and evaluation methods (including intentional and controlled conservatism). Performance Categories (PC) 1 through 4 are defined with target performance goals.

DOE Order 420.1A[1] requires use of DOE-STD-1020, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*,[3] to provide design and evaluation criteria for earthquakes, wind/tornadoes, and floods, and requires this standard to be used as guidance in implementing NPH mitigation requirements. DOE-STD-1020 specifies performance goals and relevant hazard probabilities for PC 1 through PC 4 to establish the design basis loads.[3] The goals of DOE-STD-1020 are to ensure that NPH evaluations are performed on a consistent basis, and that DOE facilities can withstand the effects of natural phenomena. Considerable new information and analysis/design methods have been developed since DOE-STD-1020 was issued. DOE-STD-1020 has been recently revised and republished to incorporate the current seismic analysis/design requirements of the *International Building Code* (IBC).[4] [Note: The IBC is a commercial code written without regard to nuclear requirements.]

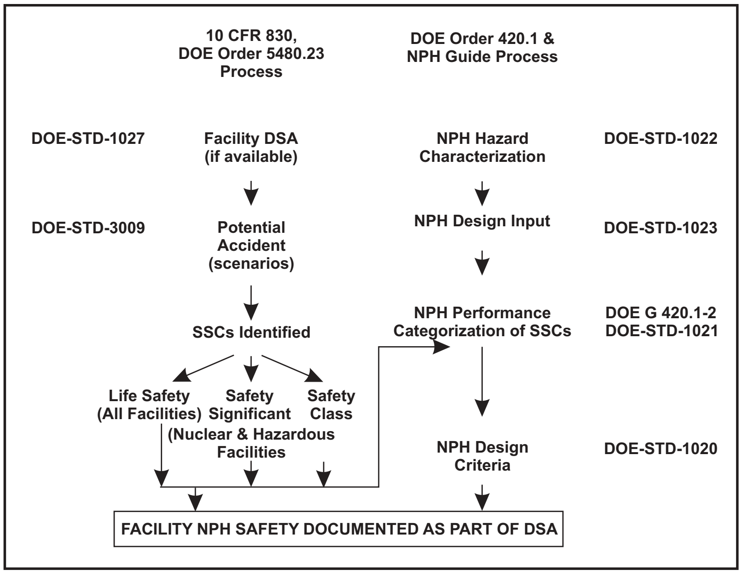

Figure 9.1 – Natural Phenomena Hazards Design Input

The overall DOE NPH design input, as well as applicable DOE Orders and standards, are shown in **Figure 9.1**.

Additional guidance addressing NPH events is provided in several other DOE NPH standards:

- DOE-STD-1021, *Natural Phenomena Hazards Performance Categorization Criteria for Structures, Systems, and Components*.[5]
- DOE-STD-1022, *Natural Phenomena Hazards Site Characterization Criteria*.[6]
- DOE-STD-1023, *Natural Phenomena Hazards Assessment Criteria*.[7]
- NFPA 780, *Standard for the Installation of Lightning Protection Systems*, 2000 edition.[8]

9.2.2 Earthquake

Earthquakes differ from other natural phenomena in that there are no advance warnings. **Table 9.1** shows the mean annual exceedance probabilities for the design basis earthquake (DBE) for various PCs.

Table 9.1 – Seismic Performance Categories and Seismic Hazard Exceedance Levels

Performance Category	***Mean Seismic Hazard Exceedance Levels P_H***	***Remarks***
0	No requirements	–
1	4×10^{-4}	Use IBC 2000, Seismic Use Group I Criteria 2/3 MCE Ground Motion
2	4×10^{-4}	Use IBC 2000, Seismic Use Group III Criteria MCE Ground Motion
3	4×10^{-4} (1×10^{-3}) (see note 2)	Analysis per DOE-STD-1020[3]
4	1×10^{-4} (2×10^{-4}) (see note 2)	Analysis per DOE-STD-1020[3]

Notes:
1. For PC 1 through PC 3, the P_H levels are based on Maximum Considered Earthquake (MCE) Ground Motion, which is generally a 2 percent exceedance probability in 50 years.
2. For sites such as Lawrence Livermore National Laboratory, Sandia National Laboratories-Livermore, Standard Linear Accelerator, Lawrence Berkeley Laboratory, and the Energy Technology Engineering Center, which are near tectonic plate boundaries.

Specific criteria regarding nuclear power plant designing for earthquakes are defined by the U.S. Nuclear Regulatory Commission, (NRC).

The two main steps in evaluating the potential impact of an earthquake for a particular facility are: (1) estimate the probability of exceeding the earthquake magnitude of interest (as discussed below), and (2) estimate the damage the facility will sustain for this magnitude of earthquake. From this assessment, the consequences can be calculated. Most DOE sites are in areas of relatively low seismic activity; thus, damaging earthquakes are considered unlikely (California sites excepted). If a recent site-specific Probabilistic Seismic Hazard Analysis (PSHA) for a site is available, it should be verified because it would document the probabilistic analysis used to determine the ground motion levels and the recurrence intervals corresponding to the various sizes of earthquakes possible at the site. An example from the Pantex site (1998) (see **Figure 9.2**) shows the results of an analysis at the Pantex soil site plotted as peak horizontal ground acceleration (expressed in units of the acceleration of gravity, g = 32.2 ft/s^2) versus the annual probability of exceedance.

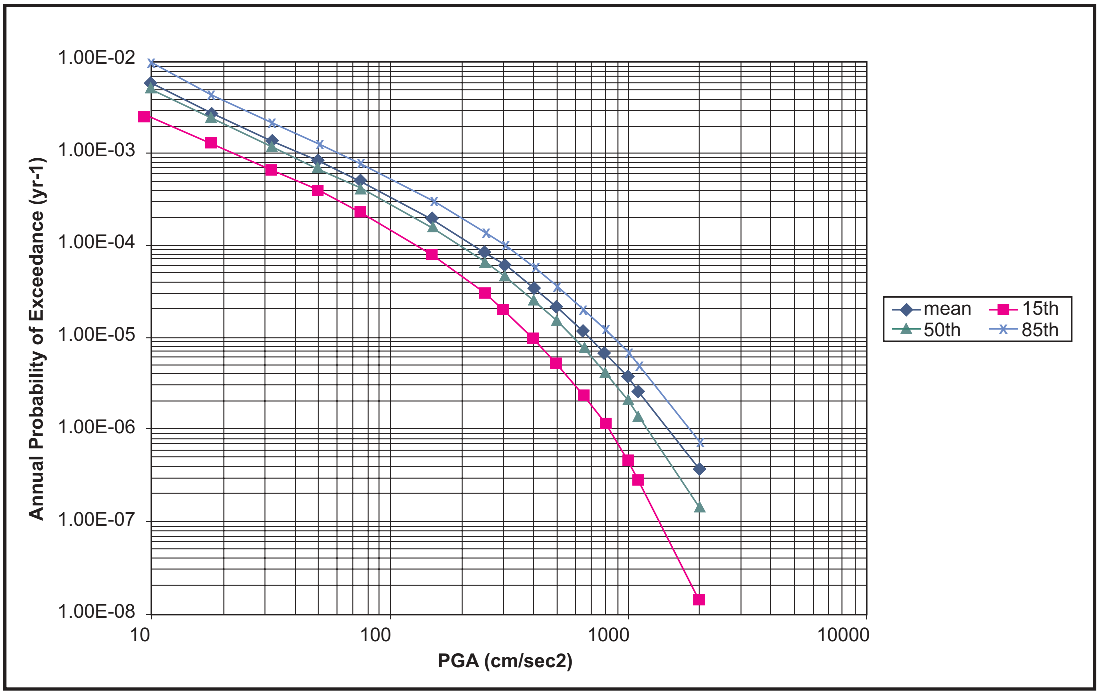

Figure 9.2 – Seismic hazard Curves for Pantex Soil Site

The earthquake problem arises from the possibility of associated malfunction of fans, dampers, filters, or other functional components of the system, or the rupture or structural damage of pressure-boundary components (ducts, housings, fan, or damper casings) when the system is subjected to rapid, violent, repetitive shaking or dislocations, either as a lumped mass or as parts of the assembly are independently dislocated from each other. Fortunately, the physical masses of air cleaning system components are generally small in relation to the massive concrete building elements to which they are anchored. If natural frequencies are greater than about 30 Hertz (Hz) and the parts of any single air cleaning unit are anchored to the same building element, a satisfactory earthquake-resistant air cleaning system can be achieved fairly easily. Problems arise when portions of the same air cleaning unit (e.g., different segments of the ductwork) are anchored to different building elements that can vibrate independently. The design and design qualification of earthquake-resistant air cleaning systems is discussed below.

Seismic Qualification of Air Cleaning Systems

External components of the system (e.g., housings, fans, etc.) should be rigidly anchored to major building elements (walls, floors, partitions). General seismic criteria for DOE facilities are provided in

DOE-STD-1020.[3] Similar information for facilities licensed by the U.S. Nuclear Regulatory Commission (NRC) is available in NRC Regulatory Guide 1.100, *Seismic Qualification of Electric and Mechanical Equipment for Nuclear Power Plants*,[9] and the NRC *Standard Review Plan*.[10]

The components should perform their intended functions and, if required by procurement specifications, should not sustain damage during or after they are subjected to excitations resulting from ground motions due to the DBE. This is demonstrated through a process called A-seismic qualification. This seismic qualification may be achieved following any one or a combination of the following methods described below: analysis, testing, and experience-based data. [Institute of Electrical and Electronic Engineers (IEEE) Standard 344, *Recommended Practice for Seismic Qualification of Class1E Equipment for Nuclear Power Generating Stations*,[11] provides excellent discussion of equipment seismic qualification procedures.]

Analysis

In general, analysis is a cost-effective tool to demonstrate seismic qualification. This method is applicable if: (1) the target component can perform its function as long as its structural integrity is maintained, and (2) the structural response of the target component can be reliably determined from analysis. In an analysis, structural responses such as stresses, strains, and displacements are calculated and compared with their respective allowable values, which are predetermined from material properties and component characteristics (e.g., clearance).

Analysis can be static, equivalent static, or dynamic. If the fundamental frequency of the component is high (e.g., greater than 33 Hz), amplification of motion through the component structure is usually negligible (i.e., the structure is considered rigid), and structural response can be determined by applying a static load (i.e., mass x 0 period acceleration) to the component. If the fundamental frequency of the component is unknown, the equivalent static (or static efficient) method can be applied in return for additional conservatism. In this method, an equivalent static force is calculated by multiplying the mass plus a static coefficient by the peak acceleration of the required response spectrum at the appropriate damping value (mass + static coefficient x peak acceleration). A damping coefficient of 3 percent is acceptable for all components except piping. Larger damping values may be justified.

A static coefficient of 1.5 has been established from experience to account for the effects of multifrequency and multimode response for linear frame-type structures. When the use of static or equivalent static analysis cannot be justified, structural responses are determined via dynamic analysis, although at additional cost. If the structural responses of the component are less than the respective allowable limits, the component will be considered qualified provided structural integrity alone demonstrates its functional operability.

Components, or the complete system, may also be qualified by structural analysis. The objective of the analysis is to predict the stresses, displacements, and deflections that will develop in critical parts of the component or system as a result of the specified input or time-history motion applied at the base (anchor points) of the component or system. The structural model is defined by the physical properties of the system to be analyzed; its mass, stiffness, and damping characteristics; and the time-varying accelerations, displacements, and relative velocity changes introduced at its foundation (anchor points).

If the mass of the component or system to be analyzed is small compared to the mass of the building element to which it is anchored, the supported component or system may be treated as a lumped-mass, multi-degree-of-freedom system with an input at its foundation (anchor points) equal to the motion of the building element to which it is attached (i.e., no interaction is assumed).

If the natural frequency of the item (component or system) is less than 0.2 Hz or more than 33 Hz, the item may be analyzed statically. The seismic forces on each element of interest are obtained by concentrating its mass at its center of gravity and multiplying by the appropriate maximum floor acceleration. Operating live and dead loads are added to the seismic loads in their appropriate directions. Displacements may be the limiting factor and must be accounted for in the design analysis. If the mass of the component or system is large compared to the mass of the building element to which it is attached, or if the item is not anchored rigidly to a building element, the interaction of the system on the building element must be considered and the system must be dynamically analyzed as a multi-degree-of-freedom mathematical model. The item (component or system) may be modeled as a series of discrete mass points connected by mass-free members, with sufficient mass points to ensure adequate representation of the item as it is supported in the building structure. The resulting system may be analyzed using the response spectrum or time-history analysis technique. A stress analysis should be made next, using the inertial forces or equivalent static loads obtained from the dynamic analysis for each vibration mode. If the response spectrum analysis technique is used, the seismic design stress usually may be obtained by taking the square root of the sum of the squares of the individual modal stresses. The absolute sum of the individual stresses should be taken, however, for closely spaced, in-phase vibration modes. In the analysis, each of the two major horizontal directions is considered separately and simultaneously with the vertical direction in the most conservative manner.

The analysis must include an evaluation of the effects of the calculated stresses on mechanical strength, alignment (if critical to proper operation of the air cleaning system), and operational (functional) performance of the components and the system as a whole. Maximum displacements at critical points must be calculated, and interference or plastic deformation must be determined and evaluated.

Testing

Either components or a complete system may be qualified by testing under simulated earthquake conditions. For a very few select cases where the component structure is simple and its potential failure mechanism is known (e.g., binding of shaft), a static test under the application of a conservative static force may be acceptable. Otherwise, dynamic testing is required. In such cases, the specimen to be tested is mounted on a biaxial or triaxial vibration generator in a manner that simulates the intended service mounting, and vibratory motion is applied independently to each of the perpendicular axes. Displacement induced in the vertical axis should be considered equal to at least 0.67 times the displacement in the major horizontal axis. The magnitudes of horizontal acceleration and displacement are those magnitudes for which the specimen is to be qualified. Where practicable, accelerations, displacements, and relative velocity change should be the maximum that the equipment can tolerate without loss of function. For fans, motors, dampers, and other operating equipment, sufficient monitoring devices must be located on the test specimen or assembly so that the maximum response is always obtained. Tests are made at several sinusoidal frequency steps that represent the range of frequencies for which the item is to be qualified at the natural frequency or at a number of predetermined frequencies, as discussed in the following sections.

Exploratory Vibration Test

An exploratory test should be made first, using a sinusoidal steady-state input of low magnitude to determine the presence and location of any natural frequencies within the range of 1 to 33 Hz, or the frequency range stated in the project specification. The test should be performed at a maximum sweep rate of 1 octave per minute and a minimum acceleration of 0.2 g, with dwell at resonance for at least 30 seconds. If no resonating frequencies are found, the item may be analyzed statically or may be tested via: (1) continuous sine test, (2) sine-beat test, or (3) multiple-frequency test. If one or more resonant frequencies are found in the exploratory test, the design of the component should, if possible, be modified to move the resonating frequencies above 33 Hz or to the maximum frequency at which the item is to be qualified. If the item cannot be readily modified, a performance test should be made at the resonant frequency and at an amplitude of at least the corresponding value for that frequency from the response spectrum for the building element of interest.

Continuous Sine Test. A continuous sinusoidal motion at the qualification frequency and the corresponding maximum acceleration is imposed for a length of time that is conservatively consistent with the service for which the item will be used. The item is operated during and after shaking to demonstrate its ability to perform its function. The test duration is specified in a detailed test procedure. The item is mounted on the vibration generator in a manner that represents its installation under service conditions. The vibratory forces are applied to each of the three major perpendicular axes independently unless symmetry justifies otherwise. Sufficient monitoring equipment must be used to evaluate performance accurately before, during, or after the test, depending on the nature of the item to be tested.

Sine-beat Test. This test is conducted by inducing sine beats of peak acceleration corresponding to those for which the item is to be qualified, at the frequency and amplitude of interest. The duration and amplitude of the beat for each test frequency must be chosen to produce a magnitude equivalent to that produced by the particular building-element response, with appropriate damping factors. For a test at any given frequency, 5 beats of 10 cycles per beat are normally used, with a pause between the beats so that no significant superposition of motion will result. Mounting of equipment and instrumentation shall be per approved methods.

Multiple-Frequency Test. Multiple-frequency testing provides a broadband test motion that is particularly appropriate for producing a simultaneous response from all modes of multi-degree-of-freedom systems. The test may be performed by applying a random excitation to the component (simultaneously in each of the three orthogonal directions), and adjusting the amplitude of the excitation in a frequency band not exceeding 1/3 octave. The resulting test response spectrum should envelop the required response for qualification.

Experience-based Data

In a similarity analysis, the dynamic and physical characteristics of the component and the required response spectrum are compared with those for a component that has already been qualified. This requires the availability of a database of qualified components. Engineers who are familiar with the component design and functional requirements should establish the dynamic similarity. Databases derived from past qualification and earthquake experience are captured in DOE/EH-0545.[12]

Combination Method

By combining different elements of the various qualification methods, a hybrid method may be developed that will make the qualification practical and potentially highly cost effective. For example, a system may be too large for a shake table, but may contain sensitive components that require qualification by testing. In such cases, the system may be structurally analyzed to determine the motions at the component locations, and these motions (e.g., expressed as response spectra) can be used as the required input motion for qualification of the components via dynamic testing. Similarly, by supplementing experience data with a simplified structural analysis, a powerful, cost-effective qualification method may be devised. Similar application has been proposed and reviewed for advanced light water reactors.[13, 14] This proposal includes duct qualification using a design-by-rule method—simple static analysis of linear duct models.

Documentation

The selected method(s) of seismic analysis, mathematical models and their natural frequencies, and input time-histories, as well as corresponding response spectra, damping values, and allowable stress criteria, must be shown in a qualification report together with the results of all tests and analyses. If the similarity analysis method is used, the comparison, including the experience data, should be documented. The documentation must provide detailed information that demonstrates the item meets specified requirements when subjected to the seismic motion for which it is to be qualified. A licensed professional engineer qualified in the analysis of such systems should certify the analytical and test results, including the operational data.

All instruments, including the heater, damper, and fan controls, should meet the requirements of IEEE 323,[15] *Standard for Qualifying Class 1E Electrical Equipment for Nuclear Power Generating Stations*, and IEEE 344,[11] *Recommended Practice for Seismic Qualification of Class 1E Equipment in Nuclear Generating Stations*. NRC Regulatory Guide 1.100,[9] *Seismic Qualification of Electrical Equipment for Nuclear Power Plants*, and NRC Regulatory Guide 1.105,[16] *Instrument Set-points*, are also applicable. Instrument controls and control panels should meet the design, construction, installation, and testability criteria in Section IA of ASME Code AG-1.[17]

The design, construction, and test requirements of Section BA of ASME Code AG-1[17] apply to Safety Class and Safety Significant systems' fans and motors. All Safety Class and Safety Significant systems must be built to ASME AG-1. Motors must meet the qualification requirements in IEEE 334,[18] IEEE 323,[15] and IEEE 344.[11] The structural design of Engineered Safeguard Feature (ESF) air cleaning systems must consider the service conditions that the components and housing may experience during normal, abnormal, and under accident conditions. The air cleaning system must remain functional following dynamic loading events such as an earthquake. The structural design of all safety class air cleaning systems, including all components, must be verified by analysis, testing, or a combination of both. Qualification criteria are contained in Section AA of ASME AG-1.[17] The design requirements for determining housing plate thickness, stiffener spacing, and size are contained in ASME-AG-1,[17] Sections AA, HA, and SA.

Equipment Qualification

The fundamental reason for qualifying equipment is to provide adequate levels of safety for the life of the facility. Equipment qualification is often a requirement for an operating license, and is designed to provide reasonable documented evidence that the system will satisfy the following three characteristics:

- Qualification goals may be generic or application specific. Generic qualification is probably best for the original equipment manufacturer because it enables use of the qualified item for a variety of applications. This type of qualification program requires test parameters that may exceed the needs of the current program, but are not extreme enough to reduce the chances of a successful qualification. An application-specific qualification limits the use of the component or system to those having the same or reduced environmental stresses.

- A mild environment qualification can usually be accomplished without determining a qualified life (per Section 4 of IEEE 323),[15] whereas a harsh environment program usually requires testing to verify performance under extreme accident conditions. Simulated aging is necessary to arrive at "end-of-life conditions" prior to accident condition testing. The walkdown requirements will be per DOE/EH-0545.[12]

- It is necessary to determine whether the components are designated as safety-related or non-safety-related. A non-safety-related item can often be excluded from the qualification process when it can be shown that a failure of that component would not adversely affect the safety function of the overall equipment.

The qualification plan must be developed in accordance with IEEE 323,[15] and must include a determination of the qualification method, listing of the environmental service conditions, description of any required aging programs, protocol of the test sequence, and a definition of the accident test profiles.

An aging program might consist of stressors such as thermal aging, mechanical/cyclic aging, radiation exposure, and mechanical vibration. All of these are designed to simulate conditions that would be encountered during the expected life of the test specimen prior to its undergoing an accident condition or test such as seismic pressure.

The requirements of IEEE 323[15] must be followed when preparing a qualification plan. The entire facility should be considered when designing an air cleaning system. Two questions must be addressed: (1) how can the system under design affect other systems and areas, and (2) how can the remainder of the facility affect this system?

There are system characteristics that apply to all air cleaning systems regardless of specific function or nature of the facility. One is that they must be capable of continuing to meet quantifiable test criteria to provide verifiable evidence of maintaining acceptance limits over the life of the installation. Therefore, an ability to maintain and test systems is as important as the ability of those systems to meet the initial performance criteria. The factors described in the following sections apply to all systems and must be addressed.

9.2.3 Volcanic Eruption

Sites, such as Hanford and Idaho National Engineering and Environmental Laboratory (INEEL), with a potential for volcanic eruption and the resulting ashfall must consider the consequences of such an event (e.g., the Hanford Reservation and the 1980 Mount Saint Helens eruption). The authorization basis documents should discuss the potential for such events, including the magnitude and duration of the ashfall event. In the event of a volcanic eruption, information and advanced notification should be available on the predicted time the ashfall will arrive. At Hanford, an eruption in the Cascade Mountains is predicted to yield an ashfall duration of approximately 20 hours. For one Hanford facility, this would require changing 95 percent intake filters every 4 hours.

9.2.4 Tornado

Structural damage from a tornado can arise from missiles, wind, or atmospheric pressure changes that occur when the funnel cloud passes over the building. Assuming the building is constructed to be tornado-resistant, damage to the air cleaning system will result mainly from pressure changes that occur in the stack, ducts, and building spaces surrounding the ducts. The design basis tornado hypothesizes that pressure on the building will decrease over time, remain at the depressed level, then return to normal. Because the operation of a ventilation system substantially relies on stable atmospheric conditions to maintain pressure differentials between the confinement zones of a building and to prevent the release of contaminants, it is likely that system upset, overrunning or reversal of fans, or even reverse flow could occur due to atmospheric depressurization, and failure of the dampers could exacerbate the condition. On the other hand, stack(s), ducts, and fans would attenuate the depressurization. The effects of high airflow rates, large pressure differentials, and sustained pressurization or depressurization on air cleaning systems and components are relatively unknown. The dynamic effects of tornadoes and pressure transients on air cleaning and ventilation systems need to be considered, and methods for describing, analyzing, and calculating the forces to which these systems would be subjected, along with their response to these forces, need to be mathematically modeled and developed. For further information on tornadoes, refer to Lawrence Livermore National Laboratory's 1985 study on the subject.[19]

Wind and tornadoes can potentially damage buildings and other structures in a variety of ways. Loose objects picked up by the wind can be turned into missiles that can penetrate a structure. The roof covering and siding material can be blown off the building. Winds passing sharp corners of the building tend to separate from the building, causing an outward pressure. In general, the windward surfaces of the building experience an inward pressure, and all other exterior surfaces experience an outward pressure. Likewise, the internal air pressure can rapidly change if air can pass into or out of a structure through openings such as those caused by a wind-driven missile. If the opening is on the windward side of the building, the internal pressure increases, reinforcing the outward pressure of the outside air on the other surfaces. If the opening is on any other side of the building, the internal pressure decreases, counteracting the outward pressure of the outside air. In any case, if the atmospheric pressure change (APC) exceeds the structural strength of the building, the building can suffer significant damage. The APC is especially important in tornadoes. See **Table 9.2** for design APC.

Table 9.2 – Summary of Minimum Wind Design Criteria per DOE-STD-1020 [3]

	Performance Category			
	1	*2*	*3*	*4*
Straight Wind and Hurricane				
Annual Probability of Exceedance	2×10^{-2}	1×10^{-2}	1×10^{-3}	1×10^{-4}
Importance Factor	1.0	1.0	1.0	1.0
Missile Criteria	NA	NA	2 × 4 timber plank 15 lb at 50 mph (horizontal); maximum height 30 ft.	2 × 4 timber plank 15 lb at 50 mph (horizontal); maximum height 50 ft.
Tornado				
Annual Probability of Exceedance	NA	NA	2×10^{-5} (see note)	2×10^{-6} (see note)
Importance Factor	NA	NA	1.0	1.0
APC	NA	NA	40 psf at 20 psf/sec	125 psf at 50 psf/sec
Missile Criteria	NA	NA	2 × 4 timber plank 15 lb at 100 mph (horizontal); maximum height 150 ft at 70 mph (vertical). 3-in.-diameter standard steel pipe, 75 lb at 50 mph (horizontal); maximum height 75 ft at 35 mph (vertical).	2 × 4 timber plank 15 lb at 150 mph (horizontal); maximum height 200 ft at 100 mph (vertical). 3-in. diameter standard steel pipe, 75 lb at 75 mph (horizontal); maximum height 100 ft at 50 mph (vertical). 3,000 lb automobile rolls and tumbles at 25 mph.

Note: These are the minimum values for APC and tornado missile criteria. Tornado hazard curves developed by Lawrence Livermore National Laboratory and applicable site-specific tornado design values should be used for DOE sites.

High-speed winds can be classified as "straight," "tornado," or "hurricane." Straight winds are nonrotating winds that cover a wide area, typically many tens of miles across, and can reach speeds exceeding 100 miles per hour (mph). They are generally associated with thunderstorms, mesocyclones, and orographic effects. Tornadoes are violently rotating winds that are highly localized, a few miles or less across, and can reach speeds in excess of 200 mph. They can accompany severe weather events such as thunderstorms and even hurricanes. Hurricanes are very large-scale rotating winds, typically hundreds of miles across. Hurricanes are important for coastal DOE sites, but not for ones interior to the continent, as hurricanes typically do not reach inland more than a few hundred miles. For any type of wind, whether straight or rotating, a building is small compared to the size of the area affected by the wind, and the response of the building is the same. A distinction is made between different types of wind because of the differences in the hazard curves, which show the wind speed as a function of the annual probability of exceeding that wind speed. For straight winds and tornadoes design speeds, see Table 9.2, which is taken from DOE -STD- 1020.[3]

The performance goals established for PC 1 and PC 2 are met by model codes or national standards. Since model codes specify straight winds at probabilities greater than approximately 1×10^{-2}, tornado design criteria are specified only for SSCs that are designated as PC 3 and higher, where hazard exceedance probabilities are less than 1×10^{-2}.

All wind speeds are 3-second gusts, which is consistent with the American Society of Civil Engineers (ASCE 7-98[20]) approach. Design tornado wind pressures on SSCs should be used with Exposure Category C, regardless of the actual terrain roughness. For SSCs in PC 3 and PC 4, it is important to determine whether tornadoes should be included in the evaluation based on geographical location and historical tornado occurrence records. Site-specific tornado hazard assessments are available for most DOE sites, and a quantitative approach should be taken. Details of the approach are presented in Appendix D of DOE-STD-1020.[3]

The weakest link in the load path of an SSC will determine the adequacy or inadequacy of the performance of the SSC under wind load. As a result, evaluation of the existing SSCs normally should focus on the strengths of connections and anchorages, as well as the ability of the wind loads to find a continuous path to the foundation or support system.

Failure caused by wind and tornado is a progressive process, initiating with an element failure. Once the initial element failure occurs at the lowest calculated wind speed, the next event in the failure sequence can be anticipated. All obvious damage sequences should be examined for progressive failures. Once the postulated failure sequences are identified, the SSC performance is compared with the stated performance goals for the specified PC. Damage to facilities can arise from both wind impacts (pressure changes) and airborne missiles driven by the wind. The PCs for facilities are related to the exceedance probabilities for the NPH events, as discussed above. In the case of wind, the PCs are also related to missile penetrations. These are given in DOE -STD- 1020[3] and are summarized in Table 9.2.

Table 3-3 in DOE-STD-1020[3] lists recommended "straight wind" missile barriers for SSCs categorized as PC 3 and PC 4. Similarly, Tables 3-4 and 3-5 of this standard show recommended barriers for "tornado" missiles for PC 3 and PC 4, respectively. Although wind pressures, APC, and missile impact loads can occur simultaneously, the missile impact loads can be treated independently for design and evaluation purposes.

9.2.5 Flood

In accordance with DOE Order 420.1A,[1] flood design and evaluation criteria seek to ensure that safety SSCs at DOE sites satisfy the performance goals described in DOE-STD-1020.[3] The determination of the design basis flood (DBFL) that must be considered in flood design for design of civil engineering systems such as structures, site drainage, roof systems, and roof drainage is addressed in DOE-STD-1023.[7] The criteria specified in terms of the flood hazard input, hazard annual probability, design requirements, and emergency operation plan requirements are described in Chapter 4, Table 4-1, of the DOE-STD-1020.[3] The mean hazard probability is 2×10^{-3} for PC 1 SSCs, 5×10^{-4} for PC 2 SSCs, 1×10^{-4} for PC 3 SSCs, and 1×10^{-5} for PC 4 SSCs.

Flooding occurs when the rate of water entry into an area or facility exceeds the removal rate. According to DOE-STD-1020,[3] both storm sewers and open channels must be sized to accommodate runoff from the 25-year, 6-hour storm. The potential effects of larger storms (up to the 100-year, 6-hour storm) should also be considered. Flooding is important because it can damage facilities, spread contamination, and potentially lead to a criticality. Flooding may be caused by locally heavy rains as well as by distant rains that cause nearby rivers to overflow. An accident analysis should examine the statistics of both heavy rain and river flooding. The water load on roofs is also a concern during periods of heavy precipitation. If drainage is blocked, ponds could form on flat roofs and possibly cause structural failure. For example, a pond 1,000 square feet in area (e.g., 25 by 40 feet) and 2 inches deep weighs over 5 tons. This could be enough to breach a roof.

Because floods have a common-cause impact on SSCs located in proximity to one another, the design basis for the most critical SSC may govern the design for other SSCs or for the entire site. Therefore, it may be more realistic economically and functionally to develop a design strategy that satisfies the performance goals of the most critical SSC and, simultaneously, that of other SSCs. Hardening a site by constructing a levee system might be more feasible for a specific site, thereby protecting all SSCs.

Flood hazard assessment consists of identifying sources of flooding (e.g., rivers, lakes, local precipitation) and the individual associated flood hazards (e.g., hydrostatic forces, ice pressures, hydrodynamic loads). On the rare occasion, an individual SSC or the entire site may be impacted by multiple sources of flooding and flood hazard. DOE-STD-1023[7] presents guidelines for conducting a probabilistic flood hazard assessment. As a part of such a probabilistic assessment, an evaluation of uncertainty is also performed. The DFB events that must be considered are shown in **Table 9.3**.

Table 9.3 – Design Basis Flood Events*

Primary Hazard	***Event Combination to be Considered with Primary Hazard***
River Flooding	1 peak flood evaluation 2 wind waves
Dam Failure	3 ice forces 4 erosion, debris, etc. 1 all models
Local Precipitation	2 wind waves 3 erosion, debris, etc.
Storm Surge, Seiche (due to hurricane, seiche, squall lines, etc.)	1 site runoff 2 ponding on the roof 3 rain and snow
Levee or Dike Failure	1 tide effects
Snow	1 snow and drift – roof
Tsunami	1 overtopping 2 wave action 1 tide effects

* For event combinations, see DOE-STD-1020[3].

Limited flood hazard assessments for some DOE sites have been conducted. Flood loads are assessed for the DBFL on an SSC-by-SSC basis. If the hazard annual probability for a primary flood hazard is less than the design basis hazard annual probability for a given PC, as mentioned above, it need not be considered a design basis event. For example, if the hazard annual probability for PC 1 is 2×10^{-3} per year, failure of an upstream dam need not be considered if it can be shown that the mean probability of flooding due to dam failure is less than 2×10^{-3}.

The strategy of hardening an SSC or site and providing emergency operation plans is secondary to siting facilities above the DBFL level because some probability of damage does exist and, as a result, SSC operations may be interrupted. Flood mitigation systems (e.g., exterior walls, flood-proof doors, etc.) must be considered in accordance with the requirements specified in the applicable regulations.

Unlike design strategies for seismic and wind hazards, it is not always possible to provide a margin in the flood design of an SSC. When a site is inundated, it will cause significant disruption. Under these circumstances, there is no margin, as the term is used in the structural sense. Therefore, the SSC must be kept dry, and operations must not be interrupted to satisfy the performance goals. Refer to DOE-STD-1020[3] for further details.

9.2.6 Lightning

DOE facilities have been struck by lightning numerous times, causing equipment damage and adversely affecting facility safety and operations. At any given time, some 2,000 thunderstorms are occurring around the world, creating approximately 100 lightning strikes every second.

Lightning is a high-current electrical discharge in the atmosphere with a path length typically measured in km. Electrical currents from lightning range from one to hundreds of kA. The upper one-percentile current (99 percent of all lightning flashes have a lower current) has been determined to be about 200 kA; this is identified (by lightning scientists) as the severe threat level. The median (50th percentile) value lies in the 20- to 30-kA range. Lightning can travel at 35,000 to 100,000 km/sec.

It is important to assess the severity and frequency of lightning strikes for several reasons. Lightning can cause a fire, a breach in a building, sensor failures or false alarms, communications and electronic component failures, and power failures that give rise to other system failures.

Lightning data for the United States is given in the ***Lightning Protection Code***, National Fire Prevention Association (NFPA) 780[8] and a yet to be published DOE Standard entitled ***Lightning Hazard Management Guide for DOE Facilities***. The probability of lightning striking a particular object located on the earth (ground) is found by multiplying the object's lightning-attractive area by the local ground-flash density (lightning strikes to ground per square kilometers per year).

For flat terrain without buildings or other structures, the probability of a lightning strike is the same throughout the area. Structures, however, especially tall ones such as stacks, water towers, and power poles, attract lightning and increase the probability of a strike at those locations, thus decreasing the probability at other nearby locations. These taller structures thus provide some protection for the shorter structures nearby. The "circle of protection" offered by a tall structure depends on its height and on the peak current in the lightning strike. The higher the structure, the larger the circle of protection. As a rule of thumb, for a medium-current strike, the radius of the circle of protection is equal to the height of the grounded lightning attractor. This is not valid for all lightning, however, as the radius of the circle of protection also depends on the current in the lightning strike—the larger the current, the larger the circle of protection. A building that may be protected by a larger nearby structure for a high-current lightning strike may not be protected from a lower-current strike. Elevated conducting wires that are horizontal and grounded can also protect facilities below them. Power lines, therefore, could be considered to provide some protection for certain buildings. In general, the stacks, water towers, and power lines of a site offer protection for only a small portion of a site.

Lightning strikes are of greatest concern to facility managers during the late spring, summer, and early fall. A review of the DOE Occurrence Reporting and Processing System database revealed that 89 percent of lightning-related events occurred during the second and third quarters of the year.

Lightning protection equipment can degrade over time or after suppressing numerous strikes, and can suddenly fail without warning. Deficiencies such as failed surge arresters or degraded insulation can cause ground faults and electrical distribution system failures. If NFPA-specified lightning protection is provided, the likelihood of lightning damage is, of course, greatly reduced.

Risk analysis should consider the consequences of a lightning strike and its likelihood of occurrence. DOE sites such as Sandia National Laboratories, the West Valley Site, Fernald, Hanford, the Savannah River Site, and Pantex are a few of the sites where damaging lightning has been reported. The risk for facilities that contain high-energy systems or components such as explosives (e.g., Pantex) would be elevated because of the potential damage from a detonation. Instruments and control systems at many facilities are also vulnerable to damage and lightning-induced malfunction. Brief over-voltages caused by lightning strikes and manmade transient voltages can immediately destroy low-power solid state components such as computer chips, or can weaken them to the point that they fail months after a lightning event.

Not every lightning strike is damaging. The amount of damage depends on the amount of current in the return strike, the magnitude of any continuing current, and the susceptibility of the target to lightning damage. Electronic equipment, for example, is more susceptible to failure from a lightning strike than a concrete pad is to fire damage. The main danger to a site from lightning is from fire, as fire can potentially lead to a release of radioactive or chemically hazardous material. Lightning-induced fire can be caused in several ways. Examples are listed below.

- Fire can be started in dry combustible material such as a wooden structure or dry grass by the weak "continuing current" between lightning strikes. About 20 percent of lightning strikes have a continuing current large enough to start such a fire. The magnitude of the peak current is not relevant here, as the return strike is too brief to start a fire.

- A lightning strike on a building can induce large currents in the electrical wiring in the building. It is possible that the high current will cause a breakdown in both the insulation on the wiring and the insulation provided by the air, causing an electrical arc to form between the wire and a nearby grounded object. A followon current from the electrical circuit would then sustain the arc and could continue for many seconds or even minutes, long after the lightning strike is gone. Combustible material in the immediate vicinity could then be ignited. Although arcing is more likely with larger-current strikes, any magnitude of strike could produce it. To be conservative, all lightning strikes on a building should be considered.

- A lightning-induced spark or voltage surge can initiate a fire. Such fires have been observed in reinforced concrete facilities when lightning struck power lines several miles away.

- Damage to electronic components from lightning strikes can create spurious control system signals. The potential for such signals to initiate the release of radioactive or chemically hazardous materials should be evaluated.

9.3 Deep-Bed Sand Filters

Some of the following material is taken directly from ERDA 76-21.[21] Although dated, it is still relevant today, and has been updated where appropriate.

Deep-bed sand (DBS) filters have been used in the ventilation and process exhaust systems of radiochemical processing facilities since 1948. The major attractions of DBS filters include large dust-holding capacity, low maintenance requirements, inertness to chemical attack, high heat capacity, fire resistance, and the ability to withstand shock loadings and large changes in airstream pressure without becoming inoperative. The disadvantages of DBS filters include high capital cost; large area; high pressure drop; high power costs; and uncertainties in selection, availability, grading, and handling of suitable sands; and issues with disposal of the spent unit.

DBS filters are deep (several feet thick) beds of rock, gravel, and sand, constructed in layers graded with about two-to-one variation in granule size from layer to layer. Airflow direction is upward, and granules decrease in size in the direction of airflow. A top layer of moderately coarse sand is generally added to prevent fluidization of finer sand. The rock, gravel, and sand layers are positioned and sized for structural strength, cleaning ability, dirt-holding capacity, and long life. **Figure 9.3** shows the cross-section of a typical DBS filter. Ideally, the layers of larger granules, through which the gas stream passes first, remove most of the larger particles and particulate mass, and the layers of finer sands provide high-efficiency removal. Below the fixed bed of sand and gravel is a course of hollow tile that forms the air distribution passages. The filter is enclosed in

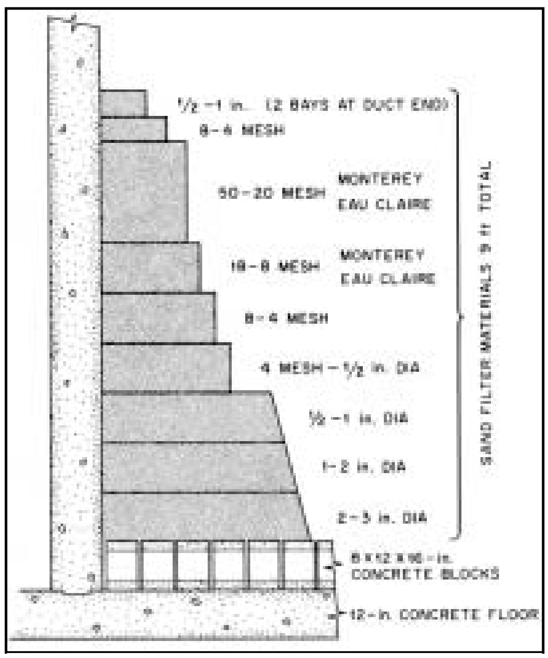

Figure 9.3 – Section through Typical Sand Filter

a concrete-lined pit. The superficial velocity is around 5 fpm, and the pressure drop across 7 layers, sized from 3 1/2 inches to 50 mesh, is from 7 to 11 in.wg. Collection efficiencies up to 99.98 percent [determined by in place test with polydispersed 0.7-number mean diameter (NMD) test aerosol have been reported.[22] The approximate capital cost of a sand filter is $300 per cfm in 2001 dollars.

A removal efficiency approaching that of a single HEPA filter has been claimed for DBS filters if the proper sands are used and the contact path is long enough. Efficiency tests of DBS filters can only be made using polydispersed test aerosols with an NMD of about 0.7 μm and the in-place test procedures described in Chapter 8. True efficiency tests of HEPA filters, on the other hand, are made with a monodispersed test aerosol with an NMD of 0.3 μm. In addition, tests of very large units, such as DBS filters, are often made under conditions that sometimes yield results that are difficult to interpret. For these reasons, although the efficiency of DBS filters approaches that of HEPA filters, it should not be assumed that the efficiency of DBS filters for submicron particles is actually equivalent to that of HEPA filters.

DBS filters have received renewed interest in the past few years because of increased concern about the effects of natural phenomena (earthquake, tornado), fire, and explosion, and because procurement and maintenance costs of alternative air cleaning methods have increased substantially. DBS filters are characteristically one-of-a-kind designs. They are literally constructed in the field as the gravel is positioned and the sand is poured in place. No standards exist, so most of the information for new designs must come from reports of previous applications. A bibliography and review of DBS filters built prior to 1970 was prepared by Argonne National Laboratory.[23]

Following initial installation of a DBS filter at DOE's Hanford Site, nine others were installed at Hanford, Savannah River, and the Midwest Fuel Recovery Plant at Morris, Illinois. All but one[22] of these were designed for cleaning ventilation air from fuel reprocessing facilities, and only five (all at Savannah River) are currently used for this purpose. There is a DBS filter in the roof of the Zero Power Research Reactor[24] at Idaho Falls, but it is for emergency exhaust cleanup only and is not operated under normal conditions. Details of existing U.S. DBS filters are given in **Table 9.4**. Properties of sands and aggregates used as the filtration media of these filters are given in **Table 9.5**.

9.3.1 DEEP-BED SAND FILTER DESIGN

A rough approximation of the collection efficiency of sand, on an activity basis, is given by the following equation:[21]

$$\eta = -\exp\left(-KL^{1/2}V^{-1/3}D^{-4/3}\right) \qquad (9.1)$$

where:

η = fractional collection efficiency on a radioactivity or mass basis

L = depth of fine sand, feet

V = superficial gas velocity, fpm

D = average sand grain diameter, inches

K = proportionality factor

[Note: The values of L, V, and D vary with sands from different sources of the same mesh size and must be determined experimentally for any given sand.]

Table 9.4 – Dimensions and Operating Data of Existing U.S. Deep-Bed Sand Filters

DBS Filter No. [a]	Plan Dimensions [b] (ft)	Design Flow (cfm)	Design Superficial Velocity (fpm)	Design Pressure Drop (in.wg)	Year of Initial Operation	Present Status of DBS
1	108×46	25,000	5.0	5.0	1948	Standby
2	108×46	25,000	5.0	7.0	1948	Standby
3	96×96	40,000	4.3	10.0	1950	C
4	85×85	40,000	5.5	12.0	1951	Active
5	240×100	20,000-30,000	4.8	~10.0	1954	Active
6	240×100	20,000-30,000	4.8	9.2	1955	Active
7	360×100	210,000	5.8	~10.0	1975	Active
8	360×100	210,000	5.8	~10.0	1976	Active
9	140×103	74,000	5.1	Not available	1974	Active
10	72×78	32,000	5.7	Not available	1974	C
11	50 to 62.5 (diameter)	*E*	*D*	Not available	1968	Active
12	120 x 192	115,000	5.0	8.0	1995	Active
13	Not available					
14	Not available					

[a] Filter identification:

1. T Plant, Building 291-T, Hanford West Area, Richland, WA.
2. B Plant, Building 291-B, Hanford East Area, Richland, WA.
3. U Plant, Building 291-U, Hanford, Richland, WA.
4. Redox Facility, Building 291-S, Hanford, Richland, WA.
5. F Area, Building 294-F, Savannah River Site, Aiken, SC.
6. H Area, Building 294-H, Savannah River Site, Aiken, SC.
7. F Area, Building 294-1F (new), Savannah River Site, Aiken, SC.
8. H Area, Building 294-1H (new), Savannah River Site, Aiken, SC.
9. SRL, Building 794-A, Savannah River Laboratory, Aiken, SC.
10. Midwest Fuel Recovery Plant (MFRP),[c] Morris, IL.
11. Zero Power Plutonium Reactor Facility, Argonne National Laboratory, Idaho Falls, ID.
12. S Area, Defense Waste Processing Facility, Savannah River Site, Aiken, SC
13. F Area, Building 235-F, Savannah River Site, Aiken, SC.
14. Pit Conversion and Disassembly Facility (PCDF), Savannah River Site, Aiken, SC (under construction).

[b] Inlet side shown first, outlet side italicized.

[c] MFRP is not engaged in reprocessing, only storage; sand filter is active.

[d] This is an emergency relief system.

Values for the proportionality constant, *K*, for several sands tested at Hanford are:

Type of Sand	K
Hanford	0.053
AGS flint	0.045
Rounded grain sand (Ottawa, Eau Claire, Monterey)	0.035

Collection efficiency on a radioactivity basis gives a higher number than the collection efficiency on a count basis, as reflected by the test aerosol test, because larger, more easily collected particles may carry more radioactivity and bias the analysis to give greater value to larger particles. The relationship between count and activity collection efficiency cannot be determined without accurate information on aerosol size distribution and the relationship of aerosol size to radioactivity.

Table 9.5 – Properties of Sands and Aggregates Used in Existing U.S. Deep-bed Sand Filters

Property	Filter No. [a]									
	1	2	3	4	5	6	7	8	9, 12	10
Depth of bed, feet	9	8.5	8	8	8	8	7.5	7.5	7.5	8
Number of layers	9	8	7	7	7	7	6	6	6	
Depth of layers (inches)										
Granule size range, mesh (unless inches noted)										
Layer A 2-3 inches	12									
2 1/2-1 1/4 inches		12								
3-1 1/4 inches					12	12	12	12	12	
3-1 inches			12	12						18
Layer B 1-2 inches	12									
1 3/4-5/8 inches		12	12	12						12
1 1/2-5/8 inches					12	12	12	12	12	
Layer C 1-1/2 inch	12									
3/4 inch ~ 6		12	12	12						
5/8-1/4 inch					12	12	12	12	12	
Layer D 1/2 inch -4	12									
3/8 inch -3										12
Layer E 4-8	12	6	6	6	6	6	6	6		6
1/4 inch -8									6	
Layer F 8-20	12	12	12		12	12	12	12	12	6
8-18				12						
Layer G 20-40										
30-50					36 [c]	36	36	36	36	
20-50			36	36 [c]						36

[a] See Table 9.4 for locations corresponding to number.
[b] Cable and wire mesh of footnote a catenary cross-section support, deep bed.
[c] Removed 12 inches from G layer, July 1972, to reduce pressure drop.

The approximate void fraction of a sand bed is generally about 0.4. Sand permeability tests have shown that intense vibration can cause extreme compaction, resulting in near doubling of the pressure drop. [25, 26, 27] Factors that must be considered include the effects of compaction, steam injection, relative humidity, and velocity change on efficiency and pressure drop. Besides permeability and filtration requirements, the sand must be abrasion- and fracture-resistant and must resist corrosion from the fumes likely to be present in the exhaust airstream.

Filter life is determined by the increase in pressure drop and the decrease in gas flow caused by the collection of solids within the sand bed. Filter life can be significantly reduced if solids collection is concentrated in small fractions of the bed or on the finer sand. Uniform concentration of coarse aggregate layers upstream of the fine sand layer tends to maximize filter life.

Clogging of DBS filters is aggravated by local decreases in porosity at the interfaces between graded layers. The mixing of aggregates (sand, gravel) at the interfaces usually results in a lower void fraction at the interface than if no mixing is permitted. The extent of reduction in void fraction depends on the characteristics of the aggregates and on the technique used to charge them into the filter bed. The lowest layer may require hand placement for the first few inches so that no rocks fall through the openings in the distribution blocks. Significant improvement in filter life can be obtained by careful attention to loading.

The DBS filter housing is a poured concrete structure, located partially underground, with walls capable of withstanding the DBE without cracking and the design basis flood without leaking. The floor has channels for distributing the incoming air and is covered by the special hollow block shown in the view of the empty sand filter. The floor and the distribution system must bear the weight of the sand column above it. With corrosion and aging, withstanding this weight has been a problem in some DBS filters. The floor should be sloped to a drain and have a built-in capability for drainage if it becomes necessary. It is often prudent not to connect the drain line so that a determination of what to do with the drainage can be made after the event if flooding occurs. The filter should be on the suction side of the fan so that it is negative to the atmosphere and all leakage is inward. See **Figure 9.4**.

Figure 9.4 – Interior of New Sand Filter at Savannah River Laboratory Before Loading of Sand and Aggregate

When a DBS filter has been used in series with HEPA filters at plutonium facilities, it should be located upstream of the HEPA filters. An isometric of this filter is show in **Figure 9.5**.

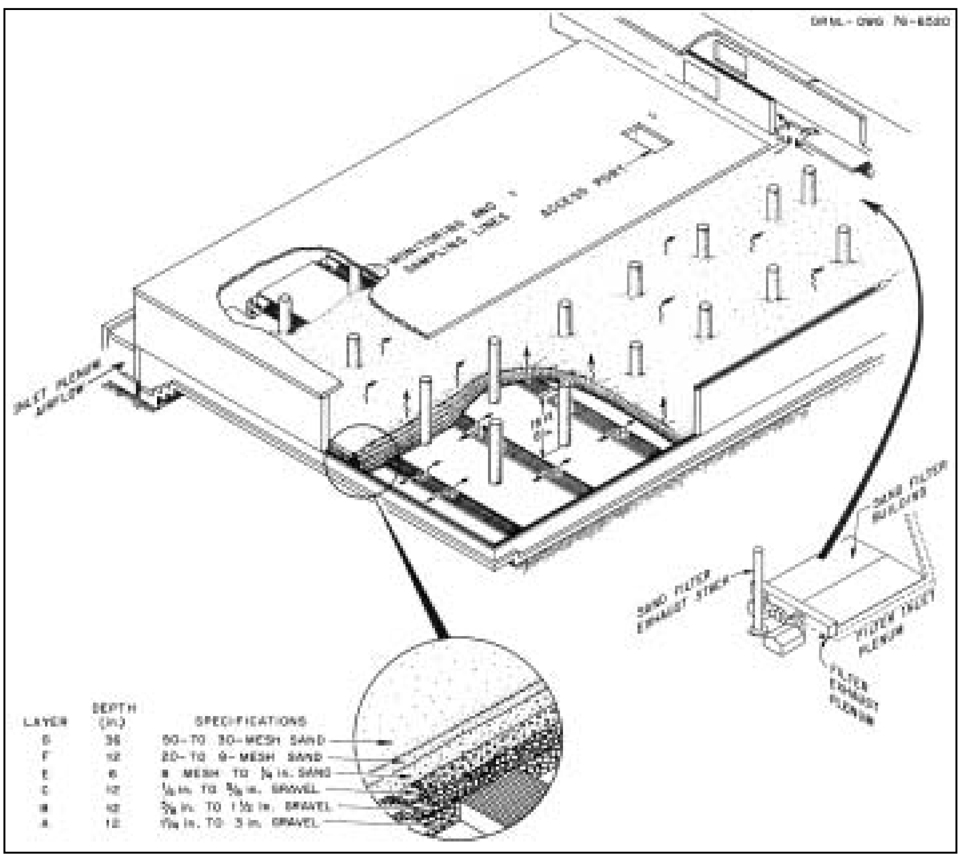

Figure 9.5 – Overall Isometric View and Details of New Sand Filter at Savannah River Laboratory

9.3.2 Deep-Bed Sand Filter Plugging

Some filters have experienced plugging at low dust loadings. In one case, the plugging was caused by moisture entering through cracks in the concrete sidewalls of the unit. In another instance, plugging was caused by crystal growth in the filter media fines, probably due to a reaction of nitric acid vapors from the process building with calcite, with dolomite present in the original sand, and with cement dust generated by severe erosion and acid attack on the concrete entry ducts and support structures.

9.3.3 Spent Media Disposal

Deactivation of existing filters is generally accomplished by sealing and abandoning the filter. Spent media are stored in place within the unit. The total unit is replaced by a new filter located close by. Present Government regulations for radioactive solid waste, though unclear, may rule out such in-place disposal in the future. If the material were handled as high-level radioactive waste, each 1,000-cfm capacity of filter would require about two hundred 55-gallon drums for disposal. A detailed analysis of filter decommissioning was performed for the PDCF Project at the Savannah River Site. This is currently the best available information on the cost of decommissioning.

9.3.3.1 Burial in Place

Burial in place (or entombment) for DBS filters is feasible and could be economical if provisions are applied during initial design of the filters to ensure that the walls, floors, and roof integrity are sufficient to satisfy the requirements of 10 CFR 61,[28] and the requirements of other regulatory agencies such as the U.S. Environmental Protection Agency and South Carolina Department of Health and Environmental Control. To ensure that the selected location of the DBS filter can be licensed, the location must be suitable for near surface disposal in accordance with 10 CFR 61,[28] Subpart D. The primary emphasis in disposal site suitability is given to isolation of the waste. This involves evaluation of long-term impacts and disposal site features that ensure that the long-term performance objectives of 10 CFR 61,[28] Subpart C, are achieved. (Note: 10 CFR 61 applies specifically to NRC facilities, but is used for guidance here).

To ensure that the facility can be licensed as a near-surface land disposal facility, initial site characterization and the installation of long-term ground water monitoring wells during construction is essential. Estimated costs associated with this method of disposition are provided in **Table 9.6**.

Table 9.6 – DBS Filter Entombment Decontamination and Decommissioning Cost Estimate**

Cost Parameter	Unit Cost/ft^3	Volume (ft^3)	Total Cost**
Licensing			500,000
Initial Site Characterization			200,000
Monitoring Well			100,000
Grout Void Space	$5.00	144,000	720,000
Cover Fill (5 meters)	$0.50	590,400	295,200
Tunnel Decon			2,073,474
		Total	$3,888,674

Assume the void space above the fill to be 4 feet high, 300 feet wide, and 120 feet long, with a volume of 144,000 cubic feet.
** All costs are for FY 2002.

9.3.3.2 Decontamination

Because of the irregular surface areas and porous nature of the clay tile, stones, gravel, and sand filter media utilized in DBS filters, decontamination methods currently available would be mostly ineffective. Ancillary materials such as concrete confinement walls and supports and steel grating, if utilized, are potential candidates for decontamination, but make up a relatively small percentage of the total mass of the DBS filter.

9.3.3.3 Onsite Disposal

Low-level waste onsite disposal techniques include:

- Onsite transport in steel containers from point of origin to storage vaults,
- Manual sorting of waste to separate out compactable waste,
- 55-gallon drum compaction, when practical,
- Return to steel containers, and
- Final interment in the waste storage vaults.

Onsite disposal techniques are well developed and currently licensed. However, existing permits limit current space availability. **Table 9.7** provides a cost estimate for onsite disposal of filter materials and stabilization by grout of the remaining structural members.

Table 9.7 – Sand Filter Onsite Disposal Cost Estimates*

Without Characterization					
Activity		***Volume (ft³)***		***Cost/ft³***	***Cost $***
Filter Media Disposal		288,000		$106	$30,528,000
Activity	***Volume (ft³)***	***Hr/ft³***	***Cost/ft³***	***Labor $/hr***	
Media Removal	288,000	0.10		$57.76	$1,663,488
Grout Fill	432,000		$5.00		$2,160,000
Tunnel Decon					$2,073,474
Total					$34,351,488
With Characterization					
Activity		***Volume***		***Cost/ft³***	***Cost $***
Filter Media Disposal		144,000		$106	$15,264,000
Activity	***Volume (ft³)***	***Hr/ft³***	***Cost/ft³***	***Labor $/hr***	
Media Removal	288,000	0.10		$57.76	$1,663,488
Characterization	288,000	0.05		$83.09	$1,196,496
Grout Fill	432,000		$5.00		$2,160,000
Tunnel Decon					$2,073,474
Total					$20,283,984
Sand Filter Specifications:					
Required Flow	***Velocity***	***Face***	***Length***	***Width***	***Depth***
160,000 cfm	5 fpm	32,000	300 ft	120 ft	8 ft
Waste Volume		***Face***			
288,000 ft³		36,000			

* All cost estimates are for FY 2000.

9.3.3.4 Offsite Disposal

An alternative approach would be for removal of filter media from the sand filter structure and disposal at an offsite near-surface land disposal site. Offsite disposal methodologies would be similar to onsite disposal impacts, except that the increased costs of offsite burial would be incurred. Labor costs for offsite disposal would be similar to those incurred for onsite disposal. **Table 9.8** provides a cost estimate for offsite disposal of filter media and stabilization by grout of remaining structural members.

9.3.3.5 Long-Term Safe Storage

This approach requires continuing surveillance and security measures to prevent inadvertent intrusion. While costs may not be severe on an annual basis, in the long term they can be significant. This alternative constitutes a continuing threat to the public and the environment. Ultimate disposal would still be necessary, but at escalated costs.

Table 9.8 – Sand Filter Offsite Disposal Cost Estimates*

Without Characterization					
Activity		***Volume ft³)***		***Cost/ft³***	***Cost $***
Filter Media Disposal		288,000		$570	$164,160,000
Activity	***Volume (ft³)***	***Hr/ft³***	***Cost/ft³***	***Labor $/hr***	
Media Removal	288,000	0.10		$57.76	$1,663,488
Grout Fill	432,000		$5.00		$2,160,000
Tunnel Decon					$2,073,474
Total					$167,983,488
With Characterization					
Activity		***Volume***		***Cost per ft³***	***Cost $***
Filter Media Disposal		144,000		$570	$82,080,000
Activity	***Volume (ft³)***	***hr/ft³***	***Cost/ft³***	***Labor $/hr***	
Media Removal	288,000	0.10		$57.76	$1,663,488
Characterization	288,000	0.05		$83.09	$1,196,496
Grout Fill	432,000		$5.00		$2,160,000
Tunnel Decon					$2,073,474
Total					$87,099,984

* All costs are for FY 2000.

9.4 References

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CHAPTER 10

FIRE PROTECTION

10.1 Introduction

A separate chapter on fire protection is included in this Handbook because fire is the dominant public risk accident in nuclear facilities. This chapter focuses on fire prevention and protection of the ventilation systems in industrial and Government facilities such as energy production reactors, fuel processing and reprocessing facilities, research establishments, special applications facilities, waste processing plants, and storage and salvage sites. High-efficiency particulate air (HEPA) filters are extremely susceptible to damage when exposed to the effects of fire, smoke, and water; it is the intent of this chapter to provide the designer with the experience gained over the years from hard lessons learned in protecting HEPA filters from fire. Fire protection for ventilation systems in commercial nuclear power plants is outside the scope of this chapter.

The presence of water around fissionable materials is a potential cause of undesired nuclear criticality. The primary agent used in the protection of HEPA filters from fire also happens to be water. This appears on the surface to be a conflict, but the professionals in both subject areas have largely come to an understanding of how the objectives of both fire protection and criticality safety can be achieved. The successful prevention of fire damage and undesired criticality often involves human or procedural aspects that are difficult to quantify, so careful analysis and coordination between these two important subject areas is of particular importance in these situations. Appropriate guidance has been developed and can be found in the DOE Fire Protection Design Standard, DOE-STD-1066-99.[1]

There are also two major issues with protecting confinement ventilation systems from the effects of fire: the effect of water on the integrity of HEPA filter median and the potential of a criticality incident occurring with the use of water in the vicinity of fissile materials. Experts have carefully developed the guidelines in this chapter with consideration for both of these issues. Study of the history of fire and fire suppression system behavior in actual fires and in research and testing has shown that HEPA filter media integrity can be assured by following the recommendations in this Handbook. The prevention of criticality occurrences is more situation-specific, however. While fire protection and criticality experts do agree on general acceptability of means of fire protection of fissile materials, each specific situation must be evaluated individually by qualified persons in both the fire protection and criticality safety fields. None of the criticality mishaps known to have occurred in the world has been caused by water from a fire suppression system, but some fires have caused extensive damage and contamination because water-based fire suppression systems were not present.

The ventilation air cleaning system of a nuclear facility is responsible for confining the radioactive smoke that results from fires. There are three major objectives to fighting fires in or around ventilation systems in nuclear facilities: (1) to keep the confinement ventilation system operable; (2) to suppress the fire; and (3) (if the filtration function is no longer operable) to prevent the release of radioactive materials that may have accumulated on the filters.

A confinement ventilation system must be designed to fulfill its purpose, i.e., to prevent harmful products (radioactive or otherwise) from escaping the system (sometimes referred to as the confinement) or facility, impacting the public or workers, and doing environmental damage. This chapter describes methods to ensure that confinement ventilation systems are designed, maintained, and operated in a manner to provide optimum protection against fires that could cause the confinement ventilation system to fail in its primary function.

The potential effects of fire in or around confinement ventilation systems are: (1) penetration of the system, and (2) release of hazardous materials to interior spaces outside the confinement volume. Large fires in confinement ventilation systems will produce heat- and smoke-filled combustion products that can degrade ventilation circuit components, ignite exposed materials, and/or plug the filters that prevent release of the toxic components produced during normal operations, thus causing loss of confinement. [Note: Hot gas transport can soften HEPA filter sealants, thereby weakening filter media in their frames. This, combined with the pressure differential, can blow out the filters, resulting in confinement loss][1]. Ignition of combustibles in gloveboxes or rooms can result in flaming brands and glowing embers. They may be lifted and carried by the design airflow to filter banks where they can burn through unprotected filters or ignite dust coating the interior of the ducts or trapped by filters. In either event, the unprotected filters would no longer be functional. If a fuel/air mixture filling even a small volume of a confinement system is ignited, the resulting pressure pulse can explosively breach the system. Such events are generally limited to the local elements of a system because of pressure pulse attenuation in the ducts and rapid fuel consumption during the explosion.

Fires that start inside ventilation systems have different characteristics than those that start outside the system, depending on how they are ignited. The performance of ventilation systems after ignition is determined by the system design and the safety measures provided by codes and standards.

In this chapter, topics such as fire hazards and effects, and analytical techniques are discussed, followed by a description of recommended fire safety features. In addition, a number of lessons learned from past fires at both DOE sites and commercial nuclear facilities are discussed. This chapter also refers the reader to the recognized codes and standards to be used in the fire protection design process and does not conflict with those codes and standards. The user should recognize that this is a handbook and not a design standard.

10.2 Fire History

Fires in nuclear facilities have been caused by a variety of energy sources, including electrical energy and spontaneous combustion of pyrophoric metals. While fixed fire suppression systems or operator intervention have limited the size and consequences of most of these fires, some did propagate and cause significant damage and material release. There have been numerous occurrences of fire in nuclear facilities since the beginning of the Manhattan Project and many lessons learned from those fires. Some lessons have been learned at great expense. A brief history is discussed here in the hope that the lessons will not be forgotten or ignored by facility designers and operators.

The most significant fires involving the HEPA filters of confinement ventilation systems have occurred at the Rocky Flats Plant. In 1957, pyrophoric ignition of plutonium in a production line ignited combustible cellulose filters in the production box and spread from there via laminated plexiglass window materials and other unknown combustible materials in the ventilation system to involve and destroy combustible HEPA filters in the final filter stage. Delays in fighting this fire were due to radiation safety concerns and delays in using water due to criticality concerns allowed it grow. It was extinguished soon after water was used, but a buildup of combustible vapors and dusts in the ventilation ductwork and the final filter stage ignited and resulted in a small explosion. This severely damaged the HEPA filters in the final filter stage and allowed the second-highest known plutonium release at Rocky Flats to occur.[2, 3] A significant portion of the plutonium released from this fire was deposited offsite.[3] As a result of this event, fire-resistant glass fiber HEPA filters were researched, developed, and put into service in the nuclear industry.

Another fire occurred at Rocky Flats in 1969 in a production line glovebox.[2, 3] The exact cause of this fire is unknown, but the area of origin included a storage cabinet that housed small, open metal containers filled with plutonium machine turnings. The cabinets, which were constructed of high-density pressed wood shielding material and plastic, were included in the production line to reduce radiation exposure to workers. Heat detectors originally installed in the glovebox were removed to the underside of the glovebox floor to accommodate the cabinet. A fire detector alarm alerted the fire department. When the firefighters arrived, the building was smoke-filled, indicating the fire had escaped the confinement system. While localized contamination was detected outside the building, no measurable contamination escaped the site.

History of Fire Involving Confinement Ventilation Systems

The following is a partial list of fires known to have occurred in nuclear facilities, involving nuclear materials, and having some interaction with the facility confinement ventilation system or some other significance. These come from U.S. Atomic Energy Commission (AEC) Serious Accident Reports. The AEC was a predecessor of the U.S. Department of Energy. This list is by no means comprehensive or complete.

1. *Fire in Ventilating System Filters.* AEC, Serious Accidents, Issue No. 83, July 27, 1955

   This fire involved a large bank of paper HEPA filters in wood frames (CWS Filters). Following extinguishment of a fire that had been caused by sparks from welding, re-ignition occurred on each of the following 2 days. About 2.5 tons of carbon dioxide was used to control the fire. Although no radiation hazard was involved, suppressing this fire was difficult due to the reactivity of the dust (specifics not given) in the ductwork with water.

2. *Serious Ventilating System Incidents.* AEC, Serious Accidents, Issue No. 110, November 8, 1956

   Fire started from spontaneous combustion in zirconium powder that had accumulated in ductwork incurring $150,000 in damage.

   Six hundred grams of hydride powder in plastic bags spontaneously ignited near the intake of a 6 feet × 6 feet filtering unit incurring $21,093 in damage.

   Laboratory scale testing being run in oxides generated by combustion in air of NaK, were carried by the ventilating system to a combustible filter. For unknown reasons, the NaK began splattering and ignited the filters. A loss of $8,400 was reported.

3. *Fire in British Windscale Facility.* AEC, Serious Accidents, Issue No. 128, October 15, 1957

   The fire started in the British graphite-moderated, air-cooled reactor at Windscale. Stack gas filters were very effective in removing particulate matter from the airstream, and the radioactive contamination of the surrounding area appears primarily concerned with iodine dispersed over about 200 square miles of farmland.

4. *Explosion in Glove-Box Line of Plutonium Facility*. AEC, Serious Accidents, Issue No. 129, October 28, 1957

   Vapor from a flammable lubricating and rust preventative chemical being used on a machine in the glovebox line circulated throughout all the boxes, and sparks from an electric brush being used on another machine ignited the vapors and caused an explosion. Loss not stated.

5. *Small Metallic Plutonium Fire Leads to Major Property Damage Loss.* AEC, Serious Accidents, Issue No. 130, November 27, 1957

   A small amount of plutonium spontaneously ignited within a dry box in a so-called “fireproof” building that was relatively free of combustible material. More than $300K in losses were incurred. This is the fire that occurred in September 1957, where most of the filter banks were destroyed. The initial fire released a significant quantity of flammable vapors into the confinement ventilation system, which subsequently ignited and exploded.

6. *Filter Fire*. AEC, Serious Accidents, Issue No. 41, December 2, 1958 and Serious Accidents, Issue No. 144, March 9, 1959

   Fire started in a fume hood in a chemical laboratory involving an experiment with perchloric acid. The fire involved a combustible filter under the hood and traveled through the exhaust system, reaching the main filter bank on the second floor of the building. Loss estimated at $12,000.

7. *Drybox Explosion Disperses Polonium Contamination.* AEC, Serious Accidents, Issue No. 148, October 8, 1959

   After normal working hours, an explosion occurred in a sample hood that dispersed some polonium-containing solution. The cause is not precisely known. Loss unknown.

8. *Ventilating Air Filter Clogs During Fire.* AEC, Serious Accidents, Issue No. 151, October 28, 1959

   A fire in a room under construction at an AEC plant occurred. The ventilating system had been placed in service for the room even though the room was not yet complete. The filters soon became plugged with smoke and soot. The firefighters entered the obscured room and "chopped" out the filters. The smoke soon cleared from the room, but had radioactive contamination been present, it would have been exhausted out the ventilation system

9. *Plastic Windows and a $125,000 Sprinkler Head.* AEC, Serious Accidents, Issue No. 152, October 29, 1959

   Fire occurred in a chemical laboratory in a walk-in type of hood, involving plastic doors and windows. A sprinkler head controlled the fire and limited the damage to about $350.

10. *Radiochemical Plant Explosion releases Plutonium Contamination Outside Facility.* AEC, Serious Accidents Issue No. 162, March 30, 1960

    This explosion occurred in a radiochemical pilot plant being used for processing spent power reactor fuel. A small amount of plutonium was dispersed, contaminating nearby buildings and grounds. Loss was about $360K, which includes decontamination costs.

11. *Could Sprinkler Protection Have Reduced This $200,000 Radiochemistry Building Fire Loss?* AEC, Serious Accidents, Issue No. 175, April 5, 1961

    A fire occurred on the inside of a cavern drybox designed for working with high levels of radioactivity. The fire spread to other areas within the cavern involving plastics and wood. A minor amount of radioactivity was dispersed. The loss was about $200,000.

12. *Polyester Fibrous Glass Duct Fire causes $43K Damage.* AEC, Serious Accidents, Issue No. 216, January 31, 1964

    Fire started in combustible laboratory fume hood ducting. The ducting was of polyester resin-bonded fibrous structure. The fire began around a hot plate in a fume hood and then extended into the ductwork. Fire damage was limited to the general area of ducting but smoke damage was extensive in this 4,500 square foot, one-story and basement facility. Smoke damage may have been exacerbated by the exhaust fanes having been turned off during the fire. The exhaust system was not filtered.

13. *Filter Box Fire.* AEC, Serious Accidents, Issue No. 217, February 7, 1964

    This fire occurred in a filter box on the roof of a nuclear facility. The burning filters were manually removed from the box by firefighters who then used carbon dioxide and dry chemical fire extinguishers to extinguish the fire. Some smoke backed up into the plant as a result of shutting off the blower fans. The fire was determined to have been caused by fine uranium chips which spontaneously ignited and were drawn into the ventilation system. The burning uranium chips ignited the metal mesh in the roughing filters and then the "absolute" filters as they are called in the report. The roughing filters had been cleaned 6 weeks previously and there was no evidence of buildup of dust in the ductwork itself. The "absolute" filters were less than one year old. A recommendation of this report was the use of fire-resistive "absolute" filters.

14. *Fire and the Reaction of Nitric Acid with Plutonium Ion Exchange Resin Leads to Major Property Damage.* AEC, Serious Accidents, Issue No. 237, December 4, 1964

    At 1:23 am, a sudden reversal of airflow was noted in the facility during plutonium purification operations. The purification operation was shut down immediately. The presence of a fire was discovered after about 30 minutes. The use of water was not recommended due to criticality safety concerns. The fire was extinguished in about 1.5 hours through the use of about 500 pounds of sodium bicarbonate. It was later estimated that, if water fog had been used, it could have been extinguished in 5 minutes. The fire spread through open gratings to involve all four floors of the facility. The direct and indirect loss was estimated at $397K. Although no direct mention is made of confinement ventilation system performance, this is being included as it was a significant fire in a nuclear facility.

15. *Explosion Within Glovebox Disperses Contamination.* AEC, Serious Accidents, Issue No. 242, January 11, 1965

    A methanol-air mixture in a glovebox ignited and exploded, pressurizing the glovebox and tearing off six gloves. Plutonium oxide discharged from the open ports and spread throughout the operating areas of the building. Some workers were contaminated to varying degrees. No mention is made of any contamination being released from the building.

16. *Burning Plutonium Chips Explode in Carbon Tetrachloride Degreasing Bath.* AEC, Serious Accidents, Issue No. 246, March 12, 1965

    Plutonium chips immersed in carbon tetrachloride within a glovebox spontaneously ignited and burned during operations. During the performance of the procedure in place to handle burning plutonium chips in a container, some of the burning chips fell into a carbon tetrachloride bath in the glovebox, causing an explosion with a shock wave. This ruptured the glovebox and dispersed plutonium throughout the glovebox line. There was no direct impact on HEPA filters.

17. *Cutting Wheel residues in Plutonium Waste Cause Explosion.* AEC, Serious Accidents, Issue No 258, December 17, 1965

    During an operation involving oxidation of plutonium waste in a nitrogen-inerted glovebox, in which a small amount of oxygen was introduced in a bell jar containing plutonium chips under partial vacuum, the plutonium in the jar began to smoke and then an explosion occurred within the jar. Contamination was limited to fragments thrown about the interior of the glovebox.

18. *Hazardous Solvent Causes Explosion in a Glovebox*. AEC, Serious Accidents, Issue No. 261, February 1966

    During cleaning operations, using acetone, in a glovebox where plutonium was being processed, an explosion occurred that blew out three gloves. The ensuing fire was extinguished with a 20-pound dry chemical fire extinguisher. Some workers were contaminated, and contamination was spread throughout the room. No contamination was detected outside of the building.

19. *Maintenance on Plutonium Machining Coolant Lines Leads to $17,500 Fire. Building 776/777, Rocky Flats, 1965,* AEC, Serious Accidents, Issue No. 262, March 4, 1966

    Metallic plutonium lathe operations, utilizing a circulating oil cooling system, were being conducted within a glovebox. During normal operations, oil that splashed or dripped accumulated in a drip pan with a valve in its drain line. This valve was normally open, allowing the drain pan oil to flow back to the suction side of the circulating pump. The drain line became clogged and attempts were made to unclog it by first flushing it with carbon tetrachloride (unsuccessfully), then by using a welding rod to probe and clear it. Some paper towels and a plastic pan were placed around the pipe to catch oil and prevent the spread of contamination. During the probing, sparks were noticed when the rod contacted something metallic in the line. Because the probing did not appear to be having much effect, a center punch was inserted into the drain line and struck by a hammer. The first blow caused a light spark; the second blow caused a lot of sparking accompanied by a fireball, igniting the plastic pan and paper towels. The copper drain line began to glow, indicating a fire within it. This fire was controlled using a fire extinguisher. Contamination from the fire spread throughout the Building 776 and 25,000 square feet of Building 777.

20. *Fire During Glovebox Cleanup Leads to $23,000 Damage Via Contamination Spread.* AEC, Serious Accidents, Issue No. 269, July 8, 1966

    During operations to remove the paint from the inside of a glovebox in preparation for its disposal, fire involving flammable solvents occurred in the airlock for the glovebox system. Unsuccessful attempts were made to extinguish the fire by firefighters using carbon dioxide fire extinguishers, but the fire was ultimately controlled by introducing solid carbon dioxide. Contamination was spread throughout the ventilation system ductwork and over two floors of the building.

21. *Fire Damages Hot Cell Window.* AEC, Serious Accidents, Issue No. 275, November 4, 1966

    An operation involving NaK in a shielded hot cell ignited some alcohol being used. A total-flooding carbon dioxide extinguishing system was manually actuated which extinguished the fire. The HEPA filters received some particulate contamination but not to the extent that they became plugged. The window in the hot cell was cracked due to the heat from the alcohol fire. No significant amount of contamination occurred.

22. *Glovebox Explosion Causes $42,000 Damage and Plutonium 238 Contamination Spread.* AEC, Serious Accidents, Issue No. 293, August 26, 1968

    An explosion in a series of gloveboxes where plutonium 238-contaminated wastes were being dried caused extensive damage to the gloveboxes and room. Contamination was spread into adjoining rooms and corridors. The explosion was caused by the overheating of rubber gloves, releasing flammable vapors that ignited.

23. *Waste Incinerator Incident Affirms Fire-Resistive Filter Value.* AEC, Serious Accidents, Issue No. 292, July 31, 1968

    During normal operations within a glovebox that was part of the incinerator operation, smoke from the feed-end of the incinerator indicated inadequate airflow was going through the glovebox. Maintenance personnel called to correct the problem discovered that the filter-box port cover was hot and its wood frame was smoldering. The fire department was called and the fire in the filter frame was extinguished using carbon dioxide. The filter was removed for inspection. Only the top of the four wooden sides of it were unburned. The filter medium collapse was attributed to the application of the carbon dioxide fire extinguisher. No burning of the filter medium was observed. The secondary filters in this frame were unaffected by this incident. No contamination was spread as a result of this fire.

24. *Fire - Rocky Flats Plant - May 11, 1969*. AEC, Serious Accidents, Issue No. 306, December 1, 1969

    This fire occurred one afternoon in a glovebox line in Buildings 776-777. It moved rapidly through the glovebox line due to large quantities of combustible polymer shielding in place. Carbon dioxide was unsuccessfully used to try to extinguish the fire initially. Water was used as a suppression agent by the fire department only as a last resort. Extensive damage occurred. Some contamination was detected on the roof of an adjoining building, released due to a minor HEPA filter failure. Most contamination was tracked out by firefighters during suppression operations.

25. *Incinerator Fire at Rocky Flats, July 2,1980*. Investigation Report, July 31, 1980[4]

    Incinerator operators noted a temperature rise above normal in the operation of an incinerator in Building 771 at Rocky Flats in the late morning. A temperature overheat alarm occurred in the incinerator plenum about an hour and 15 minutes later. About 90 minutes after the initial temperature rise indication, the operators received a phone call and noted other indications that there was a fire in the plenum of the incinerator. Incinerator shutdown was initiated and the fire was mostly extinguished by a water deluge system. The fire department completed extinguishing the fire. It was noted in the investigation report that two of the four causes of the fire were nitric acid attacking the urethane sealing the HEPA filter media to the frames, and the accumulation of metal fines on the HEPA filter media material. The nitrated urethane seals exhibited a temperature rise that may have ignited the metal fines on the filter media. This incident resulted in slight contamination inside the building, with no release external to the building.

26. *Fire in TRISTAN Experiment at HFBR at BNL, March 31, 1994*[5]

    This fire occurred in an experiment on the experiment level of the High Flux Beam reactor at Brookhaven National Laboratory on Thursday, March 31, 1994. It spread light contamination through the experiment level of the reactor.

27. *Cerro Grande fire effects on HEPA filters at LANL* May 4, 2000[6]

    On May 4, 2000, a prescribed burn at Bandelier National Monument, New Mexico escaped control and ultimately burned nearly 50,000 acres in and around the town of Los Alamos and Los Alamos National Laboratory (LANL). The thick smoke from this fire impacted the confinement ventilation system operations at several LANL facilities. The confinement ventilation systems in some nuclear facilities were shut down or placed on minimum ventilation to prevent filter clogging. Some facilities whose confinement ventilation systems were not shut down experienced filter clogging and had to replace filters. The facilities that shut down or went to minimum operation subsequently had re-entry and restart issues they had to address. No contamination escaped from LANL facilities as a result of these actions.

28. *Cutting Operations Ignite Residue In Bottom Of Glovebox*, Rocky Flats Environmental Technology Site, Building 371, May 6, 2003

    Exploratory cutting operations on the top of a glovebox in Building 371 at Rocky Flats Environmental Technology Site (RFETS) ignited legacy combustibles in the bottom of a large, two-story glovebox that also contained a service elevator. Fire extinguishers were used to extinguish the fire, but upon stirring of the materials by the workers the fire re-ignited. The fire department arrived soon thereafter and used 600 to 800 gallons of water form hose streams to fully extinguish the fire. Some of the firefighters received skin contamination. This incident was still under investigation at the time of the writing of this document.

10.3 Requirements and Guidelines

Decisions regarding the extent and nature of fire safety features for confinement ventilation systems are predicated to a significant degree on the regulatory environment governing the facility. That environment can be characterized as being regulated by DOE or the NRC. The applicability of any fire safety criteria to a particular design will depend on the nature of the license application (for an NRC-regulated facility), the contract (for a Federal facility) and the governing regulations (e.g., 10 CFR Part 70).[7] Proceeding with an individual design should not progress until the technical (safety) basis is clearly established.

Fire protection requirements and guidelines for confinement ventilation systems are delineated in a number of NRC and DOE source documents. These include NRC Regulatory Guides, Standard Review Plans, Branch Technical Positions, and supplementary staff position papers. DOE directives include DOE Order 420.1A, *Facility Safety*,[8] its *Implementation Guide for Fire Protection*,[9] and DOE-STD-1066-99.[1]

While these criteria are expected to be implemented, a "variance" approval process exists within both the NRC and DOE. The process generally includes a documented description of the condition, the justification for literal nonconformance, and approval by the fire protection "authority having jurisdiction" (AHJ).

Despite the differences in scope between NRC and DOE fire safety directives related to confinement ventilation systems, the following are significant common requirements:

- Compliance with applicable industry standards such as those promulgated by the National Fire Protection Association (NFPA). Prominent among these is the 800 series of standards on fire protection for nuclear facilities and NFPA Standard 90A, Installation of Air Conditioning and Ventilation Systems."[10] [Note: Cost-effective alternative means of compliance are permitted under established "equivalency" provisions.]

- Development of a comprehensive Fire Hazards Analysis (FHA). The FHA is required to consider—under all operating modes—the potential adverse impact of the spread of combustion products through the ventilation system.

- Implementation of combustible materials and ignition source controls to minimize the potential for fire.

- Use of generally noncombustible structural elements and "listed" fire protection system components that are subjected to a quality assurance (QA)/quality control (QC) program.

- Provision of fire protection defense-in-depth. This means that multiple fire safety features are available in the event that one is rendered inoperable.

- Reliance on both active (e.g., fire detectors and sprinklers) and passive (e.g., fire barriers) fire safety features.

- A comprehensive inspection, testing, and maintenance program for installed fire safety features.

- A trained staff capable of responding in a timely and effective manner to fires and related emergencies.

Specific fire safety features that are stipulated in this body of criteria are considered acceptable minimums and should be treated exactly as such. There may be, and often are, circumstances that warrant provision of additional protective measures to compensate for elevated fire hazards or unusual risks. Such hazards and risks may be revealed in conjunction with formulation of the FHA, application of fire modeling techniques, and analysis of engineering survey results, as well as after development of the Documented Safety Analysis.

An issue that has created a degree of regulatory inconsistency concerns the retroactive application of industry standards. DOE has established the concept of "codes of record," defined as the codes and standards that were in force at the time a facility design commenced.

Questions regarding the applicability of individual fire safety directives to a particular confinement ventilation design, as well as requests for interpretation of the provision of industry standards to such designs, should be directed to the cognizant NRC or DOE fire protection AHJ.

10.4 Enclosure Fire Modeling in Fire Hazards Analysis

DOE has developed a useful framework for analyzing the fire hazard in a facility. This framework considers all of the aspects of fire and its impact on facility personnel, continuity of operation, the environment, and the public. The occurrence and spread of fire is a complex process that cuts across many design and operational disciplines, making its control throughout the lifetime of a facility problematic in some respects.

The FHA should contain a conservative assessment of the following features of a confinement ventilation system:

- Description of construction,
- Identification of high-value property,
- Description of fire hazards (including a design basis fire and its effects on the confinement ventilation system) and the limits of the ability of the confinement ventilation system to withstand fires more severe than the design basis fire,
- Protection of essential safety class systems,
- Life safety considerations,
- Critical process equipment,
- Identification of the damage potential: Maximum Credible Fire Loss (MCFL) and Maximum Possible Fire Loss (MPFL),
- Analysis of fire department/brigade response and its adequacy,
- Potential for recovery from a fire,
- Potential for a toxic, biological, and/or radiation incident due to a fire,
- Analysis of emergency planning and its ability to mitigate a fire in a confinement ventilation system,
- Security and safeguards considerations related to fire protection,
- Impacts of natural hazards (earthquake, flood, wind) on fire safety, and
- Exposure fire potential, particularly as related to the potential for breaching the confinement ventilation system due to a fire that is external to the system.

The FHA considers everything involved in the design and operation of the facility. The essential analysis tools are predictive models that can be applied to define the ranges of hazards from design basis events (DBEs). An FHA can be applied during the design phase of new facilities and/or in conjunction with changes or modifications of existing operations.

Use of Fire Modeling in FHAs

Validated and verified fire models approved by DOE for use in Authorization Basis documents must be used.

Fire models for FHAs range from simple algorithms that predict thermodynamic changes in enclosures to complex programs that can account for heat, mass transfer, and smoke production in multiple enclosures. Many mathematical models have been installed in software codes and are available on the Internet bulletin boards of various government agencies. These codes can predict the development and spread of fire and smoke conditions through multiple rooms, and can account for changes in the structure and composition of enclosures. Application of these models requires considerable understanding of their use and limitations, statements of which are usually included in the instructional text published with the software codes. Reduction of complex models to simple terms supported by empirical data is often useful in predicting uncomplicated systems.

10.5 Fire Phenomena

Fire is a complex phenomenon that involves the initiation of an event and subsequent actions that can mitigate or exacerbate the event's effects. The matrix in **Table 10.1** covers: (1) the initiation and generation of harmful products from a fire; (2) the means by which these harmful effects are transported throughout the confinement ventilation system are discussed; and (3) the impacts of these harmful effects on the main components of the confinement ventilation system are discussed. The material in this section indicates the fire hazards that must be mitigated. The techniques for mitigation are presented in the next section.

Table 10.1 – Fire Phenomena Matrix

	Heat	***Smoke***	***Related Effects***
Generation	Fire growth	Initial aerosol makeup	Water vapor, chemical releases, deflagrations
Transport	Temps in ducts	Change in aerosol with time and temperature	Change with movement through ducts
Effects on filters	Media failure	Filter media plugging	Filter media plugging and failure

10.5.1 Fires Occurring Outside a Confinement Ventilation System

Fires occurring outside a confinement ventilation system generate heat that exposes the outside of ducting as well as produce combustion products that are drawn into the confinement ventilation system when it operates as intended. These combustion products will affect the components of the confinement ventilation system.

10.5.1.1 Generation of Heat, Smoke, and Related Products

Thermal Effects from Fire Initiation and Growth

Hot gases from a fire that originates outside of the confinement ventilation system will be entrained within it and will be conveyed via the duct system to the filter banks. While a certain amount of heat dissipation and dilution will occur, over time the gases may cause steady deterioration of the filter medium and may ignite combustible framing. The designer of nuclear air cleaning systems must accurately characterize the design basis fire. This characterization can be subjective, (i.e., the thermal effects of a fire are determined on the basis of judgment and experience) or the thermal effects of a fire on HEPA filters can be calculated by qualified individuals using fire models. In the latter case, the chosen fire must be sufficiently conservative (i.e., severe) to be an upper boundary for the mitigative features protecting the function of the confinement ventilation system.

Smoke Generation

Smoke contains particulates that can pose a significant "plugging" threat to HEPA filters. Smoke is a suspension of solid and/or liquid particles and gases resulting from combustion and pyrolysis. Soot is an intrinsic part of smoke. However, the term "soot" can be further refined to mean finely divided particles, mainly carbon, produced and/or deposited during incomplete combustion of organic materials. Moreover, the amount of smoke generated from any material is strongly influenced by the same conditions that effect combustion efficiency. In general, smoke is a heterogeneous combination of solid and liquid particles of varying size and composition. Their instantaneous character depends on the material of origin, combustion conditions, environment, and flow dynamics. The sizes of particulates vary from 0.002 to 0.5 µm, depending on the experience described above. Conditions related to incomplete combustion generally result in an aerosol distribution of larger mean particulate size. However, if the smoke concentration is high, particle agglomeration (smoke aging) proceeds rapidly, as does fallout and surface deposition.

Agglomerated smoke aerosols can attain diameters as large as 10 µm in plumes from fires; however, visibility is most influenced by particulates with diameters of -1.0 µm. Collections of data on smoke production rates (g of soot/g of material burned) are available and can be used to estimate visible obscuration and smoke detector response time.

Water Generation

The quantity of water generated in the fire is as important as the soot and other particulates. Water vapor can condense on the particulates in smoke, both increasing their average diameters and leading to increased agglomeration resulting in generally larger particulates. Larger particulates lead to more rapid HEPA filter plugging.

Calculating the aspects of the phenomenon of water generation from combustion is an extension of the processes described by Gottuk and Roby.[11]

Generation of Combustion Products from External Fires

Many methods exist to establish the thermal history of gaseous and particulate combustion products from a postulated fire (in most cases, the type of fire experienced in a nuclear facility would be a ventilation-controlled fire, rather than a fuel-controlled fire).

Once the masses of smoke and water generated for a given fire have been established, the temperature that occurs at the HEPA filter will determine how much water remains in the gaseous state or how much is condensed.

10.5.1.2 Transport of Heat, Smoke, and Related Products

Heat Loss in Ducts

Hot gas from fires may enter the exhaust duct system and lead to excessive temperatures at the HEPA filters if not mitigated. The two primary tools for analyzing the cooling of hot exhaust gas are: (1) dilution analysis with additional exhaust streams, and (2) duct cooling by convective and radiative heat transport.

As the combustion products from a fire travel through the length of a duct, losses occur (see **Figure 10.1**). Thermal energy is added or lost through the walls of the duct according to the temperature differential between the products of combustion gases in the duct and the atmosphere external to the duct. Solid and liquid particulates are deposited along the duct interior surfaces according to a number of factors.

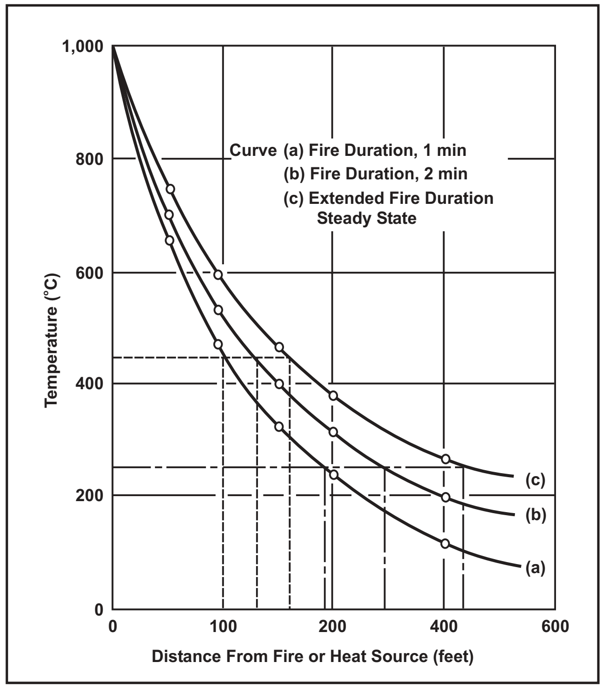

Figure 10.1 – Cooling Rate of Air in a 12-inch Diameter Duct Carrying 1,000 cfm of Air with Inlet Temperature of 1,000 Degrees Celsius

Alvares[12] studied heat transport in gases traveling through ducts to determine the losses in a duct external to a facility. Most ducts are not external to a facility, so the designer must consider this in the analysis.

Because confinement systems are part of the enclosures that support operations with nuclear materials, computer codes have been developed to predict the results of accidents on the internal conditions within the system. For fire events, the room fire models discussed above can serve as the source term for codes that treat the response of components within the confinement ventilation system. Modeling tools are available (e.g., CFAST) to help analyze heat transport in the ducts.

The phenomena noted in this section will be adequately mitigated by implementation of the fire protection provisions of DOE Standard 1066-99.[1] In those rare instances when it can be clearly demonstrated in a comprehensive FHA that these fire hazards are insignificant, alternate fire protection configurations can be considered.

Smoke and Water Loss in Ducts

A significant quantity of smoke and water may settle out in the ventilation ducts. In one configuration where the duct was located outside the fire area, Alvares[12] observed that about 60 percent of the aerosol mass (including water) was lost between the duct entrance and the HEPA inlet (about 19 feet for a 2-foot × 2-foot cross-section duct).[12]

Transport of related combustion products (e.g., smoke particulates) can be modeled using available techniques. Analysis methods for the entrainment and transport of these products in confined situations such as ducts are generally well understood. The form and dispersion characteristics of the combustion products in question also must be understood. Once this is done, the effects on the HEPA filters can be shown with time.

10.5.1.3 Effects on Filters of Heat, Smoke, and Related Products

The impact of fires on the integrity of the HEPA filters can be determined through a sequence of analyses to establish: (1) the dynamics of the design basis fire; (2) the generation of smoke, water, and heat (temperature) that enters the confinement ventilation system; (3) the mitigation of smoke, water, and heat through the ducting to the HEPA filters; and (4) the response of the HEPA filters to the smoke, water, and heat that reach them. The interaction of smoke, water, and heat play a major role in the plugging of HEPA filters, as well as the consequent rise in filter pressure drop and possible reduction in exhaust flow. This sequence of analysis will determine the potential of the design basis fire for causing structural damage to the HEPA filters and thereby increasing the filter penetration. Finally, the impact of the smoke and water loading and the air temperature on the HEPA filters must be determined.

HEPA Filter Response to Temperature

Fire-resistant HEPA filters must meet the requirements of Underwriters Laboratory (UL)-586, *High-Efficiency, Particulate, Air Filter Units*.[13] Prefilters must meet the requirements of UL-900, *Performance of Air Filter Units*.[14] These UL test methods qualify the construction materials for the filter, frame, and gaskets. To be listed by UL under UL-586[13] as a HEPA filter unit, HEPA filters are required to meet the following three criteria:

- Withstand 750 ± 50 degrees Fahrenheit heated airflow for 5 minutes at not less than 40 percent of rated capacity.
- Have a greater than 97 percent test aerosol efficiency after exposure to the hot air test and cooling.
- Withstand a spot-flame test in which a Bunsen burner flame at 1,750 ± 50 degrees Fahrenheit is placed on the filter with no after-burning when the flame is removed.

For the spot flame test, a horizontal Bunsen burner is touched to the filter at three locations for 5 minutes at each site. Afterwards, the burner flame is moved to touch the filter frame, filter pack, and sealing materials. To pass the test, flaming on the downstream side of the filter must cease within 2 minutes after removal of the burner flame. Although this test indicates the fire performance of the filter, it is a small-scale test with a limited, controlled heat source that does not replicate the temperatures experienced during actual exposure to a more severe, full-scale fire. Many fires can reach higher temperatures and more severe conditions than this test fire.

Extended exposure to temperatures above 800 degrees Fahrenheit will cause destruction of the casing of wood-cased filters and warping of the casing of steel-cased filters, allowing unfiltered air to bypass the filter. The medium of HEPA filters is thin (0.015 inch) and can be destroyed by incandescent sparks, flaming trash, or burning dust on its surface.

Although HEPA filters can withstand a temperature of 750 degrees Fahrenheit for an extremely limited time, they should not be subjected to continuous exposure to temperatures higher than 250 degrees Fahrenheit. Longer filter life and more reliable service, as well as a greater operational safety factor, can be obtained when normal operating temperatures are below 200 degrees Fahrenheit and higher temperature extremes are avoided.

Continuous operation of HEPA filters at higher temperatures is limited primarily by the filter sealant used to seal the filter core into the filter case. At higher temperatures, the sealants lose their strength, causing the filters to fail. For example, standard urethane seals are suitable for service at 250 degrees Fahrenheit, while some silicone seals can withstand 500 degrees Fahrenheit.

Because different sealants are available and different filter manufacturers rate their filters for different temperatures, the best practice for ventilation system designers and operators is to determine the manufacturer's limiting continuous service temperature if continuous operation at high temperatures is necessary. A decision to operate above 200 degrees Fahrenheit should be accompanied by controls requiring replacement filters that have been proven to be acceptable for above-normal temperatures.

HEPA Filter Response to Smoke and Water Loading

Water from combustion plays a major role in potential HEPA filter clogging with smoke aerosols. The temperature at the HEPA filter is important for determining the extent of water condensation from the fire exhaust. The HEPA filter-plugging studies suggest using the following approach to analyze the potential of fires to plug HEPA filters.

With the design basis fire and its combustion products previously established, transport of the hot gases, smoke particulates, and water vapor through the duct system must be established. The characteristics of the combustion products penetrating the prefilter or demister must be determined next. This process will yield a mass of smoke aerosols for comparison to a reference mass holding capacity for HEPA filters. The amount of water condensing on the smoke deposits is determined from the temperature at the HEPA filters and from the combustion water loading.

The nature of the aerosols has a major effect on plugging of all filters, including deep-bed sand (DBS) filters, prefilters, and HEPA filters. Previous studies have shown that, in addition to the mass of the smoke aerosols, the particle size and the state of the aerosol (liquid or solid) significantly affect HEPA filter clogging.

Figure 10.2 and **Table 10.2** illustrate some of the effects of particulates on HEPA filters.

In related tests using rolling prefilters (the media roll advances through the test duct as it plugs), Bergman et al.,[15] showed that, once a fire and the ventilation system have reached the point where the smoke generated can plug a HEPA filter, plugging can occur within 1 min, as seen in **Figure 10.3**. Tests 2 through 5 showed that they were not effective in protecting the HEPA filter from plugging until the prefilter efficiency was a minimum of 90 percent for milli-µm particles. **Figure 10.4** shows the efficiency for the different filter media used in the tests in Figure 10.3. Test 5, with insufficient media replacement in the roll, illustrates how rapidly the HEPA filter plugs when directly exposed to the proper aerosols. The plugging potential of the smoke aerosols is so great that it dominates all other parameters.

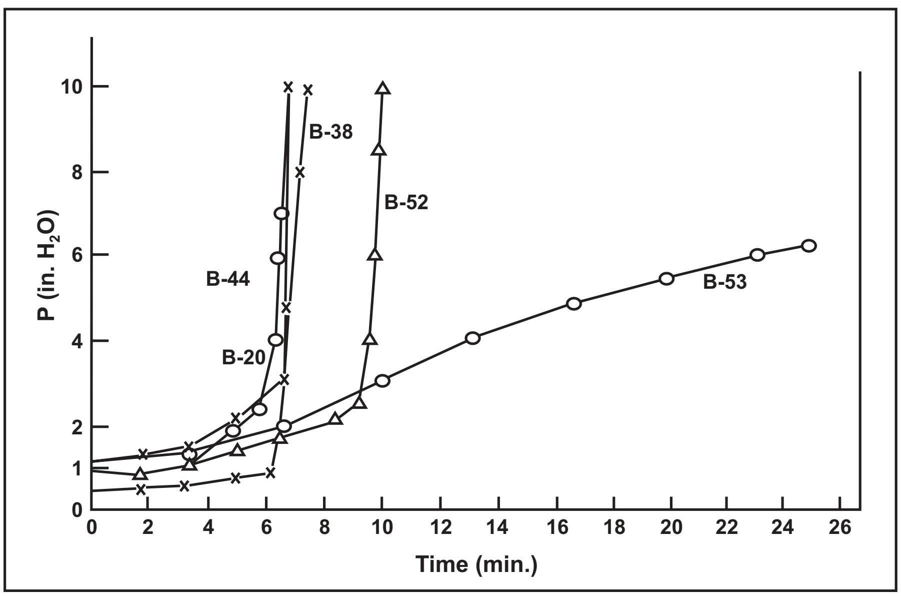

Figure 10.2 – Aerosol Loading of HEPA Filters by Smoke from Composite Cribs for the Different Conditions Shown in Table 10.2 (composite cribs consist of 40 percent wood, 14 percent PVC, 29 percent FRP, 9 percent PMMA, and 8 percent polycarbonate)[16]

Table 10.2 – Test Conditions for the HEPA Plugging Measurements in Figure 10.4 [16]

Test	HEPA Size (cfm)	Exhaust Flow (cfm)	Fuel Burn Rate (g/min)	Smoke Concentration (g/m3)	Temperature at HEPA (degrees Celsius)	HEPA wt. Gain (g)
B-44	1,000	500	3,000	6.4	65	470
B-20	500	500	1,200	4.8	86	—
B-38	500	1,000	3,000	8.6	105	574
B-52 (free burn)	500	500	1,500	7.6	70	106
B-53	500	1,000	1,680	8.4	110	550

Figure 10.5 shows an electron micrograph of the aerosols generated from composite burns. The deposits show the smoke aerosols were liquid because of the drop-like spheroid coating the fibers. The deposits have solidified because any liquid would not have remained in the high vacuum of the scanning electron microscope. Filter plugging with solid aerosols, as shown in **Figure 10.6**, does not show the same rapid increase in pressure drop as the liquid aerosols.[16]

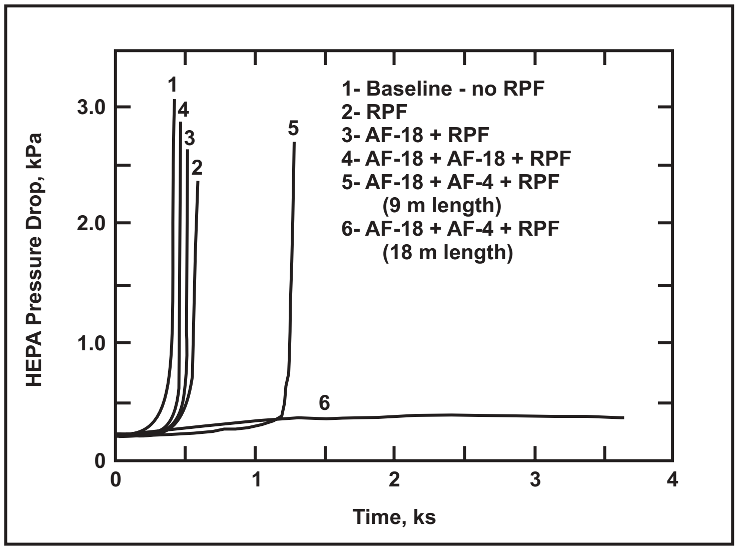

Figure 10.3 – HEPA Filter Plugging by Smoke Aerosols with Various Rolling Prefilters [15]

Prior Filter Exposure that Impacts Filter Response

Water Exposure. Water is an effective method for reducing temperature, but HEPA filters are not designed to operate when wet and will suffer structural damage. The HEPA filter medium is treated with water-repellent chemicals. Tests have shown a reduction in water repellency effectiveness with each wetting of the medium. The tensile strength of the filter medium can be reduced to failure levels with as little as one wetting. **Figures 10.7** and **10.8** further illustrate the relationships between particulates, temperature, and water-saturated air. A properly designed fire suppression system will include demisters to prevent water from reaching functional filters. HEPA filters exposed to water should be replaced immediately. HEPA filters that potentially could be exposed to water should be replaced within 5 years—immediately if actually exposed.

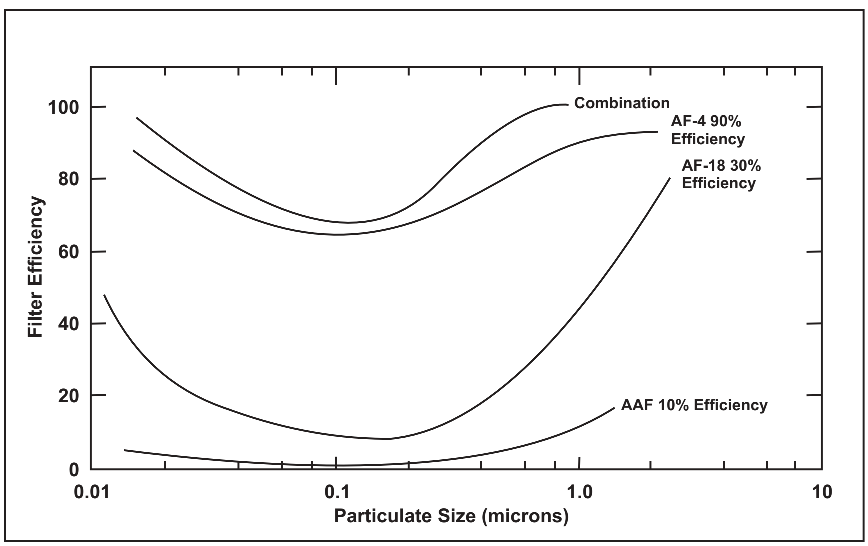

Figure 10.4 – Efficiency of Different Layers of Prefilters as a Function of Particle Size. (Efficiency Values Refer to the ASHRAE Dust Spot Efficiency. [15]***)***

Other Filter Types

Not all filter types are as subject to the thermal and combustibility effects as typical HEPA filters with combustible media. Plugging from smoke particulates can be a concern for all types of filters, however.

Figure 10.5 – Scanning Electron Micrograph of HEPA Filter Media Loaded with Smoke Aerosols from Composite Crib Fires. (Note: the drop-like globules attached to the filter fibers that suggest the liquid nature of the aerosol)[17]

10.5.1.4 Effects on Physical Integrity of the Confinement Ventilation System Components

Fires external to the confinement ventilation system may not only damage the HEPA filters inside the confinement ventilation system, they also may damage the integrity of the confinement ventilation system ductwork and enclosures. If the confinement ventilation system ductwork or enclosures are breached, some or all of the functionality of the confinement ventilation system will be impaired. This must be considered in the design of the physical components and the fire suppression systems provided in the facility.

10.5.1.5 Effects of Wildland Fires

Although documented evidence is lacking, recent wildland fire experience such as at the Cerro Grande fire in Los Alamos in 2001 demonstrated the potential for smoke to adversely affect confinement ventilation systems. Facilities in areas where this type of event may occur are required to analyze the hazard in their authorization basis documents. During the 2001 Cerro Grande fire, some confinement ventilation systems in facilities at the Los Alamos National Laboratory were shut down to prevent the rupture of HEPA filters due to clogging from smoke. Other external situations (such as volcanic eruptions or the dust from denuded landscapes) can also create abnormally dusty conditions that cause clogging of prefilters and HEPA filters and present serious threats to confinement ventilation systems. System designers and operators should implement features that minimize the probability of having to shut down confinement ventilation systems in other than extreme emergency situations. During emergency situations, if the Incident Commander determines that a confinement ventilation system has been breached and radioactive material is being released, a decision should be made whether to shut the confinement ventilation system down completely or operate it in a manner that would minimize the impact. These hazards may reveal the need for additional safeguards, including but not limited to, administrative controls of the removal of natural vegetation and other combustibles near filter inlets, installing smoke removal systems such as an electrostatic precipitator prefilter or installing additional filtration to preclude ingress of particulate into the building. NFPA Standard 1144, *Protection of Life and*

Figure 10.6 – Scanning Electron Micrograph of Sodium Chloride Aerosols on Glass Fiber Prefilter.[18]

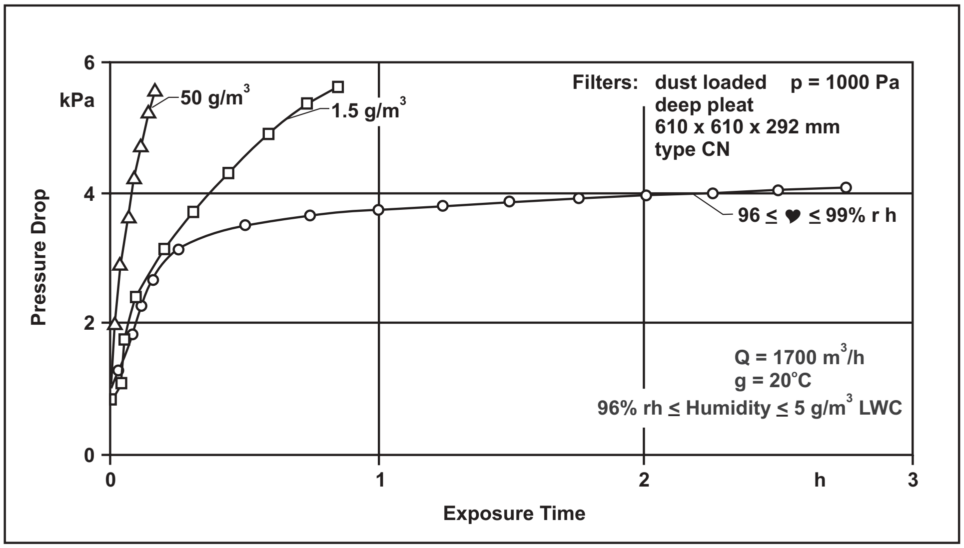

Figure 10.7 Illustration of Rapid Pressure Drop Increase with Water Saturated Air [19]

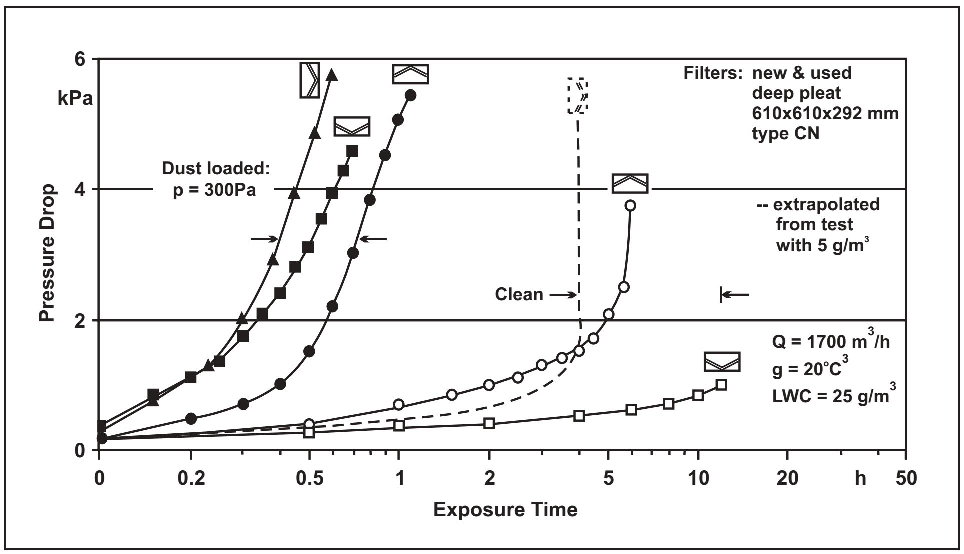

Figure 10.8 – Rapid Filter Plugging Due to Moisture Deposition on Particle-loaded HEPA Filters [19]

Property from Wildfire, [20] provides guidance on minimum defensible spaces around all buildings. High-hazard facilities would be expected to have defensible spaces exceeding these minimum values.

10.5.2 Fires Occurring within Confinement Ventilation Systems

Fire may originate from sources within the confinement ventilation system (e.g., glovebox-sized operations and small hot-cells). The effects of fires occurring within confinement ventilation systems, although similar to those resulting from fires external to the confinement ventilation system, may be different and thus require different controls.

10.5.2.1 Generation of Heat, Smoke, and Related Products

Fire events occurring inside a confinement ventilation system may appear in a number of physical forms. Fire may occur in ordinary combustible material. The amount of combustible material within a confinement ventilation system generally would not be as much as in a larger room, so the fire growth characteristics may be somewhat altered.

Fire may occur in the radioactive materials in a confinement ventilation system, or a fire involving ordinary combustibles may subsequently involve radioactive materials. A fire involving a flammable liquid or gas used inside a confinement ventilation system also may occur. These events may take the form of a flame front moving rapidly through a flammable vapor, a flame front moving rapidly enough to deflagrate and produce some overpressure, or even a detonation if the conditions for such phenomena exist.

Filter fires can occur due to either decomposition of combustible dust deposits within the filter, organic decomposition of chemical residue carried by the airstream from upstream processes, or spark/ember introduction from an upstream source. While introducing a water spray within or prior to the duct inlet can prevent the latter condition, fires originating at the filter itself cannot be satisfactorily mitigated by automatic suppression methods. Consequently, reliance is placed on the manual deluge system and fire department response.

Industrial and institutional loss experience has shown that over a period of time even "office dust" accumulations can form highly combustible residues on filters that are sufficient to cause damage if ignited. It also has been established that the concentration of these fuels need not be high to cause severe damage due to the fragility of the media. Fire-retardant chemical preparations for the filter media may initially make ignition difficult, particularly on clean media. However, this retardant material tends to become less effective over time and does nothing to retard or reduce the combustibility of dust or residue deposits from the airstream itself.

Administrative controls and alarm interlocks are designed to alert operators about impending change-out intervals that have been established to maintain dust or residue inventories below radiological actions points. It is not feasible, however, to eliminate the potential for direct filter fires or to practically reduce residue levels below those that may damage the filter itself.

10.5.2.2 Transport of Heat, Smoke, and Related Products

The transport of hot gases, smoke, water vapor, and chemicals from an internal fire through a confinement ventilation system can be modeled in much the same way as is done for an external fire. A fire occurring within the confinement ventilation system may affect the transport mechanism by altering the airflow through the system more than an external fire.

The transport mechanism also may be affected if the actual structural confinement barrier of the confinement ventilation system is involved in the fire and is contributing to its spread. The accumulation of dust and debris inside the air cleaning system ductwork over long periods of operation provides a mechanism for transporting flames from an ignition source to the filters, and also can produce soot that can clog filters in a fire.

10.5.2.3 Effects on Filters of Heat, Smoke, and Related Products

The effects of the products of combustion reaching the HEPA filters are the same for internal and external fires. The same physical parameters affect the manner in which the filters are threatened.

10.6 Fire Hazard Controls and Design Features

10.6.1 Objectives and Requirements

There are three major objectives for fire protection of confinement ventilation system:

- To prevent fires from affecting the operation of the ventilation system;
- To protect the filtration function; and
- To prevent the release of material that has accumulated on filters.

General Requirements

General requirements for the control of fire hazards that may affect the confinement ventilation system are formalized in NFPA Standards 9010[9] and 801, *Fire Protection for Facilities Handling Radioactive Materials*,[21] DOE Order 420.1A,[9] and DOE Standard 1066-99.[1]

Special hazards may cause exposure of the filters to the following: highly combustible dust loading; pyrophoric materials; chemically reactive, explosive, or corrosive vapors; or high-moisture conditions that may cause rapid degradation of HEPA filters. These should be evaluated on a case-by-case basis by a fire protection engineer who understands the process sufficiently to determine the protection warranted.

A comprehensive fire protection scheme for filter housings will include the following principles:

- The ventilation system filter housing construction materials should be noncombustible.
- Process hazards inside and outside the ventilation filter housings should be controlled.
- General area sprinklers should be provided within all process areas.
- The final filter housing should be separated from the general building area by fire-rated construction.
- Automatic water spray should be installed upstream of a demister and before the first-stage filters.
- Manual water spray should be installed at the first-stage HEPA filter.
- Fire detection systems should be installed in the final filter housing to allow early warning and activation of the extinguishing systems.
- Automatic flammable gas detection should be provided in filter housings where flammable or combustible processes are performed.

The FHA for a confinement ventilation system may indicate the need for further fire protection measures.

10.6.2 General Fire Hazard Control Features

10.6.2.1 Fuel Control

The flammability of materials must be considered in designing the confinement ventilation system. This is a first line of defense against fire, without which any ignition will lead to a dangerous situation.

The NFPA Standards and DOE fire protection requirements provide guidance on how to do this. The FHA also should address the issue of materials flammability.

If the process involves the presence of flammable vapors or liquids, the allowable concentration of flammable vapors inside the filter enclosure must be limited and controlled. The maximum permissible concentration (MPC) of flammable vapors is 25 percent of the lower flammable limit.

Control of Energy Sources

Ignition sources inside the filter enclosures must be limited to those necessary for operating the system. Electrical systems must be installed in accordance with NFPA 70, the *National Electrical Code*.[22] The presence of flammable gases or vapors in the operation of the confinement ventilation system will require specialized electrical equipment to prevent their ignition.

A number of flame-producing incidents have occurred while using aerosol generating devices (sometimes used in filter testing). Most of these incidents involved replacement aerosols with a lower auto-ignition temperature than dioxytl phithalate (DOP). In one incident, the aerosol liquid flow through the heater was initiated prior to establishing carrier airflow as recommended by the manufacturer. It ignited, shooting a flame of several feet from the discharge port. Fortunately there were no injuries, and equipment damage was limited to scorched insulation. The manufacturer modified the aerosol generator to reduce the heater block set point below the auto-ignition temperature of the polyalphaolefin (PAO) being used, and the air valve was modified to maintain minimal flow with the valve closed. Some generators use inert gas instead of air, but this does not always avoid ignition. While shutting down a generator, the operator heard a loud "pop" and observed smoke from the generator. An investigation revealed that flames were produced if the nitrogen flow was interrupted before the aerosol liquid flow was shut off. A safety cover was installed to prevent inadvertently shutting off the nitrogen switch, and the hose adapter was modified to preclude flaming if nitrogen was lost. In another incident, several discharge hoses erupted in flame when the generator ran out of aerosol liquid and the operators refilled the generator without deactivating it, allowing air to enter the system. Neither the manufacturer's instructions nor the operating procedure cautioned against this. The aerosol generators used are not approved by either Factory Mutual (FM) Global or UL to verify the safety for the intended use.

Challenge aerosols are not interchangeable. A new hazard analysis should be performed if the aerosol is changed. Equipment tolerances and emergency cut-outs should be evaluated. The manufacturer should be consulted. Training must emphasize procedural control, particularly valve sequencing. Critical warnings should be included in the operating procedures and on the instrument. Where valve sequencing is the only barrier preventing ignition, instruments should be replaced or modified by the manufacturer to make improper sequencing impossible.

Controlling Oxygen

Some operations use atmospheres inerted with nitrogen or argon as a flammability control. This is discussed for specific situations later in this section.

10.6.2.2 Passive Design Features and Fire Hazard Controls

Duct Runs

The design of the duct runs can greatly influence the effect of a fire in the facility or within the ductwork on the ability of the confinement ventilation system to perform its function. This section will address the physical configuration aspects of the ducts and filter housings. Ductwork and related equipment are required to comply with the criteria of NFPA 90A[10], *Installation of Air Conditioning and Ventilation Systems* and NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids*.[23] These standards provide explicit requirements for integrating the ventilation system with the building construction, as well as operational guidance for systems inspection, cleaning, and maintenance. Other sections address the active fire protection or cooling systems that may be needed to maintain confinement ventilation system functionality.

Another significant consideration in the design and layout of an air cleaning system is provision of separate systems for each building fire area. Buildings are subdivided into discrete fire areas to limit fire damage to only one area. If fire area boundaries are penetrated to allow passage of the air cleaning ducts, the possibility of fire spreading to multiple fire areas is introduced, potentially resulting in much more extensive fire damage.

Duct Response to Fire

There may be situations where fire dampers cannot be installed at firewall duct penetrations because of the need to maintain confinement ventilation. In some cases, ducting may traverse other fire areas before reaching the filter banks. The quality of the duct construction and installation are the most important factors in maintaining the integrity of the ducting. A number of factors need to be considered:

- Where the duct penetrates a firewall, distortion during a fire may allow flames to pass through the wall around the outside the duct. Investigators[24, 25] performed full-scale fire testing that provided insight into the performance of reinforced ducting under limited fire exposures.

- Conductive heat transfer through the duct may ignite combustible materials in adjacent fire areas. This can be mitigated by insulating or enclosing the duct as determined by the FHA.

- Duct collapse can occur due to weakening of the duct or the hangers when heated. Additional hangers and/or reinforcement will mitigate this potential problem.

- Where there are duct openings in a nonfire space, the FHA should consider the potential for fire spread and the need for additional safeguards.

Air Supply and Extraction

The method of air supply and extraction profoundly influences the efficiency with which a fire burns. Most gloveboxes are designed so that the air supply enters at the bottom on one side of the box and exits at the top on the other side. This design ensures that a vigorous fire will persist so long as fuel and air are available. If, the ventilation pattern is reversed and air enters at the top of the box and exits at the bottom, however, combustion products will mix with the supply air to weaken and ultimately extinguish the fire. This tactic is effective for all but very large enclosures.

Entrance Filters

Because the duct-entrance filter is the major dust collector, it is also the primary component in which a fire could occur. Protection of the HEPA filter downstream from sparks and burning fragments from the duct-entrance filter may be needed if the distance between them is not great. If it is less than 20 to 30 feet, a fine (20 to 30 mesh) screen may be installed downstream of the duct-entrance filter (such screens must be located where they are convenient for periodic cleaning). Because lint tends to bridge the openings, screens, and coarse filters (e.g., furnace filters), installation of fine-mesh screens on the face of the duct-entrance filter is not recommended; however, this does not preclude installation of a mesh screen for physical protection of the filter. For glovebox and hot cell applications, the duct-entrance filter should be designed for withdrawal into and replacement from the contained space. The filter should also be afforded maximum protection against the effects of or ignition by a fire in the contained space.

Prefilters

Prefilters are usually provided in the central filter house in addition to or instead of duct-entrance filters. Again, fire is more likely to occur in the prefilter than in the HEPA filter downstream. Prefilters should never be mounted directly on the face of the HEPA filter or on the opposite side of a common mounting frame with the HEPA filter (i.e., back to back). A spacing of at least 36 inches between the downstream face of the prefilter and the upstream face of the HEPA filter is recommended—not only for maintainability, but also to provide space where burning fragments and sparks can burn out or settle to the floor of the filter house.

Filter Housings

HEPA filter housings should be protected from facility fires by fire-rated construction. High temperatures in exhaust filter housings can be minimized by long runs of duct preceding the housings, by intake of dilution air from streams from other contained or occupied spaces of the building, or by cooling the outside of the duct with water spray. Cooling via water spray installed inside the duct has been employed in some applications (discussed in Section 10.6.2.3). The intent is to place the HEPA filters where they are least likely to be exposed to heat, hot sparks, and burning embers from a potential fire in the process line.

Fire Screens

A fire screen is a noncombustible sheet of meshed metal similar to a roughing filter that is intended to reduce the potential for transporting glowing embers/burning brands through the airstream from the fire source to the filter banks. The screen should be installed upstream from the prefilter(s) and ahead of the filter housings. Specific design criteria for fire screens can be found in DOE Standard 1066-99.[1]

Materials

Ideally, all construction materials used in confinement ventilation system enclosures should be noncombustible. Use of noncombustible materials for the enclosure will help limit the total amount of fuel available to burn if a fire occurs. If suitable noncombustible materials cannot be used because of process, shielding, corrosion-resistance, or other special purpose requirements, attempts should be made to minimize the quantity and surface area of the installed combustible materials. If a combustible duct material is utilized, installation of automatic sprinklers may be required according to DOE, NFPA, or FM Global requirements.

The preferred construction materials for ductwork are steel, stainless steel, or galvanized steel. If fiberglass ductwork is needed because of corrosion issues, special ductwork that meets the flame-spread criteria in NFPA 90A[10] is required. Acoustic linings or duct silencing materials are combustible and are not permitted inside air cleaning system ductwork.

Filter Construction

Wood is frequently used for HEPA filter casings. For this application, the wood is required to have undergone a fire retardant treatment that results in a flame spread of 25 or less and a smoke-developed rating of 50 or less when tested to American Society for Testing and Materials (ASTM) Standard E-84.[26] This test measures the speed at which flames will travel across the surface of the material being tested. As a comparison, the flame spread of red oak boards is 100, while the flame spread of concrete or unpainted steel is zero. Thus, even with the fire retardant treatment, wooden filter frames will burn in a sufficiently severe exposure fire.

Duct entrances and prefilters are required to be classified as Class 1 Air Filter units in accordance with UL Standard 900.[14] This is a different test method than is used for HEPA filters and is intended to evaluate the combustibility and amount of smoke generated for air filter units of both washable and throwaway types when they are clean. Class 1 filters, when exposed to flames, do not contribute fuel to the fire and will emit only limited quantities of smoke. Class 2 Filters burn moderately and emit moderate amounts of smoke. Either filter class will burn vigorously if it becomes dust loaded.

Fire Barriers

HEPA filter housings located within nuclear or hazardous process buildings are required to be separated from the remainder of the building by a minimum of 2-hour-rated fire barriers. This requirement is intended to ensure HEPA filters are protected from fires occurring in the process building. One common type of 2-hour-rated barrier is constructed of 8-inch-thick concrete block walls and a poured concrete ceiling. Another way to provide this level of protection is to locate the filter housing outside of the process building. If the filter housing is located in a separate building, no specialized fire barriers are necessary, provided the housing is located at least 20 feet from the process buildings and the exterior walls of the buildings have no unprotected openings. If the filter housing is located less than 20 feet but more than 5 feet from the process building, the filter housing is required to be constructed as a 1-hour-rated fire barrier. Filter housings are required to be installed in 2-hour-rated firewalls if they are less than 5 feet from the process buildings.

Small filter housings, which have a leading-edge surface area of 16 square feet or less, are not required to be separated from the rest of the building, provided the building has area-wide automatic sprinklers and the housing has an internal fire suppression system.

Penetrations through the air cleaning system enclosure fire barriers are only permitted for services necessary to the operation of the filtering system. Where penetrations cannot be avoided, the openings created through the fire barrier must be properly sealed with approved, fire-rated, noncombustible penetration seal materials. Penetration seals are tested and approved under the requirements of ASTM E-814, *Fire Tests of Through Penetration Fire Stops.*[27] The penetration seals must also be compatible with and capable of continued exposure to the types of materials and atmospheres present inside the filter enclosure. Doors in 2-hour-rated enclosures are required to be Class B fire door assemblies. Doors in 1-hour-rated enclosures are required to be Class C fire door assemblies. The requirements for construction and installation of fire doors are found in NFPA 80, *Fire Doors and Windows.*[28] HVAC ducts that penetrate 2-hour-rated enclosures must be protected with UL-listed fire dampers. HVAC ducts that penetrate 1-hour-rated enclosures are not required to have fire dampers. In some cases, it is necessary for ductwork that is part of the nuclear air cleaning system to penetrate fire-rated barriers. Fire dampers cannot be installed in these ducts because their operation during a fire would cause the dampers to close, sealing off the ductwork. This would prevent the filtration system from continuing to operate. Because the air cleaning system is required to be functional at all times, an alternative method of fire protection must be provided. It is recommended that a fire protection engineer be consulted to evaluate such configurations on a case-by-case basis. [Note: DOE has granted an exemption on the use of fire dampers for certain configurations of ductwork in an existing building where alterations would have been difficult due to highly contaminated conditions.] Each of the above features requires the design to be adjusted to the process under consideration. When changes are made to the process, each of the design features needs to be reviewed to ensure that nothing has been introduced that would make the fire system ineffective.

10.6.2.3 Active Design Features and Fire Hazard Controls

One of the goals of the nuclear industry has been to provide gloveboxes, caves, canyons, hot cells, fume hoods, and other radiological confinement areas with practical ventilation exhaust systems that can remain in service through a fire and can contain all the radioactive contamination made airborne by the fire. It has been established by both consensus standards and industry/government regulations that ventilation components in nuclear air cleaning systems should continue to perform their safety functions effectively under all conditions by confining radioactive or other potentially dangerous materials. To realize this for fire protection purposes, it is necessary to protect the filter housing in the exhaust system from heat, smoke, and burning material that would be generated during a fire scenario. In the event of fire, the release of contaminated smoke through a ruptured or damaged filter housing may have more serious consequences than any potential casualty losses from the fire itself.

Fire Dampers

Fire dampers in ductwork penetrating fire-rated construction <u>should not be utilized</u> in confinement ventilation systems with the following design features: (1) where the ducting is a integral part of the nuclear air filter system, and (2) where equipment is required to continuously function. Such duct material penetration of fire-rated construction without fire dampers should: (1) be made part of the fire-rated construction by either wrapping, spraying, or enclosing the duct with an approved material, or by other means of separating the duct material from other parts of the building with equivalent required fire-rated construction by either wrapping, spraying, or enclosing the duct with an approved material; or (2) be qualified by an engineering analysis for a 2-hour fire-rated exposure to the duct at the penetration location where the duct maintains integrity at the duct penetration with no flame penetration through the fire wall after a 2-hour fire exposure. [21]

Fire Detection Systems

Detection equipment for early warning of fire conditions must be provided in all HEPA filter housings. Rate anticipation heat detectors are most commonly used because of their good stability, low maintenance requirements, and relatively quick response to heat.

Sampling types of smoke detection systems has been suggested as a means to provide early warning, however, precautions must be taken to ensure they do not provide a leak path that bypasses the filters.

Alternative fire detection methods are possible depending on the specific design of the filter enclosure. If flammable liquids or gases are used and the possibility of explosion exists, rapid detection using flame detection devices may be needed.

NFPA Standard 72[29] provides the requirements for the installation of fire detection devices and systems.

Automatic Fire Suppression Systems

Prior to the Brown's Ferry nuclear power plant fire in 1975, the use of water on electrical fires was not considered a safe practice by the nuclear power industry. Following the Brown's Ferry fire (see NRC NUREG-0050, *Recommendations Related to the Brown's Ferry Fire*),[30] in Factory Mutual (now FM Global) and other organizations performed studies to test the use of water in electrical spaces (see Electric Power

Research Institute (EPRI) NP-1881[31] and EPRI NP-2660).[32] In addition, Sandia National Laboratories (SNL) performed tests on cable tray protection schemes (see NRC NUREG/CR-2377,[33] NUREG/CR-2607,[34] and NUREG/CR-3656).[35] These studies by Factory Mutual and other organizations showed that fighting fires in grouped cables could be accomplished efficiently using water (these tests were done on unenergized electrical cables, however, the conclusions on the use of water as an efficient extinguishing agent were confirmed). Following the Brown's Ferry fire and the tests performed by Factory Mutual, SNL, and others, the inhibition against using water to put out fires in all spaces with electrical equipment seemed to subside, and fire protection engineers made more deliberate assessments of the type of electrical occupancy when considering use of water as a fire suppressant.[36, 37]

Automatic fire suppression systems throughout a facility will control a fire in its early stages of growth, thus mitigating fire effects that could affect the functionality of the confinement ventilation system. Wet pipe sprinkler systems are the most common type of automatic fire suppression system and have a proven experience record of fire extinguishment. Other types exist and are described further in this section. Activation of a suppression system will extinguish an incipient fire and automatically alert dispatchers or the fire department.

Consideration must be given during the design phase to testing and maintenance of fire suppression and fire detection systems throughout the life of the system/facility. Consideration also must be given to avoiding interference with or inhibition of the safety function of other safety features (i.e., water addition/criticality controls, HEPA filters, etc.).

Wet Pipe Sprinkler Systems

Wet pipe sprinkler systems are used to control the fire potential in the areas being exhausted by the confinement ventilation system. They will control the fire to limit the threat to the facility and the HEPA filters, and also will prevent physical fire damage to the ductwork of the confinement ventilation system.

The need for wet pipe sprinkler protection is established by DOE or NRC requirements, or the FHA. The design requirements for these systems are contained in NFPA Standard 13, *Installation Of Sprinkler Systems*.[38]

Deluge and Water Spray Systems

A deluge sprinkler system is one in which the sprinklers are normally open and water flow is controlled by a valve in the line leading to the sprinkler heads. When this valve is opened, water is discharged from all the open sprinklers at the same time.

Two types of deluge systems are required for protection of HEPA filter housings. The first type, automatically-actuated deluge systems, are located upstream of the demisters. This type of system is also called a water curtain, as it consists of closely spaced, open-head, deluge nozzles connected to piping located in front of and above the demisters. When the system is activated, all of the nozzles spray water simultaneously downward, forming a wall of water. This system is intended to cool incoming air, hot sparks, and flames before the prefilters are threatened. The water curtain is located upstream of the demisters so the water spray carryover can be diverted to prevent moisture from reaching the downstream HEPA filters.

Operation of an automatic deluge spray system is initiated by a fire detection system located in the ducting—usually heat detectors. The detection system opens a deluge valve, allowing water flow to the nozzles. The spray nozzles are either open sprinkler heads from which the fusible link has been removed or special purpose nozzles designed to produce a particular pattern. The automatic system is also equipped with a locked bypass valve that can be manually opened if the detection system or the deluge valve fail to operate. Closed-head pilot sprinklers are sometimes used in place of an electrically-operated heat detection system to open the deluge valve to the nozzles. In this case, the pilot sprinklers serve only as temperature sensors and do not spray water.

Fires produce smoke that can cause rapid clogging of filters. Because the automatic spray deluge system functions much like the scrubbers that are used to clean smoke stack exhaust, there is an expectation that the automatic system may also reduce smoke clogging. However, the nozzles are not optimized for smoke reduction. In limited research with spray nozzles, it was found that smoke clogging decreased in some cases, but increased in others. Therefore, premature manual activation of the spray deluge system to reduce smoke is not recommended without further research to quantify results for specific arrangements and combustible contents. Operational procedures such as shutting down or throttling back the blowers to prevent rupture of clogged filters during a fire should be addressed in the authorization basis documents. The generic operational procedures provided here resulted from studies at a DOE site and are applicable to the procedures at most sites. Use of these procedures should be preceded by a thorough design review to ensure their specific applicability.

Demisters must be installed between the automatic spray nozzles and the HEPA filters. Demisters are specially configured metal panels that redirect the water droplet trajectory toward the floor of the enclosure. Performance criteria for demisters are contained elsewhere in this handbook. The demisters must be positioned at least 3 feet upstream of the HEPA filters, and approximately 6 inches downstream of the automatic deluge nozzles.

The second type of deluge system is a manual deluge spray system. This system is operated only if the filters begin to burn because it discharges water directly onto the first filter system. Burning cannot only breach the filters, but may also release particulate that has accumulated on the filters over time. Facilities without this manual system must rely on firefighters to attack HEPA filter fires with hose streams. The manual deluge system is intended to avoid unnecessary exposure of firefighters who must otherwise enter the hazardous environment within the housing, and also to ensure a more gentle application of water to make it possible for some filter stages to survive. The manual control valve for the manual deluge spray system is normally locked in the closed position and only accessible to firefighters. Fire department training programs should address operating procedures for these valves.

The potential for nozzle plugging or corrosion in housing deluge systems should be considered during design. Potential remedies include, but are not limited to, strainers, blow-off caps, and corrosion control measures such as use of special corrosion-resistant materials or coatings.

The automatic extinguishing systems must be designed to comply with the requirements of NFPA 13[38] and NFPA 15, *Water Spray Fixed Systems For Fire Protection.*[39] These standards provide the requirements for designing the system and selecting components, as well as associated installation requirements. Research conducted by Dow Chemical Company following the 1969 filter housing fire at Rocky Flats determined that the minimum water supply for the system must be hydraulically calculated to provide at least 0.25 gpm/ft^2 over the entire face area of the filters, or 1 gpm per 500 cfm of airflow, whichever is greater. The water curtain must be located 6 in. before the demisters. Standard deluge-type sprinkler heads must be installed on the piping at a minimum spacing of 4-foot intervals. The system must be activated by the rate-compensated heat detection system or by pilot-operated sprinklers. A manually operated release must also be installed on the deluge valve in the event a malfunction in the releasing system occurs. The use of corrosion-resistant deluge heads and piping should be considered for all installations.

Water Mist Systems

New watermist technologies are being developed that use fine water sprays to efficiently control, suppress, or extinguish fire using limited volumes of water. Their suitability for use in confinement ventilation systems has not been demonstrated at this time (refer to NFPA 750, *Standard on Water Mist Fire Protection Systems).*[40]

Sprinklers within Ductwork

Provision of wet-pipe sprinkler systems within ducts or filter housings is the exception rather than the rule, however, deluge sprinkler systems are routinely provided on carbon-filled adsorption systems in nuclear power reactors. On deluge systems for adsorption filters, fog nozzles with as fine a droplet-size distribution as possible are recommended for maximum cooling and smoke-particle capture. To limit the volume of water discharged, consideration should be given to an automatic recycling deluge system.

Demisters and HEPA Filters

Water protection for HEPA filters has been controversial due to concerns about water plugging of the filters. The research that led to this concern was based on conditions that are not reflected in an actual filter installation. Specifically, the research involved soaking filters in pans of water. However, in a properly designed confinement ventilation system, demisters prevent water from the automatic deluge system from reaching the filters. Manual deluge systems are only operated after the filters begin to burn. Consequently, water damage is no longer an issue. This topic is further discussed in DOE Standard 1066-99.[1]

Fire Department Standpipe Systems

Because the possibility of a fire that can affect the filters cannot be entirely eliminated; some provision for manual fire fighting using a standpipe system (meeting the requirements of NFPA 14 *Standard for the Design and Installation of Standpipe and Hose Systems* [41] is necessary. The fire department will almost always use its own hose packs.

The use of a hose stream can only be considered when all other automatic and manual safeguards have been determined to fail. Filters cannot be saved, but hose streams may prevent fire spread to subsequent stages of filters and avoid failure of the final filter stage that could release contamination. In addition, a hose stream can serve to prevent further damage to the filter mounting frames and housing, the duct, or the building. Similar observations can be made for the common types of sprinkler systems, both automatic and manually actuated, if they are installed inside the filter housing.

Water Runoff Collection

Facilities protected by sprinklers or deluge systems must have a provision to collect and dispose of water used for fire extinguishing. In addition, design of the water drainage system has to be consistent with the characteristic of water as a neutron moderator.

Gaseous Agent Systems

Some spaces external to the ductwork of ventilation systems are protected with gaseous agent fire suppression systems. There are NFPA standards for the design of these systems that include Halon alternatives and carbon dioxide systems. Competent technical persons should be consulted to design these systems.

Flammable Gas Detection

If flammable gases are used, the FHA may require flammable gas detection equipment in the ductwork or filter housings. The installed gas detectors must be connected to an alarm system located at a continuously attended position to ensure immediate corrective actions are taken if high flammable vapor concentrations are detected. The effective design of systems to detect flammable gases depends on the gases themselves, the airflow characteristics within the confinement ventilation system, the actions that must be taken in response to unacceptable concentrations of flammable gases, and many other factors. Systems that do not adequately address the issues may either not work at all or will provide false alarms on a frequent basis which can be an equally bad situation. Competent technical persons who are knowledgeable of the hazards present and the design of such systems should be consulted to design these systems.

Protection of Carbon-Filled Adsorption Systems

To prevent loss of confinement for radioactive iodine and iodine compounds, carbon-bed temperatures must be maintained at a level where impregnants and trapped radioiodine cannot desorb. This requires the bed(s) to be large enough that specific loadings of iodine cannot exceed 2.5 mg/g of carbon, and that airflow through the bed can be maintained at some level in excess of 6 (preferably 10) linear fpm. If bed temperatures can be maintained below the level where desorption of impregnants and trapped radioiodine takes place, carbon ignition is unlikely. If a fire should start, however, total flooding or dumping of the carbon into a container of water is the only effective means of extinguishing a carbon bed fire that is known at this time. Carbon dioxide and gaseous nitrogen are ineffective against activated carbon fires because the fire feeds on the oxygen adsorbed in the pores of the carbon, and the quantity of liquid nitrogen required to provide effective cooling would be unavailable in most cases.

Combustible Metals

Metal fires, particularly fires in water-reactive metals such as sodium, present special problems. Water and inerting agents such as Halon alternatives cannot be used, and inert atmospheres such as nitrogen and carbon dioxide require practically the total exclusion of oxygen to be effective. The fire must be treated in the operating space before it can reach the ducts or filters, which requires an effective duct entrance filter, preferably one of the HEPA type if the metal dusts are finely divided. However, most of the fire-extinguishing agents that are effective against such fires produce copious clouds of dust that, when released, rapidly threaten to plug the duct entrance filter. This in turn threatens overpressurization of the glovebox or hot cell, resulting in blowback of contamination to occupied spaces of the building. Carbon microspheres[5] have been shown to be extremely effective against plutonium, sodium, uranium, sodium-potassium, magnesium, aluminum, lithium, and other types of fire that produce intense heat. The material can be dispensed automatically or manually and produces essentially no dust when dispensed either way. In addition, it has negligible chloride content (and so poses no threat to stainless steel equipment and cells), is very easy to cleanup, is inexpensive, and is readily available.

When combustible metals are being processed, the potential presence of combustible dusts in both the airstream and inside the filter enclosure should be considered in the FHA. Appropriate hazard controls should be provided as necessary (duct-entrance filters alone will not prevent dust from entering the ducting).

10.6.2.4 Discussion of Other Filter Types

Small Filter Assemblies in Plywood Enclosures

Some smaller HEPA filter assemblies are purchased as a single package. These are often self-contained in assemblies constructed of plywood or other wooden composite material. These assemblies have male duct connections on their inlet and discharge sides, and are easily dropped into place by clamping existing ducts onto them. Given the lack of fire resistive properties of these filter assemblies, it is not recommended that they be used in new construction.

High-Efficiency Metal Fiber Filter Systems

High-efficiency metal fiber (HEMF) filter systems have only been commercially available in the United States since the mid-1980s. They are made of sintered stainless steel fibers that are welded into steel housings and steel frames. These filters have been used in small, specialized exhaust systems, but have not yet been sufficiently developed to be equivalent to HEPA filters.

In contrast to HEPA filters, HEMF filters are not weakened by moisture impingement. They can also operate for longer time periods and in hotter conditions than HEPA filters because the metal filters contain no flammable components, and are inherently resistant to high temperatures. However, the finely divided filter media in a metal filter will not resist a direct flame impingement. The resistance of the metal filter to moisture and heat makes this filter attractive for fire protection purposes. Because the use of HEMF filters is relatively new to the DOE community, only limited experiential data on the behavior of these filters in actual fires is available. They are also very expensive to purchase and operate.

Radioiodine Absorber Air Cleaning Systems

Although much discussion in the nuclear community has been generated in the past 40 years regarding fire protection of absorbers, little consensus and few conclusions have been reached about the proper method of extinguishing fires in absorbers with combustible material. Available methods include: (1) using a combination of manual and automatic water spray systems, (2) limiting airflow to the absorbers, and (3) using alternative noncombustible absorber media (e.g., silver zeolite). Absorber air cleaning systems are often used in nuclear reactor emergency ventilation confinement systems where they are frequently referred to as charcoal- or carbon-type filters. Other inorganic absorber materials are available for absorber media, including silver oxide, silver nitrate, aluminum silicate, and silver zeolite. It is generally accepted that, as a minimum, absorbers should be provided with fire detection equipment.

For carbon-type filters, American Nuclear Insurers, an insurance carrier for nuclear power plants, recommends the following fire protection:

- Charcoal filters should have a hydraulically designed, automatic water spray system that uses directional, solid-cone spray nozzles controlled by an approved deluge valve. The system should be capable of being manually actuated from a suitably remote location.

- Spray nozzles for horizontal beds or drawers should be oriented above each bed or drawer and should be designed to distribute water evenly across the top of each bed or drawer at a minimum density of 0.25 gpm/ft^2.

- Spray nozzles for vertical beds should be oriented at the top of the bed and should be designed to distribute water evenly across the top of the bed at the rate of 3.2 gpm/ft^2 of charcoal bed.

- A supervised, fixed-temperature detection system should be provided and connected to an annunciator in the control room. The detectors should be located on the downstream side of the charcoal bed to facilitate timely, automatic operation of the spray systems. The spray system should be equipped with a local alarm and should be connected to an annunciator in the control room. The airflow should terminate (with the fan shut off) upon water activation.

- For the pressure vessel-type charcoal filter, where a shut-off bypass arrangement is employed around each tank, an automatic water spray system is not required. A hose connection should be available on the side of the tank to allow the introduction of water.

Deep-Bed Fiberglass Filter Systems

Early designs of deep-bed, fiberglass filters did not address filter media replacement. Fiberglass filters plug over time, resulting in combustible deposits that may contribute to fire risk. It is generally accepted that water applied to this type of filter media will extinguish the fire. Precautions should be taken when water is applied to filter media containing radioactive material to prevent the water from being released to the environment.

Deep-Bed Sand (DBS) Filter Systems

For the most part, DBS filters are fire-resistant, chemically inert, and require no special fire protection systems. Sand filters are usually accompanied by HEPA filters. When a sand filter is used in series with a HEPA filter, it should be upstream of the HEPA filter. In this position, the sand filter can protect the HEPA filter that provides the final confinement barrier. However, HEPAs have been traditionally installed prior to the sand filters for fear of sand fires carrying over and plugging the HEPAs.

Since plugging is a "worst case" scenario for both HEPA and DBS filter arrangements, both require mitigation measures. It has been largely accepted that DBS filters, while expensive to construct, decontaminate, and demolish, offer improved performance in their ability to operate in the presence of heat and fire products. However, no quantitative test results have been found to confirm that a DBS filtration system can withstand plugging by smoke particulates. While it has been empirically shown that DBS filters can resist high heat conditions, and some qualitative testing has shown a high degree of resistance to plugging compared to HEPA filters, this does not confirm how many particulates can be absorbed and the rate or conditions under which a DBS arrangement can operate without loss of efficiency. Indeed, DOE reports to this point are largely historical rather than experimental in nature. Tests on the physical properties of smoke and its effect on DBS filters need to be performed to establish obstruction limits for DBS filters.

Self-Cleaning Viscous Liquid Filters

This type of filter uses a viscous liquid for cleaning purposes. These filters should be avoided where radioactive materials are handled because they produce radioactive sludge that requires disposal. They also require special fire protection systems because of the combustible nature of the liquid.

Moving-Curtain Single-Pass Rolling Prefilters

One noteworthy type of prefilter is the moving-curtain single-pass rolling prefilter. This type of prefilter involves manually or automatically feeding a fresh filter media across the face of the filter frame while the dirty media is rewound onto a take-up roll. When the roll is exhausted, the takeup media is disposed of and a new media roll is installed. In 1980, LLNL performed fire tests involving this type of prefilter utilizing a modified commercial moving-curtain filter. The purpose of testing this type of filter was to find a way to limit or eliminate the smoke that may be produced in a fire, thus reducing the potential for the smoke to plug the HEPA filters. The tests validated that the moving-curtain single-pass rolling prefilter could reduce the potential for aerosol plugging of HEPA filters during a fire. The final test report stated that prefilters of this type were an "experimental prototype." Those considering this type of design should obtain a copy of the report and review the basis of the conclusions as they apply to a particular case.

Electrostatic Precipitator Prefilter

Another type of prefilter used at DOE facilities is the electrostatic precipitator (ESP) prefilter. This prefilter imparts an electrical charge to particles in the airflow stream, causing them to adhere to collector plates. The ESP prefilter has been used to extend the life of HEPA filters when processes involve larger-diameter airflow particles. An ESP prefilter provides some fire protection, as long as the particles resulting from the combustion products of a fire can be properly collected on the filter throughout the fire. Most commercially available ESP prefilters cannot catch the smaller airborne particles and smoke particles associated with a burning fire. However, more work needs to be done to understand which particle sizes associated with fire can be effectively filtered by an ESP prefilter. When ESP prefilters are used, they should be made of noncombustible materials and, as with any prefilter, the user should pay careful attention to preventing dust loading on the prefilter during use. In addition, ESP prefilters should not be used where explosive concentrations of gases or dusts are present.

Regenerable HEPA Filters

A study is being conducted at Savannah River Technology Center to develop a full-scale application of a regenerable HEPA filter. Previous attempts at this task were made at LLNL and involved the stainless steel matrix. These efforts proved less than satisfactory due to weight and efficiency considerations. The latest effort at Savannah River is a ceramic matrix with a sintered stainless steel coating. A backwash system is also provided for periodic in-place cleaning of the filters. This design holds a potential for long life similar to that of conventional HEPA filters, with a reduced potential for catastrophic failure due to media breakthroughs, moisture, or fires in the ventilation system. If fully validated at the demonstration level, this system could provide a solution to many fire protection issues. Whether or not this technology can be adapted to building ventilation systems with much larger airflow requirements has not been determined as of this writing. The space, pressure drop, and resistance requirements still need to be improved to make this technology useable on a widespread basis. With the development of such newer technologies, some design changes may be expected to optimize performance.

10.6.2.5 Fire Protection Concepts for Gloveboxes

Fire protection and prevention in gloveboxes is mainly accomplished via the following methods:

- Using noncombustible construction materials. (For information on gloves and windows, which are more vulnerable to fire damage, refer to DOE Standard 1066-99.[1])

- Adhering to acceptable housekeeping policies and procedures.

- Avoiding the use of flammable materials within the box wherever possible. (When no suitable nonhazardous substance can be substituted, the amount of flammables is limited to the minimum required for immediate use. The containers used for flammable substances are safest available for the planned operation.)

- Maintaining a current in-box material inventory. (The box is not used for storage. Boxes usually are inappropriate for storage, especially for chemicals.)

- Establishing a safer, nonoperative box configuration and periodically checking it to ensure that nonoperating boxes are in a safe condition. (Precautions include isolating boxes by closing fire stops, checking through-flow, checking port covers, disconnecting electrical equipment, and removing corrosives.)

- Designing the box with down-draft ventilation (high air inlet, low outlet) to inhibit combustion while still purging the box.

- Providing a protective atmosphere. (This measure is listed last because those preceding it apply to all gloveboxes, whereas inerting is used only when there is too much risk involved in operating without a protective atmosphere. Assessing the degree of risk involved in an operation is often a subjective evaluation.)

10.6.2.6 Protective Atmospheres

The inerting atmosphere system is designed for continuous operation, whereas the extinguishing system usually has a one- or two-shot, single-incident application before reservicing is required to return the system to the ready state.

Inerting with smothering agents may require that less than l percent oxygen be present in the glovebox atmosphere. Process and product-purity considerations may require as little as 100 ppm of total atmospheric impurities within the glovebox for successful operation. Since many of the detailed considerations are similar for high-purity and fire protection inerting, and because of the widespread application of high-purity inerting, most of this discussion will involve high-purity systems. The best single reference for design, construction, and operational information is *Inert Atmospheres 2* by White and Smith.[17]

Inert-atmosphere gloveboxes that contain radioactive material are operated at pressure differentials of 0.3 to 1.0 in.wg negative pressure relative to the surroundings. The gas flow rate is usually determined by the atmospheric purity required and the purity of the incoming gas. The box atmosphere purity can be compromised by air leakage into the box or into service connections, as well as leakage from process equipment in the box.

Filter installation requirements in inert atmosphere gloveboxes are more stringent than those for air-ventilated boxes because acceptable box air leakage rates are generally less than 0.0005 box volume/hr.[2] To attain this standard, joints and fastenings between items of equipment and materials (gaskets and seals) must have extremely low gas permeability. Full-welded joints are recommended for all permanent fixtures. Gasketed joints may deteriorate in service, imposing continuing costs for periodic testing and repair.

Low-leak systems require quality construction for all components including boxes, filters, and associated ducts. Any in-leakage associated with the filter mounting or connecting duct will adversely affect the quality of the inert atmosphere that can be maintained in the box, and thus the cost of inert gas purification. Penetrations must be minimized in both number and size. The use of smaller HEPA filters allows smaller ports for maintenance. Filter changes should be planned for times when other maintenance operations (routine or special) are taking place inside the box to reduce interruptions to operations, to reduce the loss of inert gas, and to minimize the time required to recondition box spaces.

For fire protection, the preventive step of inerting is more satisfactory, though more expensive, than extinguishing a fire if it does occur. However, oxygen must be reduced below l percent before it fails to support the burning of some pyrophoric metal.[18] The use of dry air (relative humidity less than 20 percent) reduces the hazard of pyrophoric metal fires, but does not eliminate it. Moisture in the presence of heated pyrophoric or reactive metals, such as finely divided plutonium, increases the possibility of explosion by generating hydrogen. The suitability and cost of an inert gas for the process are significant factors when selecting this type of fire control. The gas flow rate in most inert gas boxes is kept as low as possible to be consistent with required box-atmosphere purity levels; low-capacity filters are frequently used. The inert gas may be purged on a once-through basis or recirculated through a purification unit. A word of caution concerning commercially available (off-the-shelf) recirculating gloveboxes: on one occasion at a DOE installation, there was a problem with oil mists developing in the recirculating pumps and being circulated along with the inert gas. Off-the-shelf items cannot be used in a confinement-type ventilation system without evaluation, nor can they be applied as “black boxes” by those responsible for operational safety.

10.7 Operations and Maintenance Practices for Fire Protection of Confinement Ventilation Systems

10.7.1 Essential Elements

The protection of confinement ventilation systems during a fire situation depends on the reliable functioning of the procedures, systems, and barriers as they were designed and intended to function. To retain that design capability, it is critical that maintenance and surveillance of systems be accomplished on an established schedule. Procedures must be practiced, and systems must be regularly inspected to locate problems that may require alteration of the maintenance practices and operational procedures. If these things are not done, the ability of the confinement ventilation system to function when needed may be impaired.

10.7.1.1 Fire Prevention

The most critical aspect of fire prevention is fuel control. The storage of any extraneous combustible materials in filter enclosures or areas where radioactive materials are being handled must be prohibited.

Procedures for the use of flammable liquids and gases must be in place and followed. Quantities of flammable liquids and gases must be limited to only those required to perform any task.

Accumulation of dust and debris inside the confinement ventilation system ductwork over long periods of operation increases the consequences of any fires that might occur. Periodic cleaning is required to eliminate the presence of undesired fuel.

Appropriate procedures and controls must be in place and followed to prevent fire involving pyrophoric radioactive materials. Much experience exists on the start of fires in nuclear facilities and confinement ventilation systems. The lessons of the past should be applied to prevent fire from occurring in confinement ventilation systems, or where a fire occurs, a loss of the first line of defense.

10.7.1.2 Procedures

Procedures for safe operation of a facility are required by law. All hazards and necessary controls must be delineated in existing operational procedures. Fire protection procedures must complement a facility's safety documentation required by law or contractual obligations.

10.7.1.3 Inspection, Testing, and Maintenance

Inspection, testing, and maintenance requirements for fire detection and suppression systems are outlined in the NFPA standards. A program should exist that follows either the NFPA standards or a carefully thought-out alternative program that provides an equivalent degree of reliability.

Inspection, testing, and maintenance plans must have been established and implemented for all systems in the facility and its confinement ventilation system, both passive and active.

Limited life materials that will wear out in a relatively short time should be identified and replaced according to an established plan.

It is important that water-based fire suppression systems be designed such that they do not have to discharge water on HEPA filter media. Any exposure to water will significantly weaken the filter media and can result in an undesired loss of filtration due to the filter media physically failing. Systems must be designed such that they can be discharge tested without having to actually spray water on the filter media.

10.7.1.4 Impairment Planning

A program must exist to handle situations where fire detection and suppression systems are impaired. Pre-plans must be developed and instituted to guide facility operations when these systems are not functioning as they should. Impairment plans also must exist for other critical facility systems. The occurrence of an impairment is not the time to develop such plans. All impairment plans must be analyzed to identify and control to the greatest possible extent the hazards that may exist under a given condition.

Impairment plans should be exercised on a regular basis to maintain proficiency in their execution.

10.7.1.5 Modifications

Modifications in a nuclear facility must follow the protocols for Unreviewed Safety Question determination. This is a somewhat roundabout means of identifying the impact to the established safety basis and all that goes with that, but it is what the current culture understands and accepts. Configuration control must be maintained when modifications are made so that all changes are tracked across all affected documentation and all impacts are identified and understood.

10.7.1.6 Other Considerations

Emergency Planning

The successful mitigation of a fire in a nuclear facility containing a confinement ventilation system requires emergency planning and exercises involving all entities that may be called on to mitigate a fire situation. Post-fire recovery plans should exist to aid in the resumption of work in the facility after a fire.

Technical Safety Requirements Tie-in

Maintenance and operational procedures may be formalized in the nuclear facility's Technical Safety Requirements.

Quality Assurance

All aspects of operations should be tied in to the facility's Quality Assurance Program, which covers all of the areas required to produce quality work and to operate safely.

Assessments

Periodic management and independent assessment are necessary to ensure that established requirements are adequate and are properly implemented.

10.8 Generic Firefighting Procedures

The following recommendations apply to firefighting procedures and instructions. They provide a strategy that minimizes the likelihood of losing filtered, forced ventilation during a fire. These procedures were derived from extensive work at Rocky Flats and are included here because they are generically applicable to all DOE facilities where active fire protection measures are installed for filter housing protection.

A special need for nuclear facilities with confinement ventilation systems is smoke venting. Obviously, smoke cannot be vented to the exterior, but there may be methods to use the confinement ventilation system to assist in removing some smoke from the fire area to enable more rapid intervention in manual suppression of the fire.

10.8.1 Control Ventilation Configurations, Volumes, and Flow Rates in the Field

An individual who is responsible for ventilation control (and successors or alternates in case of unavailability) must be established in the facility emergency planning documentation. This individual must work in consultation with the fire department sector officer stationed in the control room or at the housing to ensure a fire emergency will be successfully mitigated with minimal impact.

Differential pressure (DP) changes in the initial filter stages must be continuously monitored, even if the DP gauge readout is exceeded. Most gauges have a maximum capability of 4 to 6 in.wg, but a rapid drop from an off-scale high reading to a lower reading will confirm stage failure, as will a significant rise in DP for the next downstream stage. Attention should be focused on the first stage and the next downstream stage until a first stage failure is indicated. A rise in DP may be due to progressive filter plugging from fire particulates or wetting of the filters from deluge spray. Because the initial filter stages are usually (but not always) viewed as sacrificial, the DP may be allowed to rise to the maximum achievable by the fan. If there is only one stage of filtration, then this is not applicable.

For housings with four stages, the SOE should monitor the second- and third-stage DP at the first indication of a loss of first-stage filter integrity. The third and fourth stage DP should be monitored if the second stage fails.

Ventilation on the affected housings should be throttled when DP across the final filter stage reaches 2 to 4 in.wg (4 in.wg is the current filter change-out criterion for normal operation).

Failure of initial stages and erosion of margin in the final filter stage is permitted if continued ventilation is necessary to support effective firefighting in the facility. If the fire department officer in charge judges that ventilation no longer provides a substantial advantage in controlling or containing the fire, and the emergency commander (generic term) validates that position, action should be taken to protect housing margin (e.g., ventilation should be discontinued at 2 in.wg DP on the final filter stage). Throttling, if selected, should be performed in a manner that maintains the actual DP reading on scale within the 2- to 4-in.wg readings at all times. In no case should ventilation be continued when 4 in.wg DP is reached across the final filter stage.

At the first indication of an explosion, the first-stage DP should be monitored for a rapid or complete loss of DP as an indication of failure. The second-stage DP should be immediately monitored under such conditions and the filters should be visually inspected if possible. If the second-stage DP is less than 0.5 in.wg, or greater than 4 in.wg, or if there is visible damage to the second stage, ventilation on the affected housing should be discontinued. The decision to shut down ventilation should be preplanned and well thought out. Explosive conditions that could clearly impact multiple stages are judged to present too great a risk to any remaining stage to warrant any attempts to maintain ventilation.

Ventilation should be restored to an affected housing only by the decision of the Emergency Commander or an approved Recovery Plan.

Restoration of ventilation should be considered likely to result in a forced convection release from the facility unless other recovery efforts have confirmed no airborne contamination is present in the facility. The decision to restore ventilation also should be preplanned and well thought out.

10.8.2 Activation of the Manual Deluge System

The manual deluge system provides an important emergency capability should the first-stage filters be in danger of being consumed by fire. However, manual deluge system activation will likely result in loss of the first stage of filters either through plugging or media failure. Consideration may be given to intermittently flowing the deluge systems with the fans shut down when doing so for short time periods. Before actuating the manual deluge system, the following recommendations should be followed:

- Direct impingement of flame or burning embers on the first stage filters should be visually confirmed, if possible.

- The manual deluge system should be activated only when it is clearly required, because activation is likely to damage the filters, could cause plugging, and could stop ventilation. Early activation of manual deluge as a precautionary measure is considered imprudent. If the viewing ports are accessible, they should be used to facilitate confirmation of filter integrity (i.e., visible flaming or smoldering of filter media). Where viewing ports are inaccessible, the inner access doors to the airlocks should be used as alternative viewing ports.

- The manual deluge system should be activated only when the fire department officer in charge decides it is necessary, based on a determination from the available evidence that flame is present in the first stage of filters.

- The person in charge of ventilation control at the facility should be authorized to initiate the manual deluge system as necessary prior to fire department arrival. Possible filter plugging and shutdown of ventilation should be anticipated once manual deluge is activated.

- The initial filter stages should be monitored for evidence of plugging or blowout of the first-stage filter (DP changes) and for evidence of either particulate buildup/wetting (DP changes) or flame (visual) on the second and subsequent stages. If flame is confirmed on any downstream stage, all fans connected to the affected housing should be secured immediately.

10.8.3 Deluge System Flow Times

The following recommendations address when the deluge system flow should be terminated.

- The housing deluge system flow should be discontinued upon visual verification by the fire department incident commander or other authorized personnel if:

  – (automatic system) there is no visible smoke in the housing upstream of the spray nozzles and temperatures in the filter housings have dropped to safe levels; or

  – (manual system) the fire involving the first stage is extinguished and the spray duration is judged to have sufficiently cooled the filter media and frame.

- Only the fire department incident commander or other authorized personnel should terminate the flow prior to meeting these criteria. Ventilation should only be restored to the affected housing following a decision by Emergency Commander or in accordance with an approved Recovery Plan.

- If filter plugging is preventing effective ventilation, removal of the plugged media should restore ventilation. However, restoration of ventilation is likely to result in a forced convection release from the facility unless other recovery efforts have confirmed there is no airborne contamination in the facility.

The removal of plugged filter media in a confinement ventilation system during a fire situation is fraught with hazards, of course, and should only be done in extreme circumstances.

10.8.4 Manual Activation of the Automatic Deluge System

Early activation of the automatic deluge system could increase the potential for the first filter stage to survive. For this reason, the automatic deluge system may be activated manually rather than waiting for high-temperature actuation where early activation provides an advantage. The decision to activate the system should be made by the fire department incident commander and/or the authorized person in charge of ventilation control at the facility based on initial assessment of the fire condition. Small fires that are under control and expected to be quickly extinguished would not challenge the HEPA filters sufficiently to warrant activation of the system. In addition, the limited available data indicate that early activation is not beneficial in reducing the potential for smoke-induced plugging for those housings equipped with fog jet nozzles for automatic deluge, and the procedures should not call for early activation of the automatic deluge system for those housings. Extensive preplanning should be conducted to define as much as possible the situations in which the automatic deluge system would be manually actuated.

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CHAPTER 11

OCCUPATIONAL SAFETY AND HEALTH

11.1 Industrial Hygiene

11.1.1 Chemical Safety and Hazard Communication

Ventilation systems control exposures to toxic and radiological materials, therefore, ventilation system filters can collect hazardous materials. In addition to exposure to the hazardous materials contained in the ventilation system or on filters, workers are often exposed to chemicals, such as test aerosols, when conducting testing. Workers can also be exposed to a wide variety of process materials including large amounts of inert gas. Equipment such as cryogenic systems can vent materials such as liquid nitrogen into ventilation systems. Such materials expand to produce large volumes of inert gas, which may produce an oxygen-deficient atmosphere. Some fire protection systems may also use large amounts of gas.

Workers can be exposed to toxic chemicals by several routes such as inhalation, ingestion, contact with or absorption through the skin, and penetration of the skin via wounds. Chemicals may produce a variety of undesirable effects in the body, including: asphyxiation, irritation, anesthesia sensitization, reproductive toxicity and cancer.

U.S. Occupational Safety and Health Administration (OSHA) standards (29 CFR 1910.1200, *Hazard Communication*)[1] require employers to implement a hazard communication program to inform workers about the risks associated with chemical use. The Hazard Communication Standard requires that employers take specific actions, including making material safety data sheets for each material available to employees and training employees to recognize hazardous materials and use them safely.

Hazards of materials are also described on container labels. Personnel should be in the habit of reading the labels of containers of materials they are using for the first time to become aware of potential hazards.

Workers may consult material safety data sheets for information on hazardous materials such as components, possible toxic effects, other hazards such as fire and explosion, sources of additional information, and recommended control measures. Exposure limits for specific chemicals are contained in 29 CFR 1910, Subpart Z.[2] Additional recommendations on exposure limits are contained in the American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TLV) list.

11.1.2 Noise

Noise can be a significant concern for personnel working on ventilation systems. Motors, fans, and other machinery along with airflow can create significant levels of sound. Even when workers shut down ventilation systems, equipment rooms often contain other sound sources. Routine maintenance and surveillance activities may also expose workers to increased sound levels. It is common at most sites for facility engineers to make periodic walkthroughs to verify proper operation of filter systems, thus putting workers at risk in a high noise environment. The practice of removing hearing protection while in the high noise is discouraged. Removal of hearing protection increases the worker's exposure to noise and may violate regulations.

While sound can affect the human body in various ways, the most important is loss of hearing. Several types of hearing loss have been identified, but two, conductive and sensorineural (involving the sensory nerves), are more important in the workplace. Conductive hearing loss occurs when sound pressure cannot reach the inner ear. Conductive hearing loss is rarely the result of workplace exposures, but may be caused by extremely high peak noise levels such as an explosion or a traumatic injury to the ear. Sensorineural hearing loss is the inability of the ear to convert pressure variations into nervous impulses that the brain can interpret as sound. The most important workplace-related cause for sensorineural hearing loss is exposure to high levels of sound. Sound-induced hearing loss can happen gradually over a period of years, which makes the hearing loss difficult to detect. Another reason that this type of hearing loss is difficult to detect is that excessive sound usually causes hearing loss at some frequencies more than others. The person suffering from sensorineural hearing loss may be able to hear sounds such as speech, but may not be able to understand what is being said.

OSHA regulations require that employers implement a hearing conservation program for employees exposed to high levels of sound. This program includes sound measurements, training, record-keeping, and audiometric testing.

The minimum standard for noise protection and hearing conservation is the OSHA regulation for noise, 29 CFR 1910.95.[3] Sound intensity is measured on the decibel (dB) (A) scale [dBA]. The dB(A) scale measures sound intensity over the whole range of audible frequencies (different pitches), and then it uses a weighing scheme which accounts for the fact that the human ear has a sensitivity to each different sound frequency. For further information on sound intensity scales, see the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) *Handbook of Fundamentals*, Chapter 7, "Sound and Vibration" 2001.[4] Code of Federal Regulations, 29 CFR 1910.95,[3] requirements allow exposures to noise of 90 dBA for 8 hours and halves the permissible exposure time for every 5-dBA increase in noise level. Some hearing conservation programs are based upon allowing exposures to 85 dBA for 8 hours and halving the permissible exposure time for every 3-dBA increase in noise level, as specified in the TLV for noise. Noise levels are often given in dBA units. The definition of a dB of sound pressure ("noise") level is such that noise intensity is reduced 10-fold for every 20 dB reduction of noise level.

Excessive sound is best reduced with engineering controls such as vibration isolation and selection of quieter equipment. However, those who work with ventilation systems may need to use administrative controls and personal protective equipment (PPE). Administrative controls may involve changing work schedules to reduce the length of exposure and/or the number of workers exposed. This may include rotating employees' duties or work locations so that no employee receives a significant exposure. Another administrative control is scheduling sound-producing work during hours when fewer workers are around.

If engineering and administrative controls cannot completely reduce the sound to acceptable levels, then workers must use hearing protective devices to provide additional control. The ability of such devices to reduce sound levels is expressed as the Noise Reduction Rating (NRR). The U.S. Environmental Protection Agency (EPA) defines the NRR as, "A single number noise reduction factor in decibels, determined by an empirically derived technique which takes into account performance variation of protectors in noise reducing effectiveness." According to EPA regulations, the NRR must be shown on the hearing protector package. In general, those devices with a higher NRR are better at reducing sound levels. However, NRR values are determined under ideal laboratory conditions and do not indicate exact sound level reduction under actual workplace conditions. Adjustments of the NRR are described in OSHA Standard 29 CFR 1910.95, Appendix B.[3] Selection of the specific adjustment method is dependent upon the employer's noise measuring instruments. Specific devices should be selected based on several factors such as the NRR, comfort, and interference with other personal protective devices such as respirators. There are three common types of hearing protective devices: aural inserts, superaural protectors, and earmuffs. Aural insert protectors are commonly referred to as earplugs. They come in many shapes and sizes and are made from a variety of materials. Superaural protectors seal the opening of the ear canal. A light band holds a soft material in the opening of the ear canal. These devices are generally easier to insert and remove than earplugs and are easier to reuse. However, some workers may find such devices uncomfortable, and they may not provide as much sound reduction as earplugs. Earmuffs consist of two cup-shaped devices that fit over the entire external ear and seal against the side of the head. A spring-loaded headband holds the cups in place. Earmuffs are generally more durable than earplugs and are easy to use. However, to be effective, earmuffs must form a complete seal to the side of the head. Anything that interferes with the seal (e.g., temples of glasses, hair, respirators) may significantly reduce the effectiveness of the muffs. A relatively new kind of earmuff uses electronic devices to cancel the incoming sound. These muffs are quite expensive, but may be useful in some situations.

11.1.3 Shock-Sensitive Materials

Laboratory personnel commonly use perchloric acid to prepare organic and inorganic materials for analysis. Perchloric acid is a strong oxidizing agent and reacts with many materials to form chemical compounds that are susceptible to detonation by heat, friction, or impact. Other shock-sensitive or reactive materials such as nitrates may also collect in ventilation systems. The accumulation of such compounds in hoods, fans, and ducts presents a potentially hazardous situation for maintenance personnel and others who may be exposed to ventilation systems. There are numerous examples of the accumulation of shock-sensitive compounds at U.S. Department of Energy (DOE) facilities, including the Chemical Metallurgical Research Building at Los Alamos National Laboratory in New Mexico.

There have been several explosions and fires at DOE facilities caused by contact with perchlorates. The most serious occurrence (1962) killed one worker and injured two others during routine maintenance work.[5] On several occasions at DOE sites, workers have had to stop activities when they found perchlorates in unexpected locations or at higher-than-expected levels.

Two articles in *Applied Occupational and Environmental Hygiene*[6, 7] describe activities conducted at Oak Ridge National Laboratory (ORNL) to address potential perchlorate contamination of ventilation systems. A team of laboratory personnel, including chemists, industrial hygienists, and fire protection engineers implemented a program with the following objectives:

- Identify ventilation systems where laboratory personnel have or are now using perchlorates.
- Develop sampling and analysis protocols.
- Develop procedures for estimating the amount of perchlorate present in the samples.
- Determine the threshold for what constitutes serious contamination.
- Generate a plan for decontamination of ventilation systems contaminated with perchlorates.

Identification of perchlorate contaminated ventilation systems may be difficult because some systems have been in use for many years, laboratory personnel have used the systems for a variety of purposes, and former users may be difficult to contact. Laboratory personnel may use questionnaires to identify locations where perchlorates have been used. Questionnaires should be supplemented with visits to known current and former users. Laboratory records can also be useful in identifying perchloric acid usage.

The *Applied Occupational and Environmental Hygiene* articles[6,7] describe a step-by-step process for decontaminating perchlorate-contaminated ventilation systems. The first step is containment of the contamination. Personnel should take precautions during sampling and dismantling operations to prevent the spread of contamination. This includes removing or protecting any equipment or furnishings which may be contaminated by a leak or spill. This is especially important when the ventilation system is radiologically contaminated. The second step is wetting. ORNL personnel used continuous wetting during aggressive penetration of a system such as sawing, drilling, or separation of rusted parts. The next step is testing. Safety and Health personnel should sample all ventilation systems with known usage of perchloric acid, as well as a portion of systems without known usage. Industrial hygienists should select specific sampling locations within each ventilation system based on a determination of the likely point of accumulation and the feasibility of accessing the sampling location. ORNL personnel determined that, for most systems, samples should be taken at points in each system as close as possible to where air enters the duct work, within the fan housing, and at or near the exit from the stack. Due to the possibility of detonating perchlorates, sampling within a ventilation system may present a risk of injury to personnel (staff sample for perchlorates by swabbing about two square feet of surface with wetted gauze pads). Staff should minimize the number of samples, but should take enough to form a representative picture of perchlorate contamination. Maintenance personnel can provide valuable information on means of entry.

During the ORNL study, staff wore personal protective equipment such as ballistic-rated body shields to perform sampling activities. After examining the results of initial sampling, ORNL staff determined that perchlorate salts often accumulated at the entrance to filter housings. Staff sampled fan housings by cutting a small incision in the fabric acoustical coupling between the duct and the fan, then sprayed the internal surfaces of the fan housing and fan blades with measured quantities of deionized water. They then collected the rinsate from the fan housing by suction.

The two articles cited above also describe methods for analyzing perchlorates. Analytical methods vary considerably regarding sensitivity and possible interferences. The articles state that a ventilation system is positive for perchlorates if rinsate is found to contain more than 750 milligram (mg) of perchlorate per liter, or if swab samples indicate a perchlorate level of greater than 70 mg/m^2.

The next step is removal of contaminated equipment, if feasible. Disassembly may make decontamination easier. The inside and outside of the ductwork should be wetted by spraying or misting. This wetting may wash some contamination from the system, but is done for safety rather than decontamination. ORNL personnel used nonsparking tools when sawing or cutting on ventilation systems. During drilling, they used a continuous flow of water over the drill bit. [Note: When planning work involving spaying or misting, criticality safety issues must be considered.]

Workers decontaminate ventilation system parts by soaking, if possible, followed by wet scrubbing. After washing, workers should test the parts for remaining contamination and further decontaminate as necessary. When decontamination is complete, the ventilation system parts may be repaired, replaced, or disposed of (ORNL staff caution that perchlorate contamination may be found outside as well as inside ventilation systems).[6, 7]

11.1.4 Heat Stress

Workers may have to change or test filters without the aid of mechanical handling devices, and this work can be done in locations with little, if any, heat or air conditioning. In addition, the workers might be required to wear personnel protective devices that increase the potential risk of heat stress.

The human body has a remarkable ability to regulate internal temperature within a narrow range, even when exposed to large fluctuations in environmental conditions. Normal metabolic processes produce heat, and the amount of heat produced is related to the level of physical activity. The body can also exchange heat with the environment by convection, radiation, or direct contact. The direction and magnitude of the exchange depend on the relative differences in temperature. The principal method of losing body heat is by sweat evaporation. The rate of evaporation depends on air temperature, air movement, and relative humidity (RH).

Heat stress can cause several problems. The first is simple discomfort, which is highly subjective and depends on factors such as type and amount of clothing worn, age, previous experience, and/or degree of acclimatization to heat. In addition to water, sweat contains sodium and other minerals. If a person loses too much sodium, they may suffer from painful muscle spasms (heat cramps). Excessive loss of water may also cause dehydration, which can lead to a condition known as heat exhaustion. A person suffering from heat exhaustion can maintain their body temperature within a reasonable range, but may become fatigued, faint, or suffer from other symptoms. A person suffers heat stroke when the temperature regulation system is overwhelmed and the body temperature rises. The skin of someone suffering heat stroke is hot and dry. Heat stroke is a life-threatening condition, and the victim must get medical attention quickly. If allowed to continue, elevated body temperature may have serious consequences such as brain damage or death.

Portable fans, coolers, or other equipment may be helpful in removing heat from the work environment and supplementing the body's ability to lose heat through sweat evaporation. Control of heat stress greatly depends on replenishing body water. Workers can lose several kilograms of water during a workday, and they should be provided with and encouraged to drink water. Salted water or "sport drinks" may be useful in some situations (it is best to consult an occupational physician in such cases). Workers may be required to wear PPE such as special clothing or respirators that can increase the chance of dehydration because workers are reluctant to leave a controlled area and doff the equipment to drink water. Placement of fans and water intake in contaminated areas need to be well thought out. Administrative controls may be used to reduce the risk of heat stress. The ACGIH (2001 Threshold Limit Values for Chemical Substances and Physical Agents)[8] recommends a work-rest cycle to reduce the effects of heat stress. The relative proportions of work and rest depend on the level of physical activity and environmental conditions. Workers and supervisors should also consider clothing and the need for fluid intake as factors in determining a work-rest cycle. PPE, such as ice vests and suites or hoods with vortex coolers are available for use in hot environments. However, this equipment requires additional resources such as air for the coolers and may also increase the workers' effort and interfere with their movements. The OSHA Technical Manual, Section III, Chapter 4, "Heat Stress," also contains useful information and an extensive bibliography on this topic.[9]

11.1.5 Confined Spaces

Filter maintenance and testing sometimes requires work in confined spaces. Confined spaces may expose workers to additional hazards and may require special training and planning before work is conducted. Numerous work-related deaths and serious injuries have occurred in confined spaces. OSHA regulations require identification and posting of confined spaces, however, workers should be alert to unposted spaces.

A confined space is an area that meets the following three criteria:

- A person can bodily enter the space and perform assigned work.
- The space has limited or restricted means for entry and exit.
- The space is not designed for continuous human occupancy.

According to OSHA Standard 29 CFR 1910.146,[10] some confined spaces are called "permit-required confined spaces." In addition to the above three criteria, permit-required confined spaces meet one or more of the following criteria:

- The space contains or has the potential to contain a hazardous atmosphere (this could include airborne toxic materials, flammable or explosive materials, or oxygen deficiency).

- The space contains a material with the potential for engulfment of an entrant.
- The space has a configuration, such as a sloping floor, which could trap an entrant.
- The space contains any other recognized serious safety or health hazard.

Workers should be aware that their work activities could introduce a hazard into a confined space, thereby redefining the space as a permit-required confined space. OSHA requires employers to implement a comprehensive confined space program including a permit process for controlling entry into confined spaces. It is important to note that "entry" into a confined space happens when a worker places any part of their body into the space. The permit identifies hazards present in the confined space, documents atmospheric testing, and lists who may enter the space and who is responsible for activities such as atmospheric testing and rescue.

Before workers enter into and during work in a confined space, qualified personnel using properly calibrated and maintained equipment must conduct atmospheric testing. OSHA standards require testing for three types of airborne hazards before entry into a confined space.

- Oxygen content,
- Concentration of flammable gases and vapors, and
- Concentration of toxic materials.

Monitoring should also be conducted for the duration of the confined space entry. If testing identifies atmospheric hazards, employers must institute controls such as ventilation or respiratory protection before allowing entry. Planning for a confined space entry must include planning for emergencies. This is very important because a large portion of workers killed or injured in confined spaces are would-be rescuers. An emergency plan must include:

- Potential rescue methods,
- Available rescue personnel,
- Available and appropriate rescue equipment for the specific confined space, and
- Methods of summoning rescuers.

During a confined space entry, at least one person (the attendant) must remain outside the space. This person may perform other duties such as air monitoring and providing assistance in handling materials and tools, but must maintain continuous communication with entrants and must not leave the area without obtaining a qualified replacement. Depending on the complexity of the work to be done, the number of entrants and other factors, additional attendants may be required. Supervisors authorizing entry should consult with an industrial hygienist to determine protective measures.

Eliminating inputs of hazardous materials, such as inert gasses, toxic solids/liquids/gasses, and even water, as well as hazardous energy, (e.g., inadvertent startup of motors and fans), is an essential part of confined space safety. Vigorous application of lockout/tag-out is normally required (see Section 11.3.3). Hazardous materials are often blocked by "double block and bleed", in which two valves (one valve just is not enough) are closed between the material source and the confined space while a third valve between them that dumps to an unoccupied and safe location is opened. Segmented pipes can be rendered safe by removing a segment and securely placing a flange on the opened ends and/or by misaligning the ends so flow from the source cannot hit the end leading to the confined space.

11.1.6 Biological Hazards

Biological hazards consist of bacteria, viruses, fungi, and, to a lesser degree, rickettsia and parasites. Pathogenic organisms can also gain access via these same entrances, but may also gain access by puncture through intact skin and by contact with the mucosa (the moist tissue, of the eyes, nose, and mouth). Some of these organisms may cause infections, and some may produce allergic reactions in susceptible persons. Ventilation systems may provide an environment that promotes the growth of fungi and bacteria (such as legionella). Workers should be on the lookout for signs of such environments (e.g., visibly moist areas or standing water, unusual odors). It is important to look for such signs during routine maintenance and surveillance as well as during filter testing and replacement. Filters, low spots in the duct work, duct lining and internal structures such as vanes can be locations for growth of bacteria and fungi. Respirators, protective clothing, and good sanitary practices such as washing, are effective means of reducing exposure to biological agents. Biological hazards may also include rodents, reptiles, insects, and arachnids. Animals and their droppings may be a source of plague, hanta virus, histoplasmosis and other diseases.

11.1.7 Respiratory Protection

Engineering controls and administrative controls are preferred over PPE, and respirator use is normally discouraged unless engineering controls or containment devices are not available or are not completely effective in minimizing airborne radioactivity or protecting workers from chemical hazards.

Respiratory hazards fall into one of the following classes: oxygen deficiency, gases and vapors, and particulates. The choice of a specific respirator depends on the specific hazard to the workers. An atmosphere containing less than 19.5 percent oxygen is considered oxygen-deficient. Gases and vapors include a great variety of substances with a variety of toxic effects and chemical characteristics. Particulates include dusts, fumes, mists, and sprays that also have a wide range of characteristics.

There are two general types of respirators: air-supplying and air-purifying. Air-supplying respirators provide the wearer with breathing air from a tank carried by the wearer, air from a chemical reaction, or air from a hose connected to a stationary tank or compressor. Air-purifying respirators use adsorbents and/or filters to trap unwanted materials before the air can reach the wearer. There is no respirator available that is designed to remove all unwanted materials from the air. Selection of air-purifying respirators, therefore, must be based on the specifics of the hazardous materials involved.

If there is a possibility for generating airborne radioactivity, as may be the case in removing high-efficiency particulate air (HEPA) filters, then full protective clothing, including respiratory protection, should be worn. Respirators come in a variety of types (such as respirators fitted with particulate cartridges or gas filtering cartridges and respirators with supplied air or self-contained breathing equipment) to complete supplied-air hoods or full body suits. Actual use of any respirator should be chosen based on the protection factor it affords and on the airborne radioactivity or chemical concentrations in which it will be used. Degree of protection is not the only factor in selecting a respirator. Air line respirators provide a long-term air supply, but there is risk the air hose will become tangled or pinched shut. Self-contained breathing apparatus provide additional freedom of movement, but have a limited air supply and may interfere with access in tight spaces. Respirators may affect a worker's vision. If the worker requires corrective lenses, special glasses that fit inside the respirator must be provided, because normal glasses can interfere with the seal.

DOE requires its respiratory protection program to be conducted in accordance with DOE Order 440.1A, *Worker Protection Management for DOE Federal and Contractor Employees*,[11] which endorses the most restrictive requirements of the American National Standards Institute (ANSI) Z88.2, *Practices for Respiratory Protection*,[12] or 29 CFR 1910.134, *Respiratory Protection*.[13] Individuals should be aware of the following basic requirements governing the use of respirators.

Personnel must:

- Have a medical examination certifying them as fit to perform their jobs while wearing protective respiratory equipment;

- Be trained in the proper use of respirators;

- Be fit-tested to ensure the respirator is properly sealed on the face and that only the respirator for which the individual is tested will be worn;

- Be clean-shaven in the area where the respirator fits onto the face; and,

- Be aware of any adverse conditions or stress resulting from respirator use, and leave the work area if necessary.

Employees who are required to wear respirators must participate in an established respiratory protection program. A complete respiratory protection program consists of the following elements:

- The program must be the responsibility of a qualified administrator.

- The program must be based on workplace-specific procedures.

- Respirator selection must be based on hazard assessments.

- Respirator wearers must participate in a program of medical evaluation.

- Respirator wearers must be fitted for the specific type and model of respirator to be worn.

- The program must include procedures for cleaning and maintaining respirators.

- Respirator wearers must receive training.

- Employees must use only respirators approved by the National Institute for Occupational Safety and Health.

- Management must periodically evaluate the effectiveness of the respiratory protection program.

Respirator wearers are responsible for protecting their assigned respirator from damage, inspecting the respirator before and after each use, and promptly reporting any suspected damage or malfunction. Wearers may clean and sanitize their respirators if given that responsibility by the respiratory protection program. Wearers must not modify their respirators in any way.

11.2 Radiation Protection

This section is concerned with radioactive waste materials contained in the process airstreams that potentially could be released to the environment, radiologically safe removal and replacement of HEPA filters used to minimize potential releases, and contamination of local work areas where workers could be exposed. [Note: HEPA filters are usually supplemented by other filters such as the roughing filters that form part of the basic engineering design features of the air handling systems of a facility.]

Radiation protection organizations are responsible for administering radiation safety programs that promote the use of radiation and radioactive materials in a manner that protects workers, the public, and the environment. Health physics programs cover a wide spectrum of activities across not only the DOE complex, but other areas as well. Humans are subjected to radiation every day because of natural radioactivity in the environment. Radiation is found in air, soil, water, foods, materials used to build homes, and even in the human body. Radiation and radioactive materials also are used in many ways that benefit humankind, including many diagnostic and therapeutic medical procedures, electricity production, in smoke detectors, and food preservation, to name just a few. Radioactive waste products are generated as a result of these beneficial uses of radioactive materials. These waste products can be in the form of solids, liquids, and gases, and disposing of them efficiently and effectively presents a challenge.

Radiation safety is the responsibility of both the radiation protection program and the individuals onsite. The steps and actions required to maintain occupational exposures at levels that are as low as reasonably achievable (ALARA) are described below. It is incumbent upon each individual working in a controlled area to understand these basic requirements and ensure they are considered when performing work that can result in exposure to radiation. For example, each individual must know and understand the meaning of radiological postings, the radiation levels in the areas where they work, and the importance of following procedures and abiding by the instructions in the procedures and in the Radiological Work Permit (RWP). Workers must also be provided with the training required to work in specific areas.

11.2.1 Radiation Protection Considerations for HEPA Filter Removal and Replacement

DOE regulation (10 CFR 835)[14] and DOE Order 5400.5, *Radiation Protection for the Public and Environment*,[15] specify the basic requirements for ensuring that radiation doses to workers and the public are kept below specified limits and maintained at ALARA levels. In addition to DOE regulations, the EPA, as promulgated in 40 CFR Part 61,[16] also limits exposure of the public via the air pathways from DOE facilities. In addition, there are standards and guidance documents[17-25] that aid in interpretation and implementation of the regulations in 10 CFR 835,[14] from which much of the information in this section is derived. Some background material and some of the basic elements involved in radiation safety programs are discussed in the following sections. Although these elements are applicable to most tasks involving radiation and/or radioactive materials, the focus in this Handbook is on radiologically safe removal and replacement of HEPA filters.

11.2.1.1 ALARA

The regulations contained in 10 CFR 835[14] that govern workers in the DOE complex mandate the documentation of a DOE-approved radiation protection program (RPP). The content of the RPP is to be commensurate with the nature of the activities performed, but must include formal plans and provisions for applying the ALARA process. Giving due consideration to the economics of various activities, this means that all activities involving radiation or radioactive materials must be performed using a process that maintains exposure to radiation at the lowest level reasonably achievable. The formal plans for maintaining exposures at ALARA levels should include provisions for and descriptions of the following elements:

- A formal written, high-level management policy statement invoking management's commitment to the ALARA process;

- An ALARA Committee consisting of members of various disciplines that advises management on improving progress toward minimizing radiation dose and radiological releases;
- An organization specifically designed to implement the ALARA program;
- A formal ALARA training program;
- ALARA design reviews of new processes and equipment;
- Internal assessments and audits to evaluate the ALARA program;
- Pre- and post-job review and analysis;
- Individual and collective dose estimation; and
- In some cases, mock-ups or dry runs.

Newer air handling systems have generally incorporated the ALARA philosophy in the initial design, which is the primary means that should be used for minimizing exposures. However, older air handling systems may not have benefited from these concepts. As such, existing ALARA programmatic requirements (e.g., administrative controls, procedures, etc.) must serve to minimize personnel exposure. These requirements are discussed below. A maintenance and surveillance plan such as required by ASME N510,[26] can be a valuable component of an ALARA program. Practice on mock-up filter installations can help worker's complete tasks more quickly, shortening the duration of radiological exposure.

11.2.1.2 Training Requirements

All individuals must receive training in accordance with the requirements of 10 CFR 835[14] before being allowed unescorted access to controlled areas and before receiving any occupational dose of radiation. Specific topics listed in the regulations must be covered in the training program. In addition, various levels of training, commensurate with the positions of the individuals, should be provided in accordance with DOE-STD-1098-99, *Radiological Control Standard*.[18] Radiation workers receive detailed training in understanding the nature and hazards of radiation and understanding their responsibilities for implementing ALARA principles. Personnel most affected include technical support personnel, personnel responsible for developing work plans for working in controlled areas, and personnel responsible for implementing radiological control measures. Training includes the basics of the ALARA concepts and techniques used to minimize their exposures such as shielding, containment devices, the use of special tools, and the importance of careful planning prior to conducting the work.

In addition, on-the-job training is critical for tasks performed in areas where radiation levels can be high. It is important to be familiar with the task and to be prepared with all tools required on the job to minimize the time spent in an area and to eliminate the need for stopping the job and leaving the area to acquire tools. This may also consist of conducting dry runs before attempting any job in a high radiation area. In some air handling systems that use HEPA filters, the filters can have very high radiation levels. Although there are different procedures for changing these filters, personnel must be trained in each procedure as necessary. A dry run is recommended for personnel who may use a bag-in/bag-out system for the first time.

11.2.1.3 Radiation Surveys

HEPA filters are designed to collect particles down to 0.3 micrometer (µm) with an efficiency of 99.97 percent. The airstreams in which the HEPA filters are used can contain highly radioactive particles. As such, the filters become contaminated and can sometimes have significant radiation levels when they are due for replacement. The filter housings and the filters themselves should be surveyed prior to filter removal and replacement, and personnel should be familiar with these radiation levels. In addition, surveys for radioactive contamination should be performed periodically during this process to monitor the location of surface contamination, and surveys of airborne radioactive material should be performed. The radiation surveys are usually discussed as part of the pre-job review. In most situations, a member from the RPP must be present to perform the radiation surveys. However, in some instances where maintenance personnel or work groups have been trained and qualified, surveys may be performed by the individuals in the group. Such instances may be site-specific, and self-surveys should be discussed with health physics personnel.

11.2.1.4 Internal Dosimetry

The internal dosimetry program generally consists of the two elements listed below, each of which is designed to either minimize the intake of radioactive materials, evaluate actual or suspected intakes, or calculate potential doses resulting from these intakes.

- An individual monitoring program, (if bioassay is unavailable, inadequate, or not as accurate as air monitoring data).

- A dose evaluation program to evaluate air sampling and bioassay data to determine the individual doses.

Health physics personnel provide these services and usually determine who will participate in the bioassay program based on regulatory and programmatic requirements.

Radiological workers are required to participate in an internal dosimetry program, including routine bioassays if, under normal conditions, they are likely to receive a committed effective dose equivalent of 1 mSv (100 mrem) or more from all occupational radionuclide intakes in a year [10 CFR 835.402(c)].[14] For typical HEPA filter removal without the use of bag-out systems and for personnel who rely more on the use of respiratory devices, participation in a routine bioassay program will likely be required.

11.2.1.5 Posting and Labeling

Radiation protection staff should determine the appropriate access controls and warning signs for the replacement of HEPA filters. A bag-in/bag-out system is preferred. However, in some circumstances, it is not possible to use a bag-in/bag-out system for changing HEPA filters. In these situations, compensatory precautions must be taken. If the filter housing is contained within a room, the door to the room can be posted with the appropriate radiation and/or contamination area sign(s) and access can be restricted. In the event the area around the filter housing is an open area, physical barriers such as ropes and stanchions can be placed so that access into the area is controlled by the barriers or by personnel. Entrance to areas that are barricaded must be posted with appropriate radiation and/or contamination area signs to inform personnel of the potential hazard in the area.

After the HEPA filters are removed from the system, they must be surveyed and labeled with radiation and/or contamination labels that identify their magnitudes. Other materials such as contaminated tools and used protective clothing must be bagged, surveyed, and labeled appropriately before they are removed from the area.

11.2.1.6 External Dosimetry

Personnel who work in controlled areas where they are likely to receive doses at or above those specified in 10 CFR 835.402[14] are required to wear dosimeters for monitoring their effective dose equivalent. Film badges, track-etch dosimeters, thermoluminescent dosimeters, or other radiation-sensitive devices specified by radiation protection personnel could be used to measure the external dose. Dosimeters are typically used to monitor dose to the whole body. In some circumstances, additional dosimeters may be required and would be specified on the RWP. Such dosimeters may be used to monitor the extremities if remote handling of the radioactive sources is not feasible, or for monitoring the lens of the eyes depending on the specific job and the nature of the radiation fields. Extremity dosimetry is especially important for filters with unusually high levels of radiological contamination. This is another reason planning is important. The location of the extremity dosimeters will be specified by health physics personnel. Care must be taken to avoid contamination of the dosimeters.

11.2.2 Work Requirements

In addition to the requirements mentioned above, there are a number of prerequisites before approval is granted for individuals to perform work in radiological areas. These prerequisites begin with the work group initiating an RWP that contains information about the work to be done and submitting it to the health physics staff. Based on the information provided, health physics personnel will make the necessary radiation and contamination surveys and establish a radiological control area around the work site. Health physics personnel will also establish and specify on the RWP those additional requirements to be followed before, during, and after completion of the work. Some of the information that should be included on the RWP is described in the following section.

11.2.2.1 Radiological Work Permit (RWP)

The RWP is an administrative mechanism used to establish controls for the work to be accomplished. The RWP contains information that informs workers of the radiological conditions in an area and prescribes basic requirements for conducting the work in a safe and expeditious manner. The RWP generally includes the following information (DOE-STD-1098-99).[18]

Description of the work:

- Radiological conditions in the area,
- Dosimetry requirements,
- Pre-job briefing requirements,
- Training requirements for entry,
- Protective clothing and respiratory protection requirements,
- Radiological control coverage and stay-time controls, as applicable,
- Limiting radiological conditions that may void the RWP,
- Special dose or contamination reduction considerations,
- Special personnel frisking considerations,
- Technical work document number, as applicable,
- Unique identifying number,

- Issue and expiration dates, and
- Authorizing signatures.

The RWP should be integrated with other work authorizations that address health and safety issues, such as those for industrial safety and hygiene. The RWP also serves the purpose of relating doses received with specific jobs to support the ALARA program.

A typical RWP for the removal and replacement of contaminated or radioactive HEPA filters would specify the applicable items listed above, as well as some special instructions. These special instructions may include ensuring a radiation survey is conducted before each filter is removed or replaced; using continuous air monitors (CAMs) during the process; stopping work if there is a breach in any containment system such as the bag-in/bag-out system or any sleeving material that may be used; ensuring the work crew has participated in a whole body count or *in vitro* bioassay (e.g., urinalysis) if respirators are to be worn; specifying the maximum allowable exposure for each individual conducting the work; and/or requiring a post-job briefing. All conditions specified on the RWP must be thoroughly understood and implemented.

11.2.2.2 Pre-job Review and Briefing

HEPA filter removal and replacement is not a simple task. It is performed infrequently, so it should be carefully planned (as should all work in radiological areas). A pre-job review and briefing should be conducted to ensure all personnel are familiar with the task and the radiological requirements that may be imposed. The briefing should include the following items:

- A review of the RWP to ensure all conditions and requirements are understood and met;
- A review of the instructions regarding hold points;
- A review of the radiation survey that normally accompanies the RWP, taking particular note of the areas of highest and lowest radiation levels;
- The scope of the work to be conducted (i.e., how many filters will be replaced, what technique will be used, what location is the system in, etc.);
- Information concerning whether the area around the system is to be barricaded and step-off pads used, or if a bag-in/bag-out system is to be used;
- Coordination with operations personnel to ensure the system to be worked on is not needed and is tagged out;
- Established conditions for stopping work (e.g., unexpected radiation levels, contamination due to system breach, dropped filter, etc.);
- Established plans for cleanup and restoring the area;
- Identification of the tools and equipment needed and assurance of their availability;
- Scheduling of the work at a convenient time to avoid delays in the work process (i.e., not near break time or lunch);

- Ensuring that preparation for disposal of filters is coordinated with the waste management group;
- Minimizing the material to be taken into the area to limit waste generation;
- Reviewing the individual and collective doses estimated for the job; and
- Establishing the number of personnel required for the job.

This review should be conducted with all personnel who will be involved in the job and with operations personnel who have control over the system where the work will take place.

11.2.2.3 Hold Points

Hold points may be predetermined for operational reasons or may result from unusual conditions that occur during performance of the task. Predetermined hold points should be specified in the procedure/technical work document or on the RWP (as indicated above). These hold points would exist in situations such as a breach in any control system or an increase in radiation on the HEPA filter beyond expected levels (based on the original survey). Obvious stop-work conditions would exist if personnel felt discomfort due to use of respiratory equipment, heat stress, or fatigue for any reason.

11.2.2.4 Air Monitoring

Air monitoring is required by 10 CFR 835.403(a)(2)[14] to characterize the airborne radioactivity hazard where respiratory protective devices for protection against airborne radionuclides have been prescribed. The use of containment devices is often not amenable for removal and replacement of some HEPA filters. In such situations, respiratory protection equipment could be prescribed and air monitoring would then be required. Care must be taken to locate the air monitoring equipment to ensure the sample represents the concentrations of airborne radioactive material that workers would breathe if respirators were not worn or to warn workers of the release of airborne radioactive material. The potential intake of radioactive material can be determined using these measured concentrations and the protection factor for the particular respirator used. Health physics personnel would designate the type of monitoring and the location of the monitors. They also would collect the data from the air monitoring devices and make any required calculations.

11.2.3 Technical Work Document

The technical work document/procedure provides guidance to the personnel who will perform the task. A procedure is required for removal and replacement of HEPA filters. This procedure must be written for the specific method to be used and must include step-by-step instructions. Typical procedures for removal of HEPA filters with and without a bag-out system are described briefly below.

11.2.3.1 Use of a Bag-Out-System

A bag-out system is a good example of implementation of the ALARA process. It minimizes the possibility of creating an airborne radioactivity area, in some cases may eliminate the need for respiratory equipment, and may minimize the need for followup bioassays on the work crew. This system should be used whenever possible, as recommended in a Lessons Learned Communication[23] reported by Brookhaven National Laboratory describing the use of a glovebag system to remove a large HEPA filter**.** Planning is essential. For example, having the right tools available will minimize interruptions and waste produced.

11.2.3.2 Filter Removal without a Bag-Out System

If use of a bag-out system is not possible, the steps taken for opening the housing and removing and replacing the HEPA filter would be essentially the same as described above. The used filter would require careful handling to avoid spreading contamination and would have to be wrapped in some suitable material such as plastic. However, additional health physics measures would be required, including barricading the area around the filter housing, ensuring the area is posted to warn personnel of the radiological conditions, performing air monitoring, placing a step-off pad at the entrance to the area, and providing a frisker for personnel to survey themselves for contamination after completion of the job. All personnel should wear full protective clothing, including respirators, and frisk themselves for contamination before leaving the area. The personnel may also be required to submit to a whole body count or bioassay as required by local programs.

11.2.3.3 Filter Removal from Man-Entry Housings

If a man-entry housing is required, two teams of two persons each are required to enter the filter housing. One team will enter upstream of the filter stage; the other will enter downstream of the filter stage. Similar health physics/radiation protection measures will be required as used in the "removal without bag-out systems." The filters are changed while the filter system is operating. One team blanks off the side of the filter mounting frame opposite the filter. The other team will replace the damaged/used filter. The filter will be placed in a plastic bag. The mounting surface will be cleaned. A new filter will be installed. The blank will be removed. The filter will be removed from the housing and the two teams will exit the housing. All workers, and the used filter, will be monitored by the health physics/radiation personnel.

11.2.4 Post-Job Requirements

To obtain some lessons learned, provide additional training, and assist in supporting the ALARA program, a post-job review should be held. This review should focus on the manner in which the work was conducted to provide an opportunity for personnel to learn from their success or failure, as the case may be, in performing the work. Such post-job reviews and discussions also aid in ensuring the safety of personnel who will perform the task in the future, and are normally conducted in an expeditious manner.

11.2.4.1 Whole Body Counts

Whole body counts or in vitro bioassays (e.g., urinalysis) are not normally provided for all radiological workers unless they are required to wear respirators. However, depending on the procedure used for removal and replacement of the HEPA filters (e.g., whether respirators were worn), whole body counts or bioassays may be required upon completion of the job. In addition, whole body counts would be required if there were an unexpected release of airborne radioactive materials, if contamination were detected on an individual's face, or if there were a failure in the protective clothing or control devices. Whole body counts are not suitable for detection of all radionuclides and are only one part of the bioassay program for the detection of internal contamination. Health physics personnel should be consulted to ensure the appropriate method is used for evaluation of any potential internal contamination.

11.2.4.2 Contamination Surveys

Contamination control is an important and necessary part of any health physics program. Contamination should be limited through engineering controls and proper work practices. However, it is not always possible to prevent contaminating surfaces when opening contaminated systems or working on contaminated equipment (e.g., changing HEPA filters). Since contamination is easily transferred from one area to another via either air movement or transport on shoes or protective clothing, it is necessary to establish controls at the work area. To ensure contamination is not spread outside of the work area, health physics personnel should establish a contamination control zone. A rope barrier usually designates this control zone along with appropriate postings specifying the levels of contamination and/or radiation in the area. Entrance to these areas should require the individual to wear appropriate protective clothing (sometimes multiple layers, depending on the levels of contamination). A step-off pad is usually placed at the entrance and exit from the contamination areas where personnel remove their contaminated clothing prior to leaving the area. Upon completion of the task in the contamination zone, the following steps must be taken to restrict the contamination from being spread by personnel and equipment:

- **Personnel Surveys.** Personnel exiting the contamination area may be required to remove their protective clothing at the control point. Personnel must frisk themselves with a radiation-monitoring device that is maintained at the step-off pad. Existing procedures should be followed to ensure personnel use the proper techniques for removing protective clothing and performing a whole body frisk if portable monitoring devices are used. Care must be taken to ensure the frisking is performed in a slow, methodical manner to ensure the detection capability of the instrument is not compromised. Personnel should also frisk any personal items brought into the area such as pencils, papers, jewelry, badges, etc.

- **Equipment Surveys.** A trained individual, normally from the health physics program, must monitor the equipment leaving the work area. However, for HEPA filter removal and replacement, it is unlikely that equipment other than the hand tools necessary to change the filter will be brought into the area. Some of these tools may be designated radiological tools because they have fixed contamination and may be maintained separately from uncontaminated tools. Health physics personnel should determine whether the tools have been contaminated with removable contamination by performing smear surveys. The HEPA filter itself must be enclosed in some containment device such as plastic, treated as radioactive, surveyed for contamination and radiation, and appropriately labeled. It should then be held or transported for disposition possible incineration, or direct disposal as radioactive waste.

- **Area Surveys.** Upon completion of the task (i.e., removing the HEPA filter(s) and securing the system housing) the area must be surveyed for radiation and contamination. If contamination is found, the area must be decontaminated and resurveyed until removable contamination no longer exists. A radiation survey must be performed in the area to ensure that the conditions that existed prior to the work did not change and the area is appropriately posted as necessary.

11.2.4.3 Waste Disposal

The final step upon completion of the work is to perform housekeeping in the area while the area is being cleared for general use by health physics. Some of these housekeeping chores involve gathering all the protective clothing for transport to the laundry or shipping to an offsite laundry service and ensuring that all waste materials are packaged and labeled appropriately for disposition as waste. These materials include the step-off pads, the containers in which the used HEPA filters are placed, and any miscellaneous materials used in performing the work.

11.3 Occupational Safety

11.3.1 Electrical Safety

Electrical potentials in excess of 200 volts are common around ventilation systems. Therefore, employees performing filter testing must be aware of electrical hazards. OSHA regulations and prudent practice limit electrical work to qualified personnel. Only a qualified person may perform any repair, installation, or testing of electrical equipment. Workers need to be aware of exposed energized parts in the vicinity of the work. Electrical circuits must be considered energized until opened and locked out according to established procedures and must be tested to verify that the circuit is de-energized. If it is necessary to de-energize electrical circuits to conduct work, the circuits must be de-energized and locked out by qualified personnel. A significant factor in preventing electrical accidents is awareness of possible electrical hazards. Workers should point out hazards to qualified persons. A good housekeeping program can significantly reduce electrical hazards.

Personnel should examine electrically powered equipment and tools for problems. Personnel must not use equipment with frayed or damaged cords or with missing ground pins from the plug (including extension cords). If testing equipment is custom-built, has not been tested by a nationally recognized testing laboratory, or has been modified, the workers should consult qualified electrical safety personnel before using the equipment. Workers should not assume that low voltage controller circuits are free of hazards. Even relatively low voltage may cause injury or startle the worker and cause a fall. Some controller circuits contain higher voltages.

11.3.2 Machine Guarding

Ventilation systems contain rotating shafts, moving belts, gears, and other moving equipment that may present hazards to workers. Such hazards have resulted in serious injuries and even death. Any mechanical device that may cause injury must be guarded. Even a relatively small, unguarded portion on a mechanical device may be enough to cause serious injury. For example, in the past a small portion of a rotating shaft snagged a jacket worn by a worker, causing serious injury. Besides illustrating the danger of even a small exposed moving part, this incident illustrates the danger of wearing loose-fitting clothing while working around moving parts.

Workers should be concerned with three specific types of mechanical hazards: the point of operation where work is performed (e.g., a fan); power transmission equipment including components such as drive belts and pulleys; and other moving parts such as shafts, couplings, and gears.

Workers should not remove guards unless absolutely necessary, and only after all energy sources are shut off and locked out.

11.3.3 Lockout/Tag-out

Work on ventilation systems may expose workers to energy sources or toxic materials that may cause serious injury or death. All potentially hazardous energy sources must be secured, relieved, disconnected, and, if possible, reduced to a zero energy state before personnel start work. Energy sources may include high pressure, heat, electric current, and mechanical energy. Workers should also isolate sources of toxic materials that may present a hazard. Hazard sources must be locked out in accordance with the employer's Lockout/Tag-out program. Simply shutting off a switch or closing a valve is insufficient to control energy or toxic materials. Sources must be locked in such a manner that only those workers potentially exposed to the hazards may remove the lock, and workers will not be exposed to hazards due to someone opening a valve or flipping a switch.

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APPENDIX A

CARE AND HANDLING OF HEPA FILTERS

H. Gilbert and J. H. Palmer[1]

High reliance can be placed on the high-efficiency particulate air (HEPA) filter if precautions are taken in handling, storage, and installation. Inspection upon delivery, upon withdrawal from stock, and before and after installation is important. A filter unit should be inspected each time it is handled to guard against installation of a damaged item.

The precautions and recommendations in this Handbook are based upon field experience and development.

A.1 Packaging and Shipping

Packaging practice varies among the filter unit manufacturers. Normally, units are packaged in cardboard cartons with various means of providing internal strengthening and impact resistance of the carton. A carton will usually contain one of the larger units, such as the 1500-cfm, $24 \times 24 \times 11\ 1/2$-inch unit; or it may have two 500-cfm, 24×24, $5\ 7/8$-inch units. The smaller sizes, the 125-cfm, $12 \times 12 \times 12\ 7/8$-inch, and the smaller units, frequently are packaged in individual cardboard cartons and crated in multiples.

When a filter is placed in the carton, it is inserted so that the pleated folds are vertical to prevent damage in shipment. To prevent sagging of the pleats, vertical positioning of the pleats must be maintained during subsequent handling and storage. Most important, filter units should also be installed vertically for operation.

The shipping carton is marked with a vertical arrow and the notation "this side up" to indicate positioning of the carton in the transport vehicle. Other markings, "handle with care," "use no hooks," etc., may be found on some containers.

When a filter unit is shipped with pleats in the horizontal position, the vibration that occurs during transportation and the jarring that usually accompanies handling often cause the filter medium to split or to break at the adhesive line, which will appear as a hairline crack.

Occasionally, the manufacturer positions a filter unit improperly in the container. Cartons frequently are not placed in trucks according to the vertical arrow, and they are not handled consistently with the care designated. Consequently, inspection to verify that filters have been packed properly is necessary upon delivery at destination. Experience has shown filters should not be shipped by rail.

A.2 Receiving and Unloading

Inspection starts when a delivery of filter units reaches the purchaser, even while the load is still aboard the carrier. As the shipment is being unloaded, each carton should be inspected for external damage and improper positioning in the cargo space (i.e., the carton placed with arrow directed horizontally). Damaged cartons, including those with corners dented and those improperly oriented in the truck, should be set aside

[1] *Updated and adapted from H. Gilbert and J. H. Palmer, High-Efficiency Particulate Air Filter Units, USAEC Report TID-7023, August 1961.*

for particularly careful inspection of their contents. Damage will be more prevalent when filter units are loaded with mixed cargoes or are shipped in a partially loaded carrier.

The filter unit must be removed carefully from its carton. The acceptable method for removal is to open the top flaps of the container after removing the sealing tape. With flaps folded back, the carton should be inverted or upended gently to place the exposed end of the filter unit on a flat surface, preferably the floor. The surface must be clear of nuts, bolts, and similar protrusions. Then withdraw the carton from the filter unit. Attempts to remove the filter unit from the carton by grasping below the exposed filter case can result in irreparable damage if fingers puncture the delicate filter medium attached immediately below the case.

A.3 Shipping

HEPA filters should be shipped under controlled conditions insofar as practicable. Too often, after the cartons have been carefully arranged in a truck-trailer body, the shipper removes them at an interchange station, stacks them temporarily in the terminal (under completely uncontrolled conditions), and then stacks them into another truck-trailer. Handling under such conditions is usually careless, and attention to proper orientation of the cartons may be nonexistent. As a minimum, it is recommended that cartons be steel-banded to a skid or pallet, no more than 6 1/2 feet high, in the specified vertical orientation. Plywood crates are preferred (see Figure 3.14). Skids (pallets) must not be stacked one above the other unless bracing is provided in the truck-trailer body or railroad car to prevent the weight of the upper load from resting on the lower. This will force the shipper to keep the cartons in their proper orientation and prevent him from throwing or dropping them indiscriminately.

Another control is to require that the filters be packed properly in a scaled truck-trailer body or in a sealed containerized-freight unit, not to be opened until arrival at the specified delivery point. The trailer or containerized-freight unit should be unloaded by personnel employed at the delivery site who have been thoroughly instructed in the proper care and handling of HEPA filters. Mixed-load shipments should be avoided.

A.4 Storage

Following receipt and inspection, the filter unit should be repacked carefully in the carton in which it was shipped and received. All packing material for internal strengthening of the carton and for protection of the filter unit should be replaced properly. Pleats of the filter unit should be positioned to conform to the orientation marking on the carton; this should be done routinely whether the filter unit will be installed at an early date or whether it will be stored.

Cartons of filter units should be positioned in storage to conform to the vertical arrow, and manufacturer's recommendations for storage heights should be followed. When recommendations are not available, filter units $24 \times 24 \times 11$ 1/2 inches and $24 \times 24 \times 5$ 7/8 inches should be stacked not more than three filter units high. Alternate the position of each level so as to not have one filter support the one above it.

Mixing other items and materials with filter units in storage should be avoided to prevent damage to the filter units. Recommended aisle widths consistent with good warehousing practice should be provided to reduce damage of filter units from materials-handling equipment and other traffic. Filter units should not be stored in locations where they will be exposed to dampness, excessive heat or cold or rapidly changing temperatures. An NQA-1 Level B storage or equivalent should be used.

A.5 Handling

Mechanical warehousing equipment is recommended for handling large quantities of filter units. Skids and pallets should be used to provide a flat bed for movement of the units. Chains, slings, and hooks obviously must not be used. The cartons should be placed on the pallet so that the arrow on the carton points vertically.

In physically handling a packaged filter unit, a person must make certain that the carton is picked up at opposite corners and deposited carefully on the floor or other surface. The carton should not be dropped or jarred. Any filter unit dropped, whether or not in the carton, should be reexamined for damage as prescribed in Appendix B.

When a filter unit is lifted, it must be grasped only along the outer surface of the case. Even slight contact of fingers at almost any point within the case can puncture the filter medium.

A handle or grip is sometimes attached permanently to the wood filter case for ease of installation and removal of the filter unit. In such instances, care must be taken in attaching the handle. Screws should not be pounded for starting, and nails should never be used. The recommended method is to drill starting screw holes, making certain that the drill and the length of screws do not penetrate through the frame and pierce the filter medium attached (screws must not be longer than 3/4 inches). Pounding may crack the filter medium and possibly loosen the adhesive seal that bonds the filter pack within the frame. Attachment of a handle to a metal-frame filter unit is not recommended.

Filter units should be kept in shipping cartons when moved from one location to another. When transferred for installation, the units should be unloaded at a point, which so far as practicable, will reduce physical handling. Filter units should remain in cartons until ready for installation and then should be unpacked as prescribed in Section A.2.

If for any reason an unpackaged filter unit must be placed with its face on the floor or other surface, the surface must be cleared of every object or irregularity that might damage the filter pack.

A.6 Installation

Personnel responsible for installation of the filter unit must be carefully instructed in proper handling technique. They should know that the filter pack within the frame is delicate and must not be damaged during installation. Equally important is that the filter unit must be installed so that unfiltered air will not leak past the unit. The following installation procedure, as a minimum, should be used:

1. Carefully remove filter unit from shipping carton, following the procedure described under Section A.2.

2. Carefully inspect both faces of the filter unit for cracks in the filter medium, for damage of separators, and for separation of the filter pack at the frame.

3. Ensure that the gasket is cemented firmly to the frame and that the gasket pieces are butted or mated at the joints.

4. The gasket must be compressed firmly. Compression should be applied evenly and equally at all points in increments of 5 feet-pound or less, with the filter frame completely covering the opening.

5. Install the filter with pleats and separators in the vertical position. This will eliminate sagging of pleats from accumulated weight of materials stopped by the filter unit.

APPENDIX B

RECEIVING INSPECTION DIRECTION AND CHECKLIST

The visual inspection should be performed by a person trained in the design and construction of a high-efficiency particulate air (HEPA) filter.

When visual inspection is made, a strong lamp should be used to examine the exposed areas of both faces to ensure that no breaks, cracks, or pinholes are evident. In addition, a less intense light, such as a flashlight, can be used in a darkened room. The inspector should look for visible defects with the light projected along the full length of each channel created by the separators.

Translucent spots will likely prove to be variations in thickness of the filter medium, which occur during manufacture. Breaks or cracks in the medium usually show up on the surface edges of the filter pleats but often are not readily detected. Minor cracks can be of major importance. If the filter unit is installed with this pleat-edge damage, the cracks can be extended by air movement through the unit. After examining each channel, the inspector should examine the adhesive seal around the filter unit face to be sure that the seal is complete and unbroken. When one face of the filter unit has been inspected, the other face should be examined in the same manner and with the same care.

After the inspector has completed a thorough scrutiny of both faces, he should check the corner joints of the frame for adhesive sealing and tightness. Gasketing about the edge of the frame should be inspected for tight mating of gasket strips and good physical condition. Gasket strips should also be examined for full adhesion to the frame.

Cartons showing damage or dented corners and those that are found loaded in improper position upon delivery and that were set aside after being unloaded from the carrier, require careful inspection. The filter unit should be examined at all corners and particularly at the point of carton impact for damage to separators and medium. Exterior damage to several protruding separator edges in a small area will not influence filter unit efficiency if the medium is not mashed, punctured, or broken. Even though the medium many not be broken on one face, damage may occur at the opposite edge of the pleat on the other face. Large areas of mashed separator edges, even though the medium is not damaged, will obstruct the passage of air through the filter unit and thus reduce its life. Improperly stowed filter units should be inspected particularly for cracks alongside the adhesive seal, for extreme sags in pleats and separators, and for slits or breaks in the medium. The procedures outlined above, including examination with lamp and flashlight, should be used for routine inspections.

Repair of a damaged filter unit, particularly the medium, should not be attempted by the user. Any repaired unit must be retested by DOP penetrometer to ensure that hidden damage does not exist which will reduce filtering efficiency. Repair and retest thus become uneconomical for most users.

Materials used in construction of the filter unit must comply with the purchase specification. Compliance, so far as practicable, should be determined at the time of inspection. Filter units that have been inspected and found damaged, defective, or not in conformance with the purchase order should be separated from acceptable units; identified; and, accompanied by necessary records, referred to the purchasing, receiving, or other appropriate department for proper disposal.

Visual inspection of the filter unit to detect physical damage is necessary. Inspection, however, is not a substitute for DOP testing with a penetrometer. Such testing will readily disclose a defective filter unit, even when faults in the unit cannot be found by visual inspection. High penetration due to faults results in an excessive release of particles to the atmosphere. The penetrometer also measures the pressure drop, or resistance of the filter unit to the rated airstream. Excessive resistance should not be greater than specified by the purchase order. If not specified, penetration should not exceed 0.03 percent and new resistance should not be more than 1.3 in.wg at rated airflow.

Nuclear-Grade HEPA Filter Inspection Checklist

PURPOSE: This checklist should satisfy the HEPA filter's compliance with significant portions of DOE-STD-3020, *Specifications for HEPA Filters Used by DOE Contractors.*

The inspector should ensure that the following records are on hand for each HEPA filter:

- Vendor Certificates of Conformance
- Oak Ridge Filter Test Facility test records (ORFTF)
- Shipping records

Object of Inspection	***Inspection Method***	***Determination***
Packaging	Visual	The filter packaging shows no signs of damage.
	Visual	The filters are packed in individual and durable containers.
	Visual	The filters were crated or palleted.
	Visual	The filter cartons were not stacked more than 3 cartons high.
Filter Construction	Metal ruler	The dimensions of the filter conform to a height of 24 inches by a length of 24 inches (within a tolerance of +0, -1/8 inch [-3 millimeter (mm)] by a depth of 11 1/2 inches (within a tolerance of 1/16 in. [+1.6 mm], -0).
	Metal ruler	The filter face diagonals are within a tolerance of +0, -1/8 inches [-3 mm] total..
	Metal ruler	The width of the filter's gasket surface is 3/4 in. (19 mm) (within a tolerance of ± 1/16 inches [± 1.6mm]).
	Visual	There are no signs of repaired pinholes or other defects.
	Visual	The separators extend at least 1/8 inch (3 mm) beyond the pleats of the filter medium.
	Visual	The plane formed by the edges of the separators is at least 1/4 inch [6 mm] from the plane of the filter frame.
	Square and visual	The pleats are straight. They do not deviate more than 1/2 inch (12 mm) from a line drawn from one end of the pleat to the other end of the pleat.
	Visual	The pleats are perpendicular (~90 degrees) to the top and bottom of the case panels.
Wooden Filter Cases	Visual	The case panels are joined with rabbet joints.
	Certificate of Conformance	The case panels are double nailed or double screwed with coated box nails, corrosion resistant plated screw nails, or flathead wood screws.
	Visual	The end points of the fasteners do not penetrate the inside or outside surfaces of the case.
	Visual	The frame faces, edges, and inner surfaces and inner surfaces are thoroughly coated with sealant to minimize permeability.
	Visual	The frame face sealant does not reduce the ability of the gasket to adhere to the frame.
	Visual	There are no splinters or rough edges that might penetrate or cut workers' gloves or injure the fingers of personnel handling the filters.
Metal Filter Cases	Visual	The metal cases have a double-turned 3/4-inch- (19 mm) wide flange on each face, or a fluid-seal socket or sleeve.
	Visual	The case panels have been assembled into a frame by riveting or bolting the corners.
	Certificate of Conformance	The case panels have been assembled into the frame by potting a sub-assembly consisting of the filter pack and side panels into the top and bottom panels (but not the corners), using an adhesive meeting the requirements of DOE-STD-3020.

Task	***Inspection Tool***	***Determination***
Gaskets [Note: The gaskets can be a one-piece gasket or made up of strips joined at the corners by a keyhole joint, keystone joint, or another interlocking type joint.]	Visual	The gaskets are glued firmly and continuously to the case.
	Visual	The gaskets are not loose, peeling, or distorted.
	Visual	The gasket does not extend more than 1/16 inches (1.6 mm) over either side of the seating surface at any point
	Certificate of Conformance	The edges of the joint area are thoroughly coated with adhesive, meeting requirement of DOE-STD-3020 before assembly.
Faceguards	Visual	The faceguard edges are firmly embedded in adhesive.
	Visual	The faceguards are installed so that projecting wires or edges do not form a puncture hazard to personnel handling the filter.
	Visual	The wires or edges do not project onto or beyond the gasket-mounting surface.
Performance Specifications	Certificate of Conformance	The filter manufacturer has provided objective evidence (hard copy) that the filters meet the following performance requirements.
Penetration	Visual	Aerosol penetration for any HEPA filter will not exceed 0.03 percent (0.0003) for 0.3µ diameter particles. Note: It is acceptable for the filter manufacturer to perform the aerosol testing with a smaller particulate size aerosol than the standard 0.3 µm aerosol.
Air Flow Resistance	Visual	Airflow resistance across the HEPA filter will conform to the limits listed in Table 1 of DOE-STD-3020. Tests for resistance to airflow will be conducted at flow rates expressed in actual cubic feet per minute.
Qualification Testing Specifications	Certificate of Conformance	The filter manufacturer will provide objective evidence (hard copy) that the HEPA filters provided meet the test requirements of Sections 6.1.3 to 6.1.5 of DOE-STD-3020.
Resistance to Fire and Heated Air	Visual	Labeling or certification (by Underwriters Laboratory), in accordance with UL-586, will provide evidence of satisfactory compliance with applicable requirements for resistance to fire and heated air.

APPENDIX C

DETERMINATION OF HEPA FILTER LIFE

Despite the difficulty of determining HEPA-filter life based on research data, a conservative interpretation of these data can be used to set age limits. The age limit[1] can be set based on the data derived from the observed decreases in the tensile strength of dry filter media with age and the further reduction in strength due to water exposure.

Although filter life cannot be directly estimated using the data, there is a significant decrease in tensile strength with age for both the unfolded and folded media. Test results also showed a decrease in media tensile strength with age, although the trends were not as distinct because of the scatter in the data.

The extrapolated unfolded data suggests the tensile strength fails at 13 years. Tests indicated that folded media do not have the required 2.5-pound/inch tensile strength even when new and is extremely low at 7 years. Research showed that the tensile strength of new filter media is directly proportional to the pressure drop at which the HEPA filter shows structural failure at the pleats. By applying this relationship to aged HEPA filters, the minimum pressure drop for structural damage decreases with age. Similarly, the burst-strength data show several filters with very low burst strength after 7 to 8 years. Thus, under dry conditions, the filter media fail the required tensile strength or have very low burst strengths after 7 to 13 years, or an average of 10 years. Based on this data, it is recommended that HEPA-filter life under dry conditions be set at 10 years.

When the filter have been exposed to water, the strength of the filter media is further decreased, thereby reducing effective filter life. Even if a demister is used, the high humidity resulting from the water sprays would most likely cause the filter to become wet. Tests have shown the combined effect of both age and water exposure. Water exposure reduces the age limit for the same strength criterion. For example, the occurrence of water exposure would shift the age limit for a dry media form 7 years to 3 years. Exposure to water will reduce the HEPA tensile strength to less than the initial acceptance tests. Thus, a filter that could fail at 7 to 13 years when dry could fail at about 3 to 7 years, or an average of 5 years, when the potential for water exposure exists. Filters that actually become wet should be replaced quickly.

The water repellency of the filter media also appears to decrease with age. However, this decrease may be largely due to water adsorption by deposited particles. Research found that folding the filter media decreases the water repellency even for new filter media. Tests also showed a decrease in water repellency with folded media and found that even the pleats of new media absorb water. The pleat water absorption coupled with its inherent weakness, makes the pleats especially prone to structural failure.

A 5-year maximum age of HEPA filters for ventilation systems having in-duct water sprays can be justified because of decreased tensile and burst strengths and decreased water repellency resulting from age and with media folding.

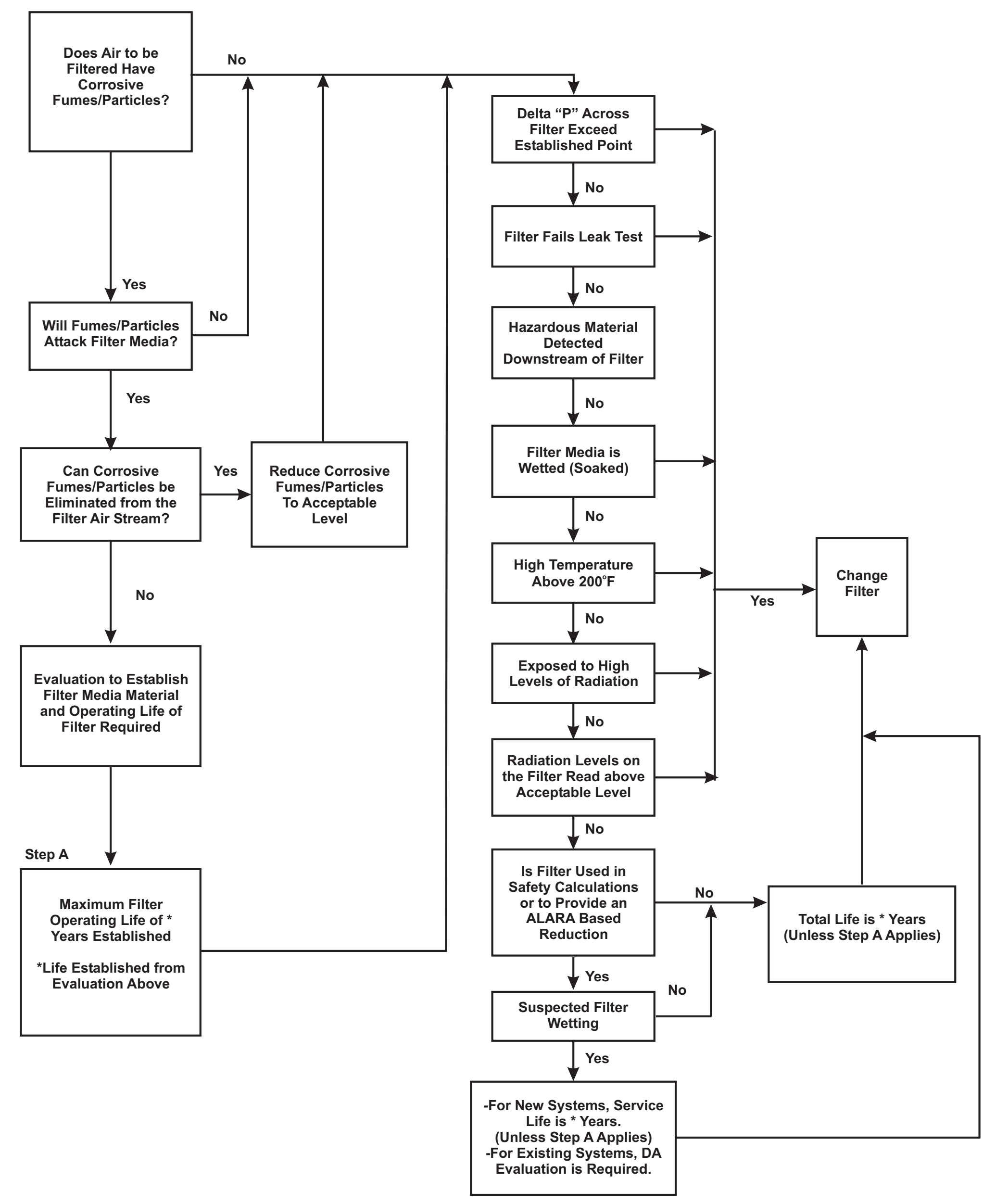
The age limits in this report are based on highly variable data, but more accurate age limits can be derived from controlled experiments in real time over 5 to 10 years using a specific filter-media roll. Until such long-term studies are conducted, establishing a 5- and 10-year HEPA filter life for wet and dry ventilation systems,

[1] *Lawrence Livermore National Laboratory, Maximum HEPA-filter Life, Werner Berman, Hazards Control Department, UCRL-AR-134141, June 1999.*

respectively, will ensure that most (although not all) HEPA filters will not suffer a significant loss in strength due to age.

Despite the difficulty of determining HEPA-filter life based on the research data, conservative interpretation of these data can be used to set age limits. The age limit can be set based on the data derived from the observed decreases in the tensile strength of dry filter media with age and the further reduction in strength due to water exposure.

The following flow chart depicts Savannah River Site's methodology for determining system specific service life and is presented merely for guidance.



*The owner/user of the facility should determine a service life of the HEPA.
Reference: Savannah River Site Engineering Standard No. 15888.