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THE DEVELOPMENT OF COAL-BASED TECHNOLOGIES FOR DEPARTMENT OF DEFENSE FACILITIES

Semiannual Technical Progress Report for the Period 09/28/1995 to 03/27/1996

By DOE/PC/92162--T6

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Department of Mineral Economics

October 21, 1996

Work Performed Under Cooperative Agreement No. DE-FC22-92PC92162

For
U.S. Department of Energy
Pittsburgh Energy Technology Center
P.O. Box 10940
Pittsburgh, Pennsylvania 15236

By
The Consortium for Coal-Water Slurry Fuel Technology
The Pennsylvania State University
C211 Coal Utilization Laboratory
University Park, Pennsylvania 16802

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EXECUTIVE SUMMARY

The U.S. Department of Defense (DOD), through an Interagency Agreement with the U.S. Department of Energy (DOE), has initiated a three-phase program with the Consortium for Coal-Water Slurry Fuel Technology, with the aim of decreasing DOD's reliance on imported oil by increasing its use of coal. The program is being conducted as a cooperative agreement between the Consortium and DOE.

Activities this reporting period are summarized by phase.

PHASE I

During this reporting period, the Phase I final report was completed.

PHASE II

Work in Phase II focused on emissions reductions, coal beneficiation/preparation studies, and economic analyses of coal use.

Emissions reductions investigations included completing a study to identify appropriate SO_2 and NO_x control technologies for coal-fired industrial boilers. In addition, work continued on the design of a ceramic filtering device for installation on the demonstration boiler. The ceramic filtering device will be used to demonstrate a smaller and more efficient filtering device for retrofit applications.

Work related to coal preparation and utilization, and the economic analysis was primarily focused on preparing the final report.

PHASE III

Work in Phase III focused on coal preparation studies and economic analyses of coal use.

Coal preparation studies were focused on continuing activities on particle size control, physical separations, surface-based separation processes, and dry processing.

The economic study focused on community sensitivity to coal usage, regional economic impacts of new coal utilization technologies, and constructing a national energy portfolio.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF TABLES

1.0 INTRODUCTION

The U.S. Department of Defense (DOD), through an Interagency Agreement with the U.S. Department of Energy (DOE), has initiated a three-phase program with the Consortium for Coal-Water Mixture Technology, with the aim of decreasing DOD's reliance on imported oil by increasing its use of coal. The program is being conducted as a cooperative agreement between the Consortium and DOE. The first phase was completed; work is underway in the other two phases.

To achieve the objectives of the program, a team of researchers was assembled from Penn State (Energy and Fuels Research Center (EFRC), Mineral Processing Section, Department of Mineral Economics, Fuel Science Program, and Polymer Science Program), Energy and Environmental Research Corporation (EER), AMAX Research and Development Center, ABB Combustion Engineering, CeraMem Separations, Inc., Comprehensive Design Architects and Engineers, and Raytheon Constructors & Engineers.

Phase I activities were focused on developing clean, coal-based combustion technologies for the utilization of both micronized coal-water mixtures (MCWMs) and dry, micronized coal (DMC) in fuel oil-designed industrial boilers. Phase II research and development continued to focus on industrial boiler retrofit technologies by addressing emissions control strategies for providing ultra-low emissions when firing coal-based fuels in industrial-scale boilers. Phase III activities evaluate current DOD boiler operation and emissions, and examine coal-based fuel combustion systems that cofire wastes. Each phase includes an engineering cost analysis and technology assessment. The activities and status of the phases are described below.

The objective in Phase I was to deliver fully engineered retrofit options for a fuel oil-designed watertube boiler located on a DOD installation to fire either MCWM or DMC. This was achieved through a program consisting of the following five tasks: 1) Coal Beneficiation and Preparation; 2) Combustion Performance Evaluation; 3) Engineering Design; 4) Engineering and Economic Analysis; and 5) Final Report/Submission of Design Package. Following is an outline of the project tasks that comprised Phase I:

Task 1: Coal Beneficiation/Preparation

Subtask 1.1	Identify/Procure Coals
Subtask 1.2	Determine Liberation Potential
Subtask 1.3	Produce Laboratory-Scale Quantities of Micronized Coal-Water Mixtures (MCWMs)
Subtask 1.4	Develop Dry Coal Cleaning Technique
Subtask 1.5	Produce MCWMs and Dry, Micronized Coal (DMC) From Dry Clean Coal
Subtask 1.6	Produce MCWM and DMC for the Demonstration Boiler
Subtask 1.7	Project Management and Support

Task 2: Combustion Performance Evaluation

Subtask 2.1 Boiler Retrofit
Subtask 2.2 Fuel Evaluation in the Research Boiler
Subtask 2.3 Performance Evaluation of the MCWM and DMC in the Demonstration Boiler
Subtask 2.4 Evaluate Emissions Reductions Strategies
Subtask 2.5 Project Management and Support

Task 3: Engineering Design

Subtask 3.1 MCWM/DMC Preparation Facilities
Subtask 3.2 Fuel Handling
Subtask 3.3 Burner System
Subtask 3.4 Ash Removal, Handling, and Disposal
Subtask 3.5 Air Pollution Control
Subtask 3.6 Integrate Engineering Design
Subtask 3.7 Project Management and Support

Task 4: Engineering and Economic Analysis

Subtask 4.1 Survey Boiler Population/Identify Boilers for Conversion
Subtask 4.2 Identify Appropriate Cost-Estimating Methodologies
Subtask 4.3 Estimate Basic Costs of New Technologies
Subtask 4.4 Process Analysis of MCWM and DMC
Subtask 4.5 Analyze/Identify Transportation Cost of Commercial Sources of MCWM and Cleaned Coal for DMC Production
Subtask 4.6 Determine Community Spillovers
Subtask 4.7 Regional Market Considerations and Impacts
Subtask 4.8 Integrate the Analysis
Subtask 4.9 Project Management and Support

Task 5: Final Report/Submission of Design Package

The Phase I activities included:

Task 1: The coal beneficiation and preparation effort was conducted by Penn State's Mineral Processing Section with assistance from Penn State's Polymer Science Program. This task involves identifying and procuring six coals that could be cleaned to <1.0 wt.% sulfur and <5.0 wt.% ash which have been, or possess the characteristics to enable them to be, made into MCWMs. The coals were subjected to detailed characterization and used to produce laboratory-scale quantities of MCWM. A fundamental study of MCWM stabilization was conducted. Additional activities included developing a dry coal cleaning technique and producing MCWMs and DMC from the resulting cleaned coal.

Task 2: Penn State's EFRC conducted the combustion performance evaluation with assistance from EER and Penn State's Fuel Science Program. The technical aspects of converting a fuel oil-designed boiler at a DOD facility were identified in this task. All appropriate components were evaluated, including the fuel, the fuel storage, handling and delivery equipment, the burner, the boiler, the ash handling and disposal equipment, the emissions control system, and the boiler control system. Combustion performance as indicated by flame stability, completeness of combustion, and related issues such as system derating, changes in system maintenance, the occurrence of slagging, fouling, corrosion and erosion, and air pollutant emissions were determined. As part of this task, MCWM and DMC were evaluated in EFRC's 15,000 lb steam/h watertube boiler. EER provided a coal-designed burner for retrofitting Penn State's boiler. In addition, EER designed the burner for the DOD boiler identified for retrofitting.

Task 3: An engineering study was performed for a complete retrofit of a DOD boiler facility to fire either MCWM or DMC. The designs were performed by EER with input from the other project participants. The designs included the coal preparation, the fuel handling, the burner, the ash removal, handling, and disposal, and the air pollution control systems. The two designs were for the DOD boiler identified in Task 4. The retrofits were designed for community/societal acceptability. The deliverables for this task were a detailed design that could be used for soliciting bids from engineering/construction firms to retrofit the candidate DOD boiler.

Task 4: An engineering cost analysis and a technology assessment of MCWM and DMC combustion were performed by Penn State's Department of Mineral Economics and the EFRC with assistance from the industrial participants. The effort involved surveying the DOD boiler population, identifying boilers for conversion, identifying appropriate cost-estimating methodologies, estimating basic costs for new technologies, developing a process model, analyzing and identifying transportation costs for commercial sources of MCWM and cleaned coal, determining community spillovers, and determining regional market considerations and impacts.

Task 5: The results from each of the tasks were summarized in a final report. In addition, the design packages for the boiler retrofits were submitted. These included the engineering design and economic analysis.

The original objectives of Phase II were to: (a) extend the Phase I boiler retrofit options by including designs to achieve further reductions in gaseous and particulate emissions, (b) prepare and characterize fuels compatible with coal precombustors, and (c) investigate precombustion as a means of using high ash, high sulfur coals. Upon investigating precombustion options for installing a system on either the demonstration boiler (15,000 lb steam/h) or research boiler (1,000 lb steam/h), it became apparent that there were limited viable options and that the complexity of the systems would likely preclude their use on small-scale, industrial boilers. A similar conclusion was presented by the U.S. Corps of Engineers regarding the use of slagging combustors in the Army[1]. Consequently, the Phase II work was revised by eliminating the precombustion fundamental, pilot-scale, and demonstration-scale studies and focusing on fundamental, pilot-scale, and demonstration-scale emissions reduction strategies. An economic analysis of precombustion strategies was conducted, as originally planned, in order to compare precombustion strategies with (low ash) MCWM and DMC combustion retrofits. The revised Phase II consists of four tasks as outlined below:

Task 1. Emissions Reduction

Subtask 1.1	Evaluation of Emissions Reduction Strategies
Subtask 1.2	Installation of an Emissions Reduction System on the Demonstration Boiler
Subtask 1.3	Evaluation of an Emissions Reduction System
Subtask 1.4	Conduct NO_x Emissions Study
Subtask 1.5	Conduct VOC Study
Subtask 1.6	Conduct Trace Element Study
Subtask 1.7	Conduct Nitrogen Occurrence Study

Task 2. Coal Preparation/Utilization

Subtask 2.1	Optimization of Particle Size Consist for CWM Formulation
Subtask 2.2	Fine Grinding/Classification/Liberation
Subtask 2.3	Fine Gravity Concentration
Subtask 2.4	Agglomeration/Flotation Studies
Subtask 2.5	Fundamental Studies of Surface-Based Processes
Subtask 2.6	Column Flotation
Subtask 2.7	Dry Cleaning of Fine Coal
Subtask 2.8	CWM Density Control
Subtask 2.9	Stabilization of CWM
Subtask 2.10	Atomizer Testing

Task 3. Engineering Design and Cost; and Economic Analysis

Subtask 3.1	Determination of Basic Cost Estimation of Boiler Retrofits
Subtask 3.2	Determination of Process Analysis
Subtask 3.3	Determination of Environmental and Regulatory Impacts
Subtask 3.4	Determination of Transportation Cost Analysis
Subtask 3.5	Determination of Technology Adoption
Subtask 3.6	Determination of Regional Economic Impacts
Subtask 3.7	Determination of Public Perception of Benefits and Costs
Subtask 3.8	Determination of Social Benefits
Subtask 3.9	Determination of Coal Market Analysis
Subtask 3.10	Engineering Design
Subtask 3.11	Integration of Analyses

Task 4. Final Report/Submission of Design Package

Portions of Phase II have been completed. The Phase II activities include:

Task 1: Task 1 activities are ongoing. In Task 1, strategies are being developed to provide for ultra-low emissions when firing coal-based fuels in industrial-scale boilers. Emissions being addressed are SO_2, NO_x, fine particulate matter (<10 µm), air toxics (volatile organic compounds and trace metals), and CO_2. Post-combustion and during-combustion technologies to reduce SO_2 and NO_x emissions from coal-fired industrial boilers were surveyed. Novel technologies that are under development but are not commercially available were also surveyed as well as proven technologies such as limestone/lime injection, selective catalytic reduction, and nonselective catalytic reduction. Options for removing the submicron particulate were investigated. In addition, methods to remove air toxics from the flue gas, such as scrubbing, were investigated.

Task 2: Task 2 activities have been completed except for Subtask 2.10, which is an atomization study being conducted by Carnegie Mellon University, which was added during this reporting period. Emphasis in Task 2 was on the refinement and optimization of coal grinding and CWM preparation procedures, and on the development of advanced processes for beneficiating high ash, high sulfur coals. CWM formulation is still an art and there was a clear need for scientifically-based guidelines for slurry design. This involved determining the optimum particle size distribution, how and why the optimum particle size distribution varies from coal to coal, and the specific roles of chemical dispersing and stabilizing agents. Extensive, physical pre-cleaning of coal is especially important in small-boiler applications. The research effort built on work conducted in Phase I.

Task 3: Task 3 economic analysis activities are nearly complete and focuse on determining the basic cost estimation of boiler retrofits, evaluating environmental, regulatory, and regional economic impacts, and analyzing the coal market.

Task 4: The results from each of the tasks will be summarized in a final report.

The objectives in Phase III are to: (a) develop coal-based fuel/waste cofiring technologies, and (b) assist DOD in improving the combustion performance and reducing emissions from existing stoker-fired boilers. This will be achieved through a combination of fundamental, pilot-scale, and demonstration-scale studies, field testing, and an engineering design and cost analysis of a stoker retrofit. Phase III consists of six tasks outlined below:

Task 1. Coal Preparation/Utilization

Subtask 1.1	Particle Size Control
Subtask 1.2	Physical Separations
Subtask 1.3	Surface-Based Separation Process
Subtask 1.4	Dry Processing
Subtask 1.5	Stabilization of Coal-Water Mixtures

Task 2. Stoker Combustion Performance Analysis and Evaluation

Subtask 2.1	Determine DOD Stoker Operability and Emissions Concerns
Subtask 2.2	Conduct Field Test of a DOD Stoker
Subtask 2.3	Provide Performance Improvement Analysis to DOD
Subtask 2.4	Evaluate Pilot-Scale Stoker Retrofit Combustion
Subtask 2.5	Perform Engineering Design of Stoker Retrofit

Task 3. Emissions Reduction

- Subtask 3.1 Demonstrate Advanced Pollution Control System
- Subtask 3.2 Evaluate Carbon Dioxide Mitigation and Heavy Metal Removal in a Slipstream System
- Subtask 3.3 Study VOC and Trace Metal Occurrence and Capture

Task 4. Coal-Based Fuel/Waste Cofiring

- Subtask 4.1 Coal Fines Combustion
- Subtask 4.2 Coal/Rocket Propellant Cofiring

Task 5. Economic Evaluation

- Subtask 5.1 Cost and Market Penetration of Coal-Based Fuel Technologies
- Subtask 5.2 Selection of Incentives for Commercialization of the Coal-Using Technology
- Subtask 5.3 Community Sensitivity to Coal Fuel Usage
- Subtask 5.4 Regional Economic Impacts of New Coal Utilization Technologies
- Subtask 5.5 Economic Analysis of the Defense Department's Fuel Mix
- Subtask 5.6 Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects
- Subtask 5.7 Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies
- Subtask 5.8 Integrate the Analysis

Task 6. Final Report/Submission of Design Package

The Phase III activities include:

Task 1: Research conducted under Phase I and Phase II of this project has revealed a number of specific areas where continued and/or more focused effort is required in order to develop more effective and more reliable coal processing systems. Specific objectives of Task 1 are centered around:

- focused investigations into specific coal-cleaning options and their associated ancillary operations; and
- integration of processing/cleaning operations for overall system optimization.

As in the previous phases, emphasis will be on fine-coal processing for the production of high-quality, micronized coal for dry coal and coal-water mixture (CWM) applications.

Task 2: DOD operates several large World War II-vintage stoker-fired boilers for steam production. The objective in Task 2 is to address DOD's concern that they are difficult to operate properly, which results in poor combustion performance and excessive emissions. Ultimately, there is the possibility that the boilers may be converted from coal to another fuel form. The objective will be achieved by surveying the operability of the stoker-fired boilers, identifying a candidate boiler for improvement, conducting field testing to determine the combustion performance and emissions, providing a performance improvement analysis to DOD, if applicable, evaluating pilot-scale stoker retrofit combustion technologies, and performing an engineering design of a stoker retrofit to fire coal in a form that is most conducive to achieve operability and environmental goals.

Task 3: In Task 3, three levels of effort investigating emissions reductions will be performed. An advanced pollution control system will be tested at the demonstration level, CO_2 mitigation and heavy metal removal will be evaluated at the pilot-scale level, and fundamental studies of VOC and trace metal occurrence and capture will be conducted.

Task 4: The activities in Task 4 will address advanced/novel combustion techniques. This involves coal fines combustion and cofiring wastes with coal-based fuels.

Task 5: The activities in Task 5 will focus on determining cost and market penetration, selection of incentives, and regional economic impacts of coal-based fuel technologies. In addition, DOD's fuel mix will be determined and a national energy portfolio constructed.

Task 6: The results from each of the tasks will be summarized in a final report. In addition, the design package for the stoker retrofit will be submitted. This will include the engineering design and economic analysis.

The status of Phase I is presented in Section 2.0. The accomplishments and status of Phase II, Tasks 1, 2, 3, and 4 are presented in Sections 3.0, 4.0, 5.0, and 6.0, respectively. The accomplishments and status of Phase III, Tasks 1, 2, 3, 4, 5, and 6 are presented in Sections 7.0, 8.0, 9.0, 10.0, 11.0, and 12.0, respectively. Section 13.0 discusses miscellaneous activities that were conducted. Activities planned for the next semiannual period are listed in Section 14.0. References and acknowledgments are contained in Sections 15.0 and 16.0, respectively. The project schedule for Phases II and III is given in Figures 1-1 and 1-2, respectively, with a description of the milestones contained in Tables 1-1 and 1-2, respectively.

2.0 PHASE I, TASK 5: FINAL REPORT/SUBMISSION OF DESIGN PACKAGE

The final report for Phase I was completed during this reporting period.

3.0 PHASE II, TASK 1: EMISSIONS REDUCTION

The objective of this task is to develop strategies to provide for ultra-low emissions when firing coal-based fuels in industrial-scale boilers. Emissions being addressed are SO_2, NO_x, fine particulate matter (<10 μm), air toxics (volatile organic compounds and trace metals), and CO_2.

Demonstration-scale SO_2 and NO_x activities are presented in Section 3.1. Demonstration-scale fine particulate matter removal is discussed in Sections 3.2 and 3.3. Fundamental bench-scale and pilot-scale NO_x emissions, volatile organic emissions, and

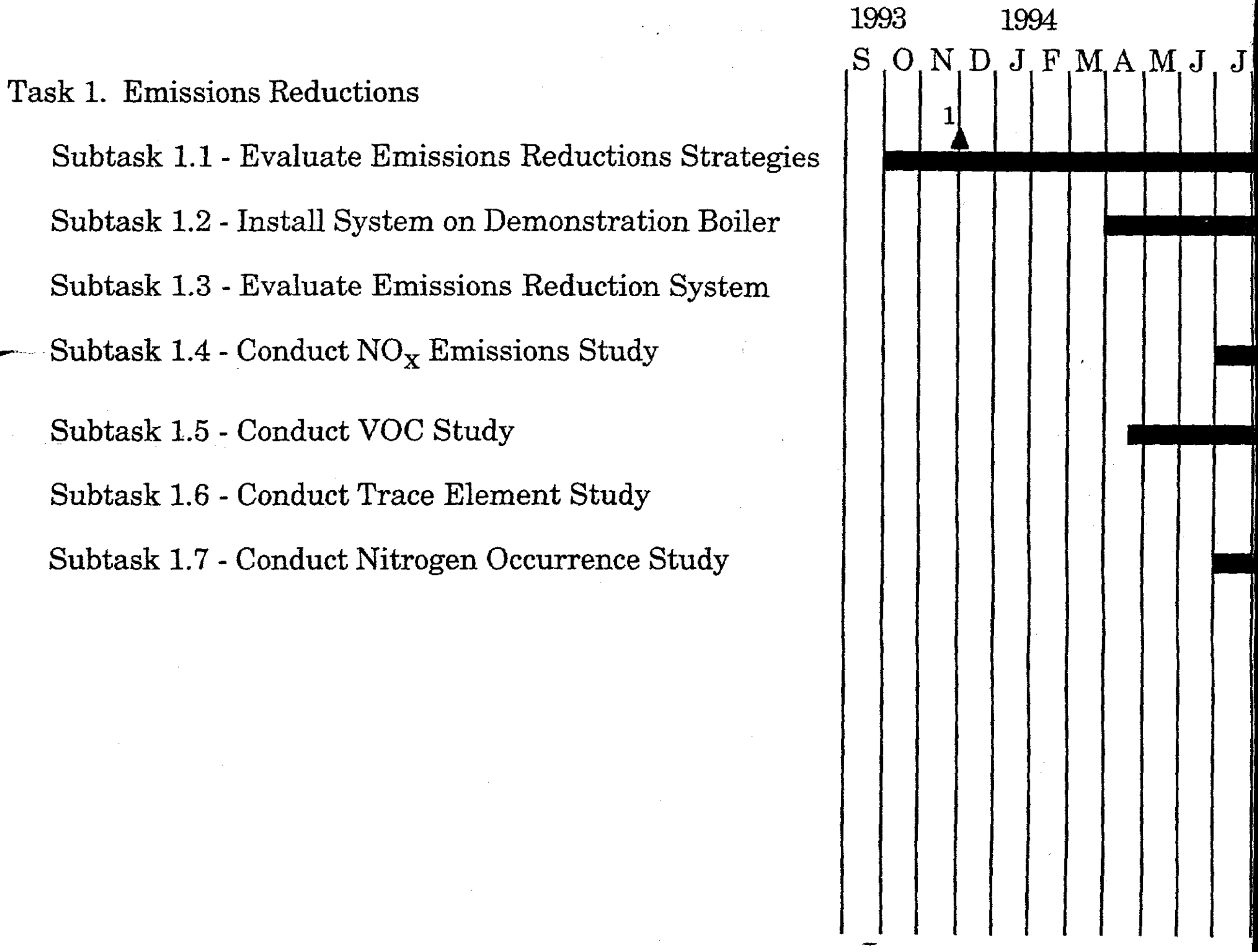
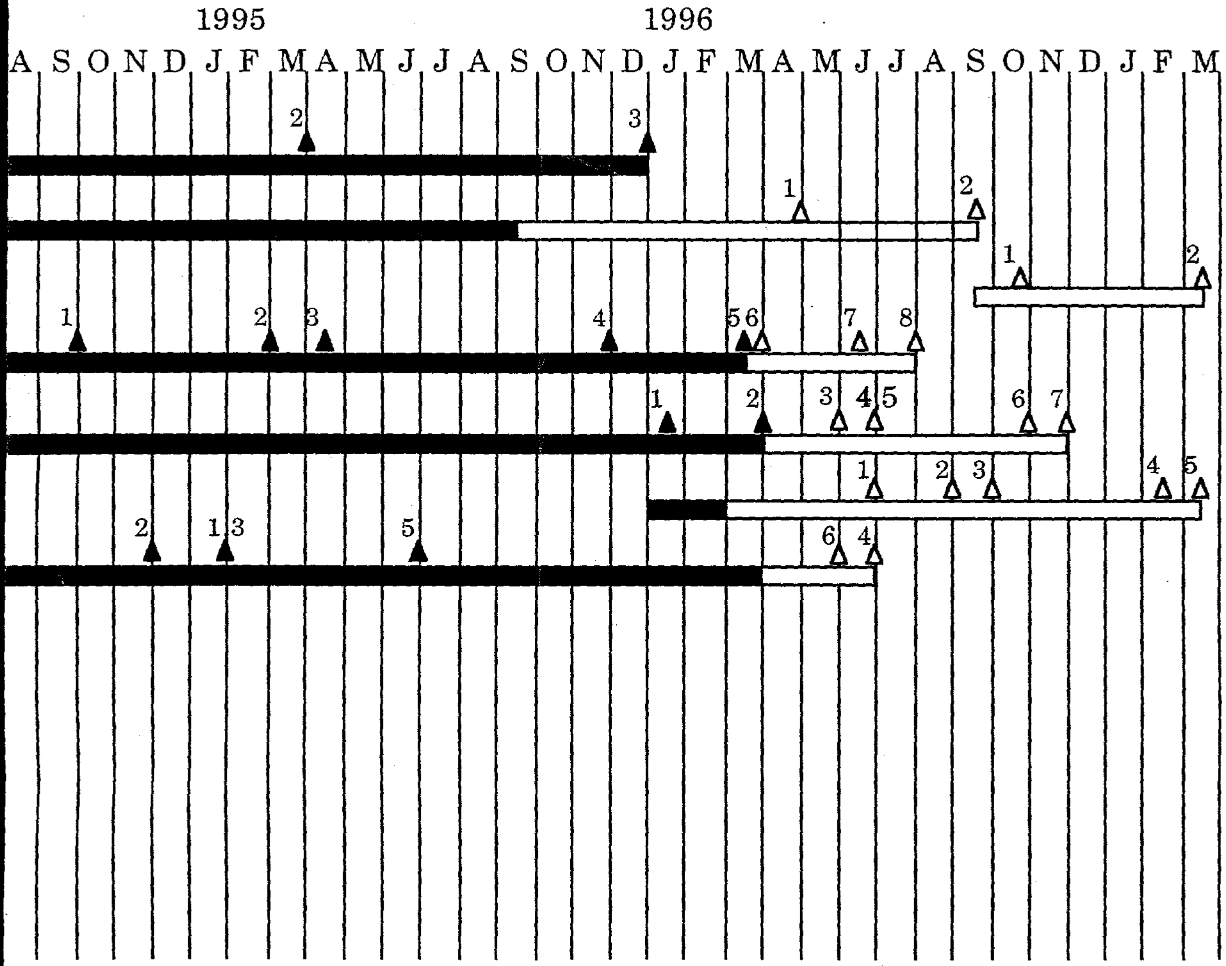


Figure 1-1. DOD Phase



ll Milestone Schedule

Task 2. Coal Preparation / Utilization

Subtask 2.1 - Optimization of Particle Size Consist for Slurry Formulation

Subtask 2.2 - Fine Grinding / Classification / Liberation

Subtask 2.3 - Fine Gravity Concentration

Subtask 2.4 - Agglomeration / Flotation Studies

Subtask 2.5 - Fundamental Studies of Surface-Based Processes

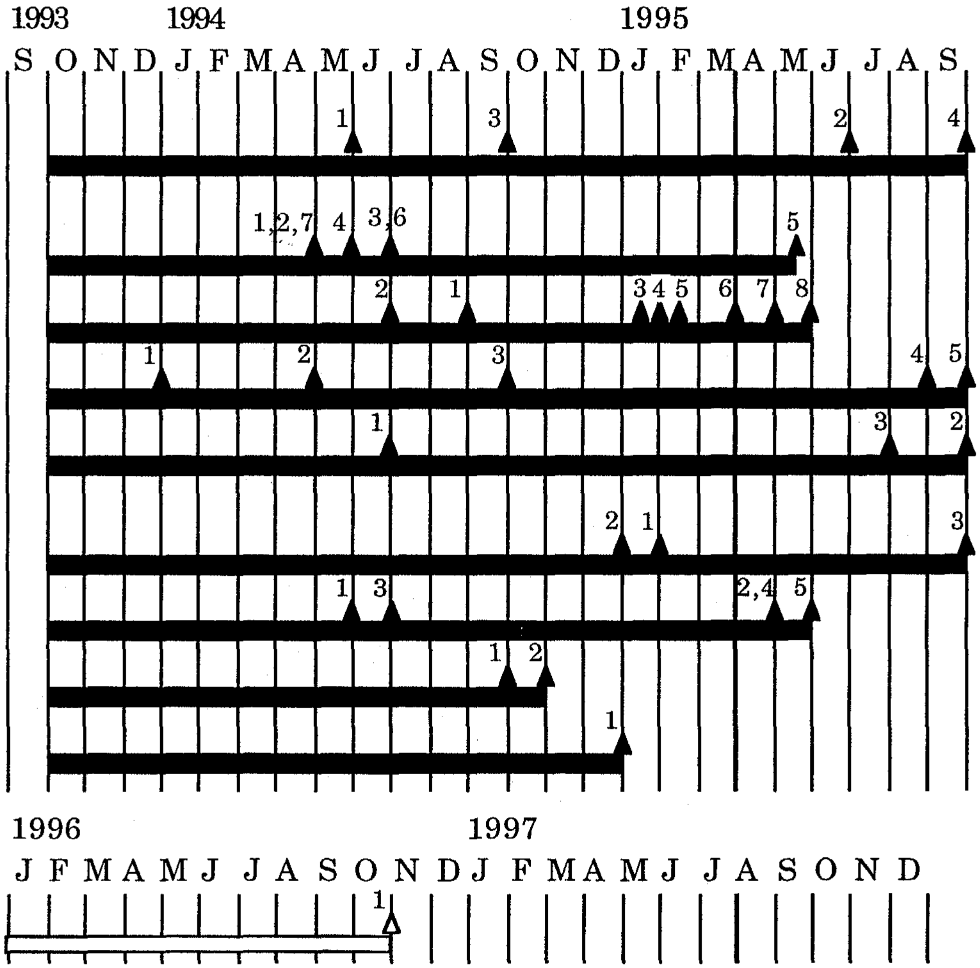
Subtask 2.6 - Column Flotation

Subtask 2.7 - Dry Cleaning of Fine Coal

Subtask 2.8 - Slurry Density Control

Subtask 2.9 - Stabilization of CWSF

Subtask 2.10 - Atomizer Testing



Task 3. Engineering Design and Cost and Economic Analysis

Subtask 3.1 - Basic Cost Estimation of Boiler Retrofits

Subtask 3.2 - Process Analysis

Subtask 3.3 - Environmental and Regulatory Impacts

Subtask 3.4 - Transportation Cost Analysis

Subtask 3.5 - Technology Adoption

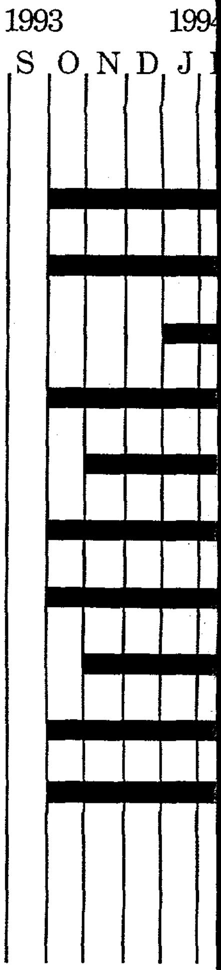
Subtask 3.6 - Regional Economic Impacts

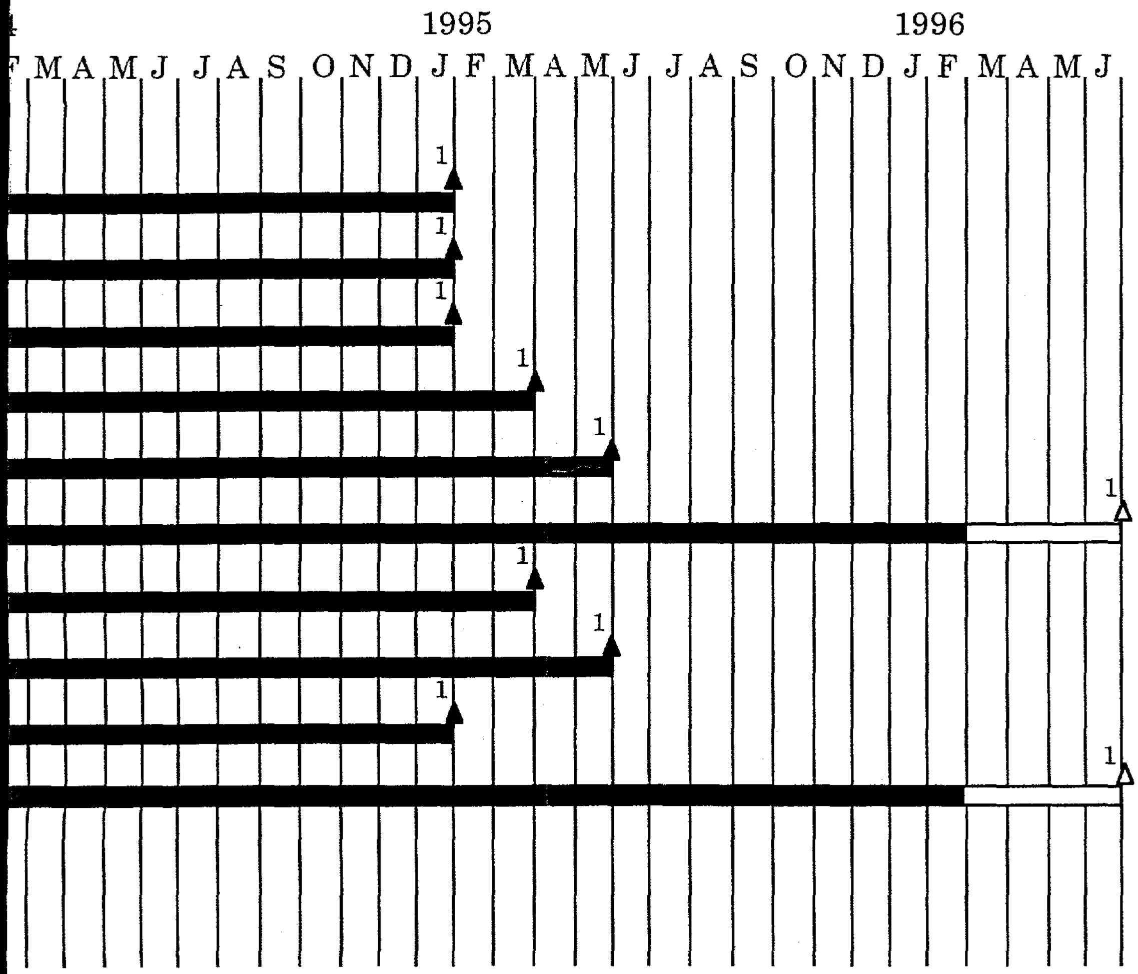
Subtask 3.7 - Public Perception of Benefits and Costs

Subtask 3.8 - Social Benefits

Subtask 3.9 - Coal Market Analysis

Subtask 3.10 - Integration of Analyses





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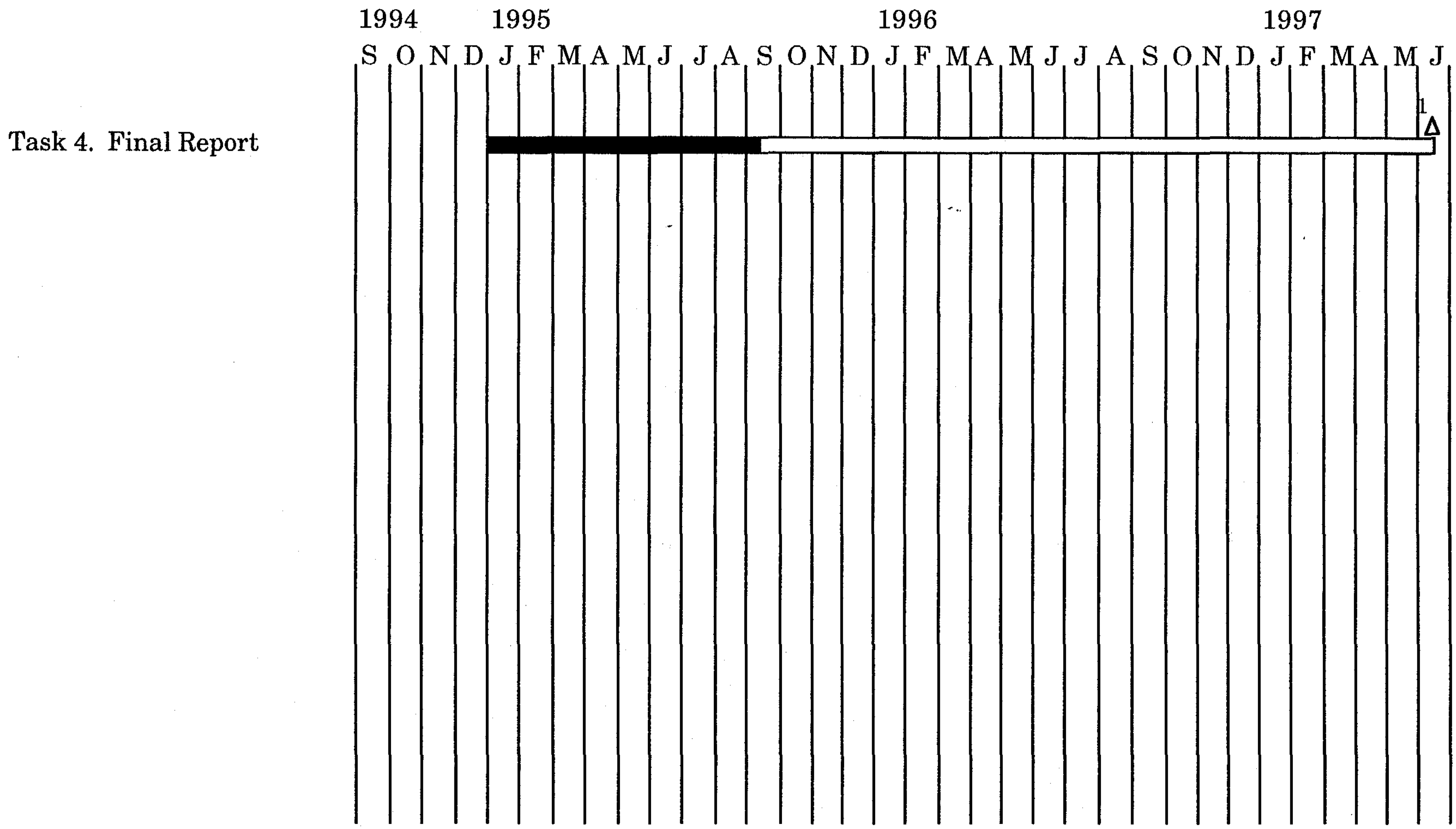
Task 4. Final Report
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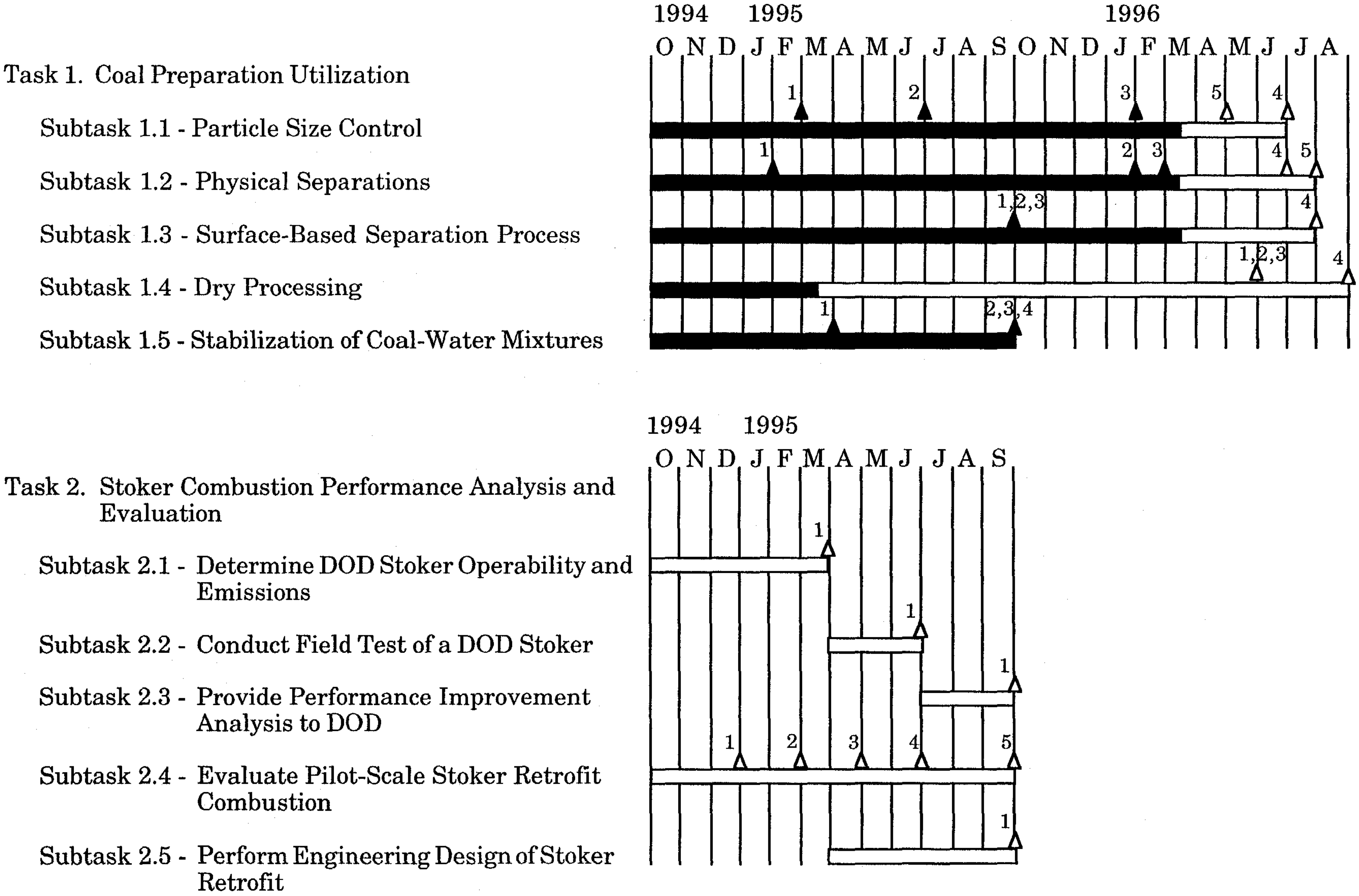


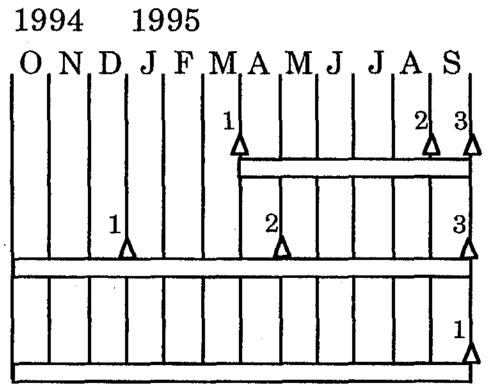
Figure 1-2. DOD Phase III Milestone Schedule

Task 3. Emissions Reduction

Subtask 3.1 - Demonstrate Advanced Pollution Control System

Subtask 3.2 - Evaluate CO_2 Mitigation and Heavy Metal Removal in a Slipstream System

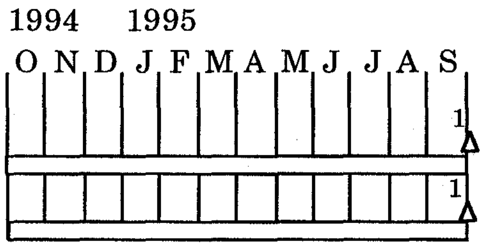
Subtask 3.3 - Study VOC and Trace Metal Occurrence and Capture



Task 4. Coal-Based Fuel Waste Cofiring

Subtask 4.1 - Coal Fines Combustion

Subtask 4.2 - Coal/Rocket Propellant Cofiring



Task 5. Economic Evaluation

Subtask 5.1 - Cost and Market Penetration of Coal-Based Fuel Technologies

Subtask 5.2 - Selection of Incentives for Commercialization of the Coal Using Technology

Subtask 5.3 - Community Sensitivity of Coal Fuel Usage

Subtask 5.4 - Regional Economic Impacts of New Coal Utilization Technologies

Subtask 5.5 - Economic Analysis of the Defense Department's Fuel Mix

Subtask 5.6 - Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects

Subtask 5.7 - Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies

Subtask 5.8 - Integration of Economic Analysis

Task 6. Final Report / Submission of Design Package

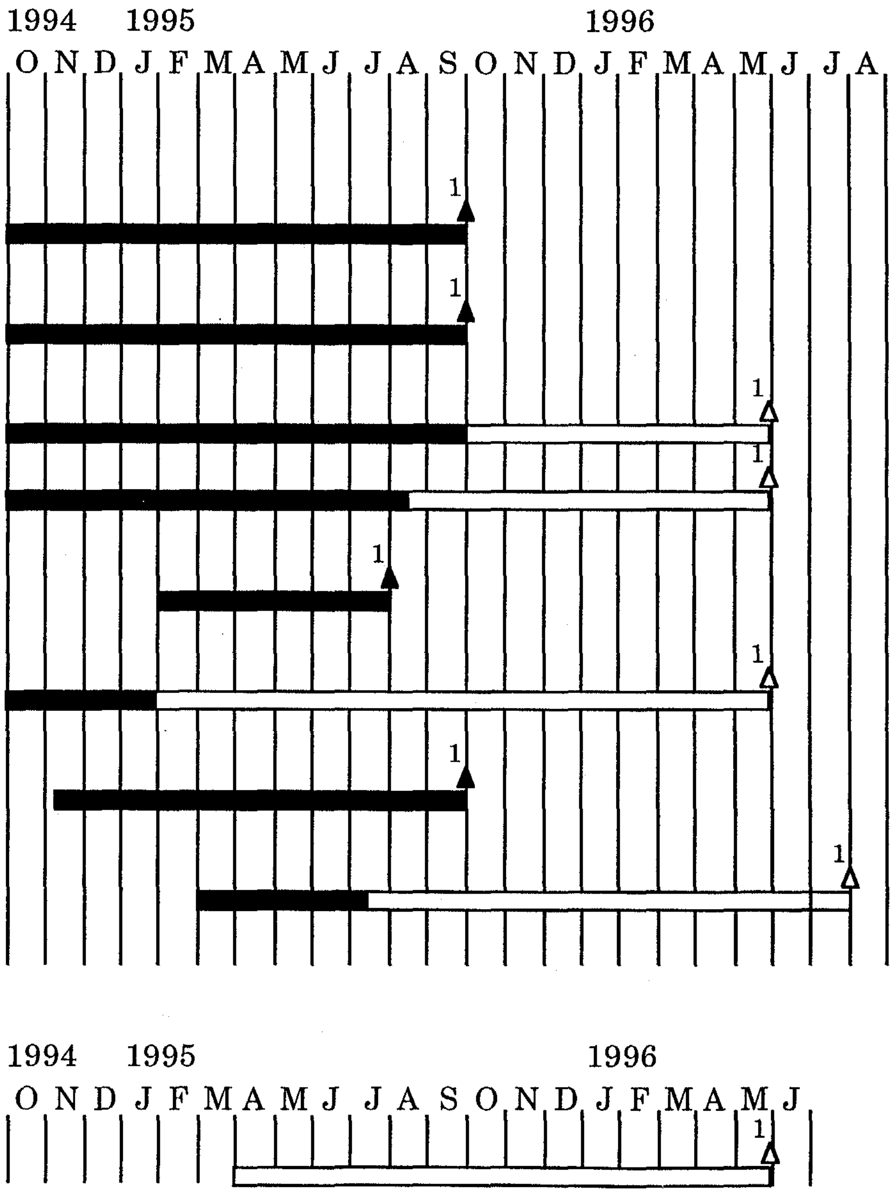


Table 1-1. Phase II. Milestone Description

Milestone	Description	Planned Completion Date	Actual Completion Date
Task 1. Emissions Reduction			
Subtask 1.1. Evaluation of Emissions Reduction Strategies			
Subtask 1.1, No. 1	Receive proposals for pollution control system	12/01/93	12/01/93
Subtask 1.1, No. 2	Complete summary report of pollution control technologies	03/31/95	03/31/95
Subtask 1.1, No. 3	Select pollution control system	12/31/95	12/31/95
Subtask 1.2. Install System on Demonstration Boiler			
Subtask 1.2, No. 1	Design pollution control system	05/01/96	
Subtask 1.2, No. 2	Complete installation of system	09/15/96	
Subtask 1.3. Evaluate Emissions Reduction System			
Subtask 1.3, No. 1	Shakedown system	10/15/96	
Subtask 1.3, No. 2	Complete system evaluation	03/15/97	
Subtask 1.4. Conduct NO_x Emissions Study			
Subtask 1.4, No. 1	Review state-of-the art in NO_x catalysts	10/01/94	10/01/94
Subtask 1.4, No. 2	Design bench-scale flow reactor	02/01/95	03/01/95
Subtask 1.4, No. 3	Design FTIR gas analysis system for the flow reactor	04/01/95	04/18/95
Subtask 1.4, No. 4	Construct flow reactor and data acquisition system	10/01/95	12/15/95
Subtask 1.4, No. 5	Shake down system and calibrate FTIR spectrometer	03/01/96	03/15/96
Subtask 1.4, No. 6	Select and acquire catalysts for testing	04/01/96	
Subtask 1.4, No. 7	Develop catalyst characterization database	06/15/96	
Subtask 1.4, No. 8	Design selective catalytic NO_x reduction system	08/01/96	
Subtask 1.5. Conduct VOC Study			
Subtask 1.5, No. 1	Modify research boiler	12/31/95	01/15/96
Subtask 1.5, No. 2	Literature survey on trace organic emissions and analytical procedures	03/31/96	04/01/96
Subtask 1.5, No. 3	Evaluate the GC/MS equipment and upgradation	06/01/96	
Subtask 1.5, No. 4	Procurement of Method 5 apparatus and auxiliaries	06/30/96	
Subtask 1.5, No. 5	Shakedown of the sampling procedures	06/30/96	
Subtask 1.5, No. 6	Conduct test program and analyze samples	10/31/96	
Subtask 1.5, No. 7	Analysis of the results	11/30/96	
Subtask 1.6. Conduct Trace Element Study			
Subtask 1.6, No. 1	Conduct literature survey on trace element emissions and analysis techniques	06/30/96	
Subtask 1.6, No. 2	Procure sampling equipment	08/31/96	
Subtask 1.6, No. 3	Shake down sampling procedure	09/30/96	
Subtask 1.6, No. 4	Characterize emissions from industrial boiler	02/15/97	
Subtask 1.6, No. 5	Analysis of results	03/15/97	
Subtask 1.7. Conduct Nitrogen Occurrence Study			
Subtask 1.7, No. 1	Optimization of sample preparation for ^{15}N NMR on coals and chars	01/31/95	01/31/95
Subtask 1.7, No. 2	First solid-state ^{15}N NMR spectra at natural ^{15}N abundance of coals obtained	11/30/94	11/30/94
Subtask 1.7, No. 3	First solid-state ^{15}N NMR spectra at natural ^{15}N abundance of chars obtained	01/31/95	01/31/95

Milestone	Description	Planned Completion Date	Actual Completion Date
Subtask 1.7, No. 4	Examination of diagenetic changes of the N-functionality in oil shale and its precursors by means of ^{15}N and ^{13}C NMR spectroscopy	06/30/96	
Subtask 1.7, No. 5	Examination of the N-functionality in vitrinite coals as a function of maturation degree by means of ^{15}N and ^{13}C NMR spectroscopy	06/30/95	06/30/95
Subtask 1.7, No. 6	Examination of changes of the N-functionality in chars as a function of retention time in combustion chamber by means of ^{15}N and ^{13}C NMR spectroscopy	05/31/96	
Task 2. Coal Preparation/Utilization			
Subtask 2.1. Optimization of Particle Size Consist for Slurry Formulation			
Subtask 2.1, No. 1	Samples of fine and coarse slurry components prepared	04/30/94	05/30/94
Subtask 2.1, No. 2	Rheological characterization of components completed	04/30/95	06/30/95
Subtask 2.1, No. 3	Models for rheology of binary mixtures developed	09/30/94	09/30/94
Subtask 2.1, No. 4	Optimization studies complete	06/30/95	09/30/95
Subtask 2.2. Fine Grinding/Classification Liberation			
Subtask 2.2, No. 1	Grinding kinetics data for wet ball milling obtained	04/30/94	04/30/94
Subtask 2.2, No. 2	Wet classifier performance evaluated	04/30/95	04/30/95
Subtask 2.2, No. 3	Dry classifier performance evaluated	04/30/94	06/30/94
Subtask 2.2, No. 4	Grinding kinetics data for stirred media milling obtained	05/31/94	05/31/94
Subtask 2.2, No. 5	Closed-circuit jet-milling data obtained	05/15/95	05/15/95
Subtask 2.2, No. 6	Slurry production simulations initiated	06/30/94	06/30/94
Subtask 2.2, No. 7	Liberation data on Type III coal obtained	04/30/94	04/30/94
Subtask 2.3. Fine Gravity Concentration			
Subtask 2.3, No. 1	Initiate magnetic fluid separation of Type III coal	07/31/94	08/15/94
Subtask 2.3, No. 2	Complete batch centrifuge testing	04/30/94	06/30/94
Subtask 2.3, No. 3	Continuous centrifuge test rig set-up	09/30/94	01/15/95
Subtask 2.3, No. 4	Initiate magnetite classification studies	10/15/94	01/31/95
Subtask 2.3, No. 5	Initiate separations of Type III coals	02/28/95	02/28/95
	Initiate micronized coal classification studies	04/30/95	03/31/95
Subtask 2.3, No. 6			
Subtask 2.3, No. 7	Evaluate dense-medium separation data	04/30/95	04/30/95
Subtask 2.3, No. 8	Evaluate size classification data	05/31/95	05/31/95
Subtask 2.4. Agglomeration/Flotation Studies			
Subtask 2.4, No. 1	Set-up device to size separate flotation products of micronized coal	12/31/93	12/31/93
Subtask 2.4, No. 2	Set-up equipment for larger scale tests using 2.2 cu.ft. flotation cells	04/30/94	04/30/94
Subtask 2.4, No. 3	Conduct agglomeration-flotation tests for micronized Type III coal	09/30/94	09/30/94
Subtask 2.4, No. 4	Conduct agglomeration-flotation tests in larger cells	03/31/95	08/31/95
Subtask 2.4, No. 5	Determine parameters for scale-up	06/30/95	09/30/95
Subtask 2.5. Fundamental Studies of Surface-Based Processes			
Subtask 2.5, No. 1	Conduct interface characterization studies to determine flotation reagent-coal interactions	06/30/94	06/30/94
Subtask 2.5, No. 2	Measure contact angles in the coal-oil-surfactant-water system	06/30/95	09/30/95
Subtask 2.5, No. 3	Determine effect of surfactants on slurry stability	05/31/95	07/31/95

Milestone	Description	Planned Completion Date	Actual Completion Date
Subtask 2.6. Column Flotation			
Subtask 2.6, No. 1	Test work on Type II coals	11/30/94	01/31/95
Subtask 2.6, No. 2	Test work on Type III coals	09/30/94	12/31/94
Subtask 2.6, No. 3	Determine scale-up parameters	05/31/95	09/30/95
Subtask 2.7. Dry Cleaning of Fine Coal			
Subtask 2.7, No. 1	Complete evaluation of Type III coal in batch separator	04/30/94	05/31/94
Subtask 2.7, No. 2	Integration of closed dry grinding circuit with TES	04/30/95	04/30/95
Subtask 2.7, No. 3	Initiate investigation of continuous TES	04/01/94	06/30/94
Subtask 2.7, No. 4	Complete charge measurements on Type II coal	04/30/95	04/30/95
Subtask 2.7, No. 5	Complete charge measurements on Type III	05/31/95	05/31/95
Subtask 2.8. Slurry Density Control			
Subtask 2.8, No. 1	Evaluate procedures for reversible flocculation of fine coal	09/30/94	09/30/94
Subtask 2.8, No. 2	Establish process engineering for thickening of fine-coal slurries	10/31/94	10/31/94
Subtask 2.9. Stabilization of CWSF			
Subtask 2.9, No. 1	Complete stabilization study	12/31/94	12/31/94
Subtask 2.10. Atomizer Testing			
Subtask 2.10, No. 1	Complete atomization study	11/01/96	
Task 3. Engineering Design and Cost; and Economic Analysis			
Subtask 3.1. Determine Basic Cost Estimation of Boiler Retrofits		02/01/95	02/01/95
Subtask 3.2. Determine Process Analysis		02/01/95	02/01/95
Subtask 3.3. Determine Environmental and Regulatory Impacts		02/01/95	02/01/95
Subtask 3.4. Determine Transportation Cost Analysis		04/01/95	04/01/95
Subtask 3.5. Determine Technology Adoption		06/01/95	06/01/95
Subtask 3.6. Determine Regional Economic Impacts		06/30/96	
Subtask 3.7. Determine Public Perception of Benefits and Costs		04/01/95	04/01/95
Subtask 3.8. Determine Social Benefits		06/01/95	06/01/95
Subtask 3.9. Determine Coal Market Analysis		02/01/95	02/01/95
Subtask 3.10. Complete Integration of Analyses		06/30/96	
Task 4. Final Report		06/15/97	

Table 1-2. Phase III. Milestone Description

Milestone	Description	Planned Completion Date	Actual Completion Date
Task 1. Coal Preparation/Utilization			
Subtask 1.1. Particle Size Control			
Subtask 1.1, No. 1	Evaluate conventional ball milling circuit	02/28/95	02/28/95
Subtask 1.1, No. 2	Evaluate stirred-media milling circuit	06/30/95	06/30/95
Subtask 1.1, No. 3	Complete baseline testing of attrition milling for the production of broad size distributions	01/31/96	01/31/96
Subtask 1.1, No. 4	Complete preliminary evaluation of dry grinding/ classifier circuit	06/30/96	
Subtask 1.1, No. 5	Initiate investigation of an integrated grinding/cleaning circuit	04/30/96	
Subtask 1.2. Physical Separations			
Subtask 1.2, No. 1	Complete preliminary investigation of magnetic fluid-based separation for fine coal cleaning	01/31/95	01/31/95
Subtask 1.2, No. 2	Complete baseline testing of dense-medium separation using the continuous, solid-bowl centrifuge	01/31/96	01/31/96
Subtask 1.2, No. 3	Initiate investigation of magnetic fluid cyclone separations	02/29/96	02/29/96
Subtask 1.2, No. 4	Complete baseline testing of solid-bowl centrifuge for micronized coal classification	06/30/96	
Subtask 1.2, No. 5	Initiate testing of integrated centrifugal/flotation system	07/31/96	
Subtask 1.3. Surface-Based Separation Processes			
Subtask 1.3, No. 1	Set up and evaluate continuous flotation circuit	05/31/95	09/30/95
Subtask 1.3, No. 2	Evaluate effectiveness of alternative bubble generators in flotation column	06/30/95	09/30/95
Subtask 1.3, No. 3	Baseline testing on selected coal	08/31/95	09/30/95
Subtask 1.3, No. 4	Evaluate flotation system performance	07/31/96	
Subtask 1.4 Dry Processing			
Subtask 1.4, No. 1	Complete deagglomeration testing using the batch triboelectrostatic separator	05/31/96	
Subtask 1.4, No. 2	Complete baseline testing of continuous triboelectrostatic separator unit	05/31/96	
Subtask 1.4, No. 3	Initiate investigation of alternative approaches to charging/deagglomeration	05/31/96	
Subtask 1.4, No. 4	Complete preliminary testing of integrated grinding and triboelectrostatic separator unit	08/31/96	

Milestone	Description	Planned Completion Date	Actual Completion Date
Subtask 1.5 Stabilization of Coal-Water Mixtures			
Subtask 1.5, No. 1	Complete PSD model extension	04/01/95	04/01/95
Subtask 1.5, No. 2	Complete construction of computer program	09/27/95	09/27/95
Subtask 1.5, No. 3	Complete PSD model comparison to experimental results	09/27/95	09/27/95
Subtask 1.5, No. 4	Complete coal oxidation study	09/27/95	09/27/95
Task 2. Stoker Combustion Performance Analysis and Evaluation			
Subtask 2.1. Determine DOD Stoker Operability and Emissions			
Subtask 2.1, No. 1	Complete stoker survey, identify stoker for evaluation	03/31/95	
Subtask 2.2. Conduct Field Test of a DOD Stoker			
Subtask 2.2, No. 1	Complete stoker field test	07/01/95	
Subtask 2.3 Provide Performance Improvement Analysis to DOD			
Subtask 2.3, No. 1	Complete performance improvement analysis	09/27/95	
Subtask 2.4. Evaluate Pilot-Scale Stoker Retrofit Combustion			
Subtask 2.4, No. 1	Complete modifications to stoker system	12/31/94	
Subtask 2.4, No. 2	Complete evaluation of anthracite micronized coal	02/28/95	
Subtask 2.4, No. 3	Complete evaluation of anthracite/water mixtures	04/30/95	
Subtask 2.4, No. 4	Complete evaluation of bituminous micronized coal	06/30/95	
Subtask 2.4, No. 5	Complete evaluation of bituminous/water mixtures	09/27/95	
Subtask 2.5. Perform Engineering Design of Stoker Retrofit			
Subtask 2.5, No. 1	Complete retrofit design	09/27/95	
Task 3. Emissions Reduction			
Subtask 3.1. Demonstrate Advanced Pollution Control System			
Subtask 3.1, No. 1	Identify low-temperature catalysts	03/31/95	
Subtask 3.1, No. 2	Install catalyst-coated filter and SO_2 removal system	08/31/95	
Subtask 3.1, No. 3	Complete demonstration of unit	09/27/95	
Subtask 3.2. Evaluate Carbon Dioxide Mitigation and Heavy Metal Removal in a Slipstream System			
Subtask 3.2, No. 1	Identify CO_2 mitigation technique	01/01/95	
Subtask 3.2, No. 2	Install slipstream	05/01/95	

Milestone	Description	Planned Completion Date	Actual Completion Date
Subtask 3.2, No. 3	Complete evaluation of CO_2 mitigation/heavy metal removal	09/27/95	
Subtask 3.3. Study VOC and Trace Metal Occurrence and Capture			
Subtask 3.3, No. 1	Complete evaluation of VOC and trace metals	09/27/95	
Task 4. Coal-Based Fuel Waste Cofiring			
Subtask 4.1. Coal Fines Combustion			
Subtask 4.1, No. 1	Complete coal fines combustion evaluation	09/27/95	
Subtask 4.2. Coal/Rocket Propellant Cofiring			
Subtask 4.2, No. 1	Complete cofiring testing	09/27/95	
Task 5. Economic Evaluation			
Subtask 5.1. Cost and Market Penetration of Coal-Based Fuel Technologies			
Subtask 5.1, No. 1	Complete study of cost and market penetration of coal-based fuel technologies	06/01/95	09/27/95
Subtask 5.2. Selection of Incentives for Commercialization of the Coal Using Technology			
Subtask 5.2, No. 1	Complete selection of incentives for commercialization of the coal-using technology	09/27/95	09/27/95
Subtask 5.3. Community Sensitivity to Coal Fuel Usage			
Subtask 5.3, No. 1	Complete evaluation of community sensitivity to coal fuel usage	06/01/96	
Subtask 5.4 Regional Economic Impacts of New Coal Utilization Technologies			
Subtask 5.4, No. 1	Complete study of regional economic impacts of new coal utilization technologies	06/01/96	
Subtask 5.5 Economic Analysis of the Defense Department's Fuel Mix			
Subtask 5.5, No. 1	Complete economic analysis of the defense department's fuel mix	09/27/95	06/30/95

Milestone	Description	Planned Completion Date	Actual Completion Date
Subtask 5.6 Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects			
Subtask 5.6, No. 1	Complete construction of a national energy portfolio which minimizes energy price shock effects	06/01/96	
Subtask 5.7 Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies			
Subtask 5.7, No. 1	Complete research on the coal markets and their impact on coal-based fuel technologies	09/27/95	09/27/95
Subtask 5.8 Integrate the Analysis			
Subtask 5.8, No.1	Complete integration of the analysis	08/01/96	
Task 6. Final Report/Submission of Design Package		09/27/97	

nitrogen occurrence studies are presented in Sections 3.4, 3.5, and 3.7, respectively. The status of the demonstration-scale trace element study is given in Section 3.6.

3.1 Subtask 1.1 Evaluation of Emissions Reduction Strategies

The objective of this subtask was to evaluate emissions reduction strategies for the installation of commercial NO_x and SO_2 systems on the demonstration boiler. The work in this subtask was conducted primarily by literature searches and discussions with manufacturers of flue gas cleanup equipment and with other researchers in the field.

Literature searches were previously conducted on NO_x, SO_2, volatile organic compounds, and trace metals removal systems[2]. The literature searches were for all coal-fired boilers and were not limited to industrial-size boilers. The information from the literature searches is being used with that received from the vendors and engineering firms to select appropriate control systems for installation on the demonstration boiler (Section 3.2).

3.1.1 Discussions with Vendors and Engineering Firms for NO_x and SO_2 Emissions Control Technologies

Vendors and engineering firms were contacted to identify the appropriate NO_x and SO_2 emissions control technologies. Of the firms contacted, Raytheon Constructors & Contractors was selected to provide a summary report reviewing the operational data on the demonstration boiler, and identifying the appropriate NO_x and SO_2 technologies for installation on the industrial boiler.

Summary of Raytheon Constructors & Contractors' Report

Raytheon Engineers & Constructors prepared a report of an SO_2/NO_x control study for Penn State's demonstration boiler. The study addressed commercially viable systems that could be demonstrated on the boiler.

In the SO_2 study, Raytheon examined five sorbent injection SO_2 control technologies, which included furnace sorbent injection (FSI), economizer sorbent injection (ESI), duct spray drying (DSD), calcium dry sorbent injection (calcium DSI), and sodium DSI. They concluded that for the furnace design, and thermal profile do not make the industrial boiler a practical application for furnace or economizer injection. The dimensions of the ductwork between the air heater and fabric filter do not provide the required flue gas residence time to evaporate slurry or humidification by water droplets. This would lead to severe wet solids deposition and ductwork pluggage for both the DSD and calcium duct injection options. From a technical standpoint, sodium duct injection is the best candidate.

In Raytheon's NO_x study, they conducted a screening analysis of combustion control (Low-NOx burners, flue gas recirculation, over-fire air, and reburning), post-combustion control (selective non-catalytic reduction (SNCR), hot-side selective catalytic reduction (HS SCR), and cold-side selective catalytic reduction (CS SCR)), and combinations of combustion and post-combustion controls (combustion controls + SNCR or SCR, and SNCR + SCR). The screening analysis was performed in an informal manner since the outcome of the analysis was as expected. Of the candidate process technologies, only SCR was considered capable of satisfying the NO_x reduction requirement of 80-90%. Therefore, the screening analysis consisted primarily of selecting between the cold side and the hot side SCR options.

Because HS SCR is significantly less costly than CS SCR, much of the evaluation of analyzing HS SCR design issues was to ensure that the technology could be successfully applied. The screening analysis revealed that there is some process uncertainty associated with application of HS SCR. The primary area of uncertainty is associated with the low flue gas temperature exiting the boiler. Past Penn State operational data showed that while the flue gas temperature is sufficiently high for HS SCR at full load, the flue gas temperature at reduced loads may fall under the minimum required by SCR. If this is the case, it would impose an operational limit on the minimum boiler load unless some means can be used to maintain the flue gas temperature over the load range.

CS SCR is technically feasible, although it is costly and quite complex. Significant space requirements need a closer look at the available space. The CS SCR process requires a gas-to-gas heater (possibly a heat pipe) for heat recovery and also requires a supplemental heating system (probably natural gas fired). Other than the uncertainty associated with space requirements, there is little process uncertainty associated with application of CS SCR. Its location downstream of the SO_2 and particulate control systems results in a fairly clean gas application, which reduces operating impact associated with cycling operation. Low flue gas temperature is not an issue since this process includes a supplemental heat system.

After reviewing the SO_2/NO_x Control Study prepared by Raytheon Engineers & Constructors, it was decided to install an SO_2 but not an NO_x control system on the boiler in Phase II. The objective of the pollution control work in Phase II is to install commercially-viable systems on an industrial boiler. Although Raytheon has identified commercially-available SO_2 and NO_x control systems, the viability of the NO_x control system is in question.

The NO_x reduction option, CS SCR, is much too complex and costly. The original objective of the program was to install an advanced system, which may be under development, onto the boiler. The program was modified to demonstrate commercial systems because the advanced systems required natural gas heaters to increase the flue gas temperature for catalyst activity. Similar to the advanced systems, the CS SCR process requires that the flue gas be heated by a natural gas source using a heat exchanger. Similar to the advanced systems explored earlier, CS SCR is an option that probably would never be applied to a coal-fired industrial boiler with the current state of the technology.

SO_2 Reduction System

The design of a sodium duct injection system was started during this reporting period. The design will be completed and the system installed during the next reporting period. The system will consist of a bag (sodium bicarbonate) unloading station, hopper with weigh cells, eductor, and piping to a port located in the ducting upstream of the baghouse and ceramic filter.

3.2 Subtask 1.2 Install System on the Demonstration Boiler

Activity is underway to install a ceramic filter on the demonstration boiler to remove ultrafine particulate and to increase the particulate collection efficiency. The ceramic filter will be installed adjacent to the existing baghouse and will be capable of filtering the entire flue gas stream. The system is being engineered such that the flue gas stream can be passed either through the baghouse or ceramic filter. An application for plan approval to modify the system was submitted to, and approved by, the Pennsylvania Department of Environmental Protection (DEP). The design of the new system, which includes the chamber to house the ceramic filters, structural supports, walkways, steps and ladders, ducting, valves, induced draft fan, and associated controls, is nearly complete. Installation of the system will be conducted from mid-July to mid-September, 1996.

The ceramic filter chamber is being designed by Penn State. Comprehensive Design Architects and Engineers (CDAE), of State College, Pennsylvania, is designing the structural supports, walkways, steps and ladders, ducting, valves, induced draft fan, and associated controls. The ceramic filters are being procured from CeraMem Separations, Inc. The design criteria of the filters are:

Design face velocity (A/C ratio)	4.00
Volume (acfm)	8,150
Temperature (F)	400
Grain loading to filters (gr/acf)	3.0
Operating pressure drop (" water column)	7-10
Filter area (sq.ft.)	2,000

The ceramic filtering device will contain 80 filters, 7" in diameter and 15" long. The current baghouse contains 120 bags, 4.5" in diameter and 10' long. It is the intent of this portion of the program to demonstrate a smaller, more efficient filtering device for retrofit applications.

3.3 Subtask 1.3 Evaluate Emissions Reduction System

No work was conducted on this subtask.

3.4 Subtask 1.4 Conduct NO_x Emissions Study

3.4.1 Objectives and Overview

The objectives for this subtask are as follows:

- To identify and/or develop a NO_x reduction catalyst that is compatible with the typical operating conditions and the economic constraints of industrial boilers, specifically:
    1. flue gas temperatures of 550°F (288°C)
    2. O_2 concentrations of 3-5 vol %
    3. H_2O concentration of 10-20 vol %
    4. SO_2 concentrations of 500-1000 ppm
    5. NO_x concentrations of 100-500 ppm
    6. No regeneration of sorbent/catalyst required
    7. Low maintenance and operating costs
- To establish the limitations of the candidate NO_x reduction catalyst so that its implementation in pilot and demonstration scale tests will be straightforward, for example, determining the relationship between space velocity and NO_x conversion efficiency for scale-up purposes
- To identify maximum allowable transients that the catalyst can be exposed to before losing effectiveness, such as swings in flue gas temperature, and sulfur and unburned hydrocarbon concentrations

These objectives will be met through the testing of commercially available catalyst technologies, or the development of new catalyst formulations based on current catalyst design experience. The intent is not to develop novel catalysts, but to tailor existing catalyst technology to the specific application of industrial boilers. Tests will be performed in an integral, fixed bed reactor on monolith supported catalysts. A bench-scale flow reactor has been under development to meet the objectives of this subtask and is now ready for experimental testing to begin. The reactor includes computerized temperature control to allow strict monitoring of catalyst temperatures and to allow temperature programmed reaction (often called "sweep tests") studies of catalyst behavior. An on-line FTIR spectrometer will provide detailed gas analyses for determination of catalyst conversion efficiency and selectivity.

The primary output from the experimental studies will be "light-off" curves, which define how the catalyst behaves as a function of feedstream temperature. Each sweep test consists of individual steady-state samples of catalyst conversion efficiency, with ascending and then descending feedstream temperature. A sequence of sweep tests for a range of feedstream compositions and space velocities will be performed to generate a database on which a NO_x control system can be designed.

Since the bench-scale reactor is now ready for testing, a detailed description of its design and capabilities follows. (See Table 3-1 for a list of components.)

3.4.2 Design

The basic design of the reactor is similar to that of Beck et. al[3] at AC Rochester. This design was chosen because of the similarity of tests that would be carried out at Penn State to the ones carried out at AC Rochester, so that direct comparison with those earlier tests is possible.

A schematic of the reactor is shown in Figure 3-1. The gases flow through the mass flow controllers into the mixing manifolds, with the three corrosive / toxic gases passing through a solenoid valve in between designed to shut off in case of emergencies. Water is injected close to the entrance of the furnace, and a bypass line with a four - way valve is present so that either the inlet or the outlet may be sent to the FTIR.

The reactor consists of a quartz tube, 24 mm ID and 1 mm wall thickness, placed in the three zone furnace of total length 300 mm. The section of the tube enclosed by the furnace is filled with quartz beads to improve heat transfer to the gas. The catalyst bed is loaded in the section of the tubing beginning at the point where the tube emerges from the furnace downstream. Monolith catalysts 25.4 mm long and ~20 mm diameter were used. The catalyst temperature was monitored using thermocouple probes inserted at the entry point, in the center of the monolith and at the exit point. This configuration allows better temperature control of the catalyst bed.

Computer control and reading of temperatures, pressure and gas flow rates were made possible by interfacing all measuring instruments to the computer through the DAS 8-PGA (for analog inputs), EXP-16 (Amplifier and multiplexer for thermocouple inputs) and the DDA-06 (for analog outputs as control signals for devices). All the data acquisition systems, along with the software drivers were purchased from Keithley Metrabyte. The total flow is set for a maximum of 9 L / min.

Fourier Transform Infra-Red spectroscopy is used for quantitative analysis of the inlet and outlet gases. FTIR was chosen as the characterization technique because other techniques are unsuited for this particular set of requirements. Chemiluminescence detectors can measure NO_x compounds and can differentiate between NO and NO_2, but cannot identify other NO_x gases, in particular N_2O. On-line flame ionization detectors measure total hydrocarbons and cannot distinguish between individual hydrocarbons. Gas-Chromatography / Mass Spectrometry (GC-MS) is relatively slow. FTIR is the only technique which, in conjunction with the 100 MHz pentium computer, can provide real-time on-line quantitative analysis. Because it is equipped with the MCT detector, it can detect in the far - infrared region as well as the near - infrared region, and so there is no

Table 3-1. Component List for Bench-Scale Flow Reactor

Item	*Number*	*Specifications*
Computer	1	100 MHz pentium, 16 MB, 1.0 GB HD
FTIR	1	Nicolet -Magna 550, MCT detector, 2 M gas cell with heating option
Furnace	1	ATS, 3 zones, each 4" long, 3.8 amps per zone
Temperature controller	3	Omega CN-2010, 0-5V Remote setpoint,
Pressure Gauge	1	MKS Baratron, 0-1000 Torr, up to 150 C
Pressure Controller	1	PID control of valve
Control Valve	1	Solenoid, with high temperature coil
Mass flow controller	5	Sierra, 0-5 V remote setpoint
DDA-06	1	Digital to analog (output)
EXP-16	1	Multiplexer and amplifier
DAS-8 PGA	1	Analog to digital (input)
Software(DAS8DLL & VTX)	1	Drivers for data acquisition boards
Vacuum pump(KNF)	1	17 SLM pumping rate, can handle corrosive gases
Syringe pump	1	11 flow settings, variable flow rates via different syringes

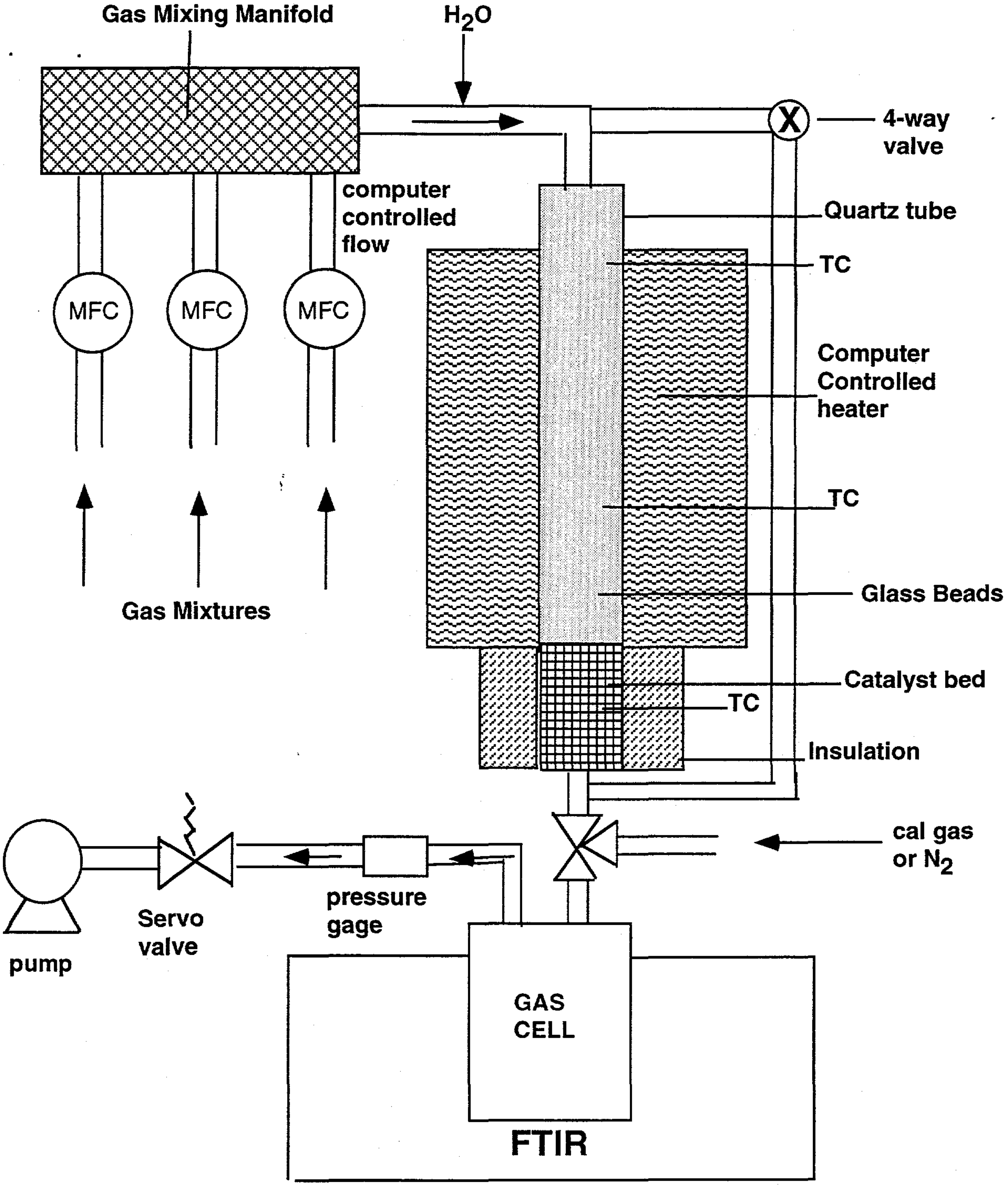


Figure 3-1. SCHEMATIC DIAGRAM OF THE BENCH-SCALE FLOW REACTOR

need to change detectors for different spectral regions. Liquid nitrogen cooling is necessary for detector operation.

To simulate real-life exhausts, water is injected into the stream in liquid form using the syringe pump, and the transfer lines are heated, so it vaporizes and to retain it in vapor phase, the full length of tubing is heated and the 2 M gas cell is also heated by a heating blanket which has its own temperature control system. FTIR calibration, alignment and spectrum collection is carried out using the Omnic software provided by Nicolet, and quantitative analysis is carried out using the QuantSetup and QuantPad software, also supplied by Nicolet. The rest of the data acquisition software is controlled by a code written in Microsoft Visual Basic (Version 3), which also acts as a trigger for spectrum collection through Omnic. This language was chosen because of its excellent user interface and ease of programming.

3.4.3 Current Status

The furnace has been wired and installed on a custom instrument rack, which also serves as a shelf for placing the mass flow controllers and the electronics box. The other face of the rack is designed to be the user interface and it houses the three temperature controllers, an alarm and the emergency switch. The flow controllers, temperature controllers and the pressure transducer were routed to the computer via a board placed on the electronics box and the Keithley boards.

The plumbing was designed with two criteria in mind: (1) to minimize the overall length, particularly after water injection, in order to minimize the heated section; and (2) to provide for sampling of both inlet and outlet gases as desired and also to provide the option of sampling or purging the FTIR.

Before quantitative analysis can be done, calibration is necessary for each of the gases which have to be quantified. This has also been done for all gases except ammonia and propylene, which tend to react with the viton valve seats. The flow controllers for these two gases are being outfitted with Kalrez valve seats making them more resistant to attack.

3.4.4 Planned Catalyst Studies

Engelhard Corporation has supplied the three catalysts that are to be considered in the first phase of testing. Follow-on tests subsequent to those presently planned may consider other catalysts, or modified formulations of these three catalysts. The initial NO_X reduction tests will be performed on a Pt-ZSM-5 monolith supported catalyst using propylene and ethylene as selective reductants. These initial tests will serve in part to shakedown the entire experimental system. They will be followed by detailed characterization of a low temperature ammonia-SCR catalyst. Subsequent tests will include detailed study of two hydrocarbon-SCR catalysts, Pt-ZSM-5 and Pt/Al_2O_3. For each catalyst, a database of sweep test results will be produced. Particular attention will be focused on the influence of feedstream SO_2 concentration on catalyst behavior and on the selectivity of these catalysts toward the formation of N_2.

The three catalysts being considered in these initial tests to varying degrees produce N_2O during the NO_x conversion process. This is a widely known drawback for precious metal-based (particularly Pt-based) NO_x reduction catalysts. From the available performance data, it is anticipated that the Pt/Al_2O_3 catalyst will achieve between 30-60% NO_x conversion, but may produce 70% N_2O and only 30% N_2 during NO_x conversion[4]. Conversions levels with Pt-ZSM-5 may be substantially higher, on the order of 60-80% using ethylene as a reductant, but detailed information on selectivity toward N_2 is not available[5]. This is a key factor to determine with the zeolite supported, precious metal-based catalysts. The third catalyst, a low temperature, ammonia-SCR, precious metal-based catalyst is the most likely catalyst to provide the 80 to 90% conversion that this project is seeking. Again, due to the precious metal catalyst, some degree of N_2O formation is expected, but the effects of feedstream composition on selectivity need to be examined in detail. This ammonia-SCR catalyst is expected to be somewhat sensitive to SO_2 concentration, and both its activity and selectivity may be affected by the level of SO_2.

3.5 Subtask 1.5 Conduct VOC Study

3.5.1 Design and Modifications to the Research Boiler

The objective of this subtask is to modify the 1,000 lb/h research boiler shown schematically in Figure 3-2 to accommodate air staging capabilities to reduce NO_x levels by about 40-50% of the base line level (without any air staging). Combustion tests were performed to evaluate the performance by firing pulverized coal and coal-water slurry fuels.

The 200 psig maximum pressure, watertube boiler is of A-frame construction, and was designed and built by Cleaver Brooks. The combustion chamber is essentially a 3'x3'x7' (63 ft^3) chamber with a maximum heat release rate of 42,000 Btu/ft^3-h. It contains 288 ft^2 of heating surface and the maximum fuel firing rate is two million (MM) Btu/h.

The boiler is equipped with nine pairs of 3-inch diameter side ports for gaseous and particulate sampling. The combustion gases are split into two convective passes, one on each side of the radiant combustion chamber. There are access doors at each end of the convective section, ash hoppers under each convective section, and a doorway into the combustion chamber.

To promote and enhance combustion when firing CWM, a 33-inch diameter ceramic quarl extends the length of the combustion chamber by two feet. The quarl is

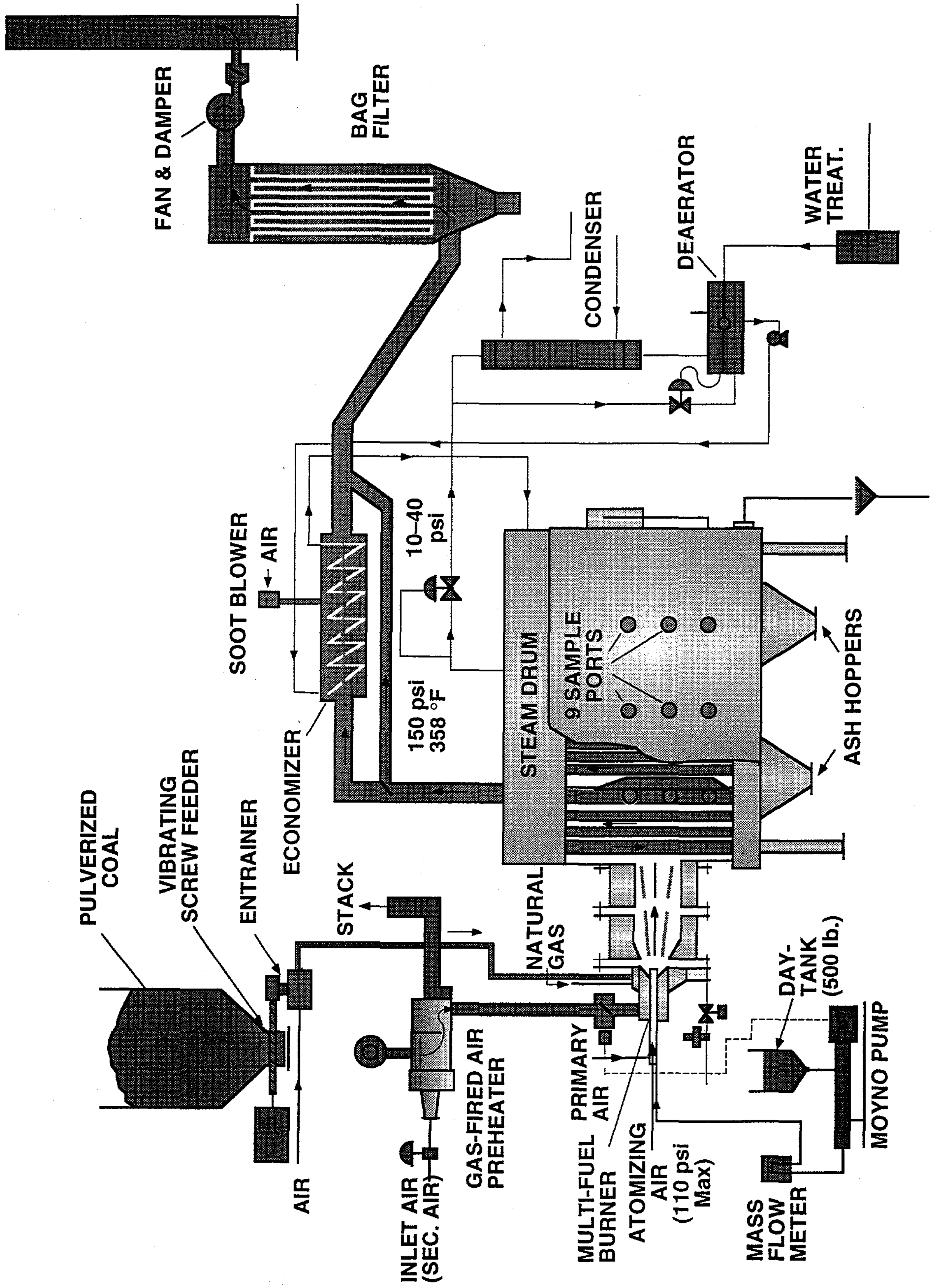


Figure 3-2. SCHEMATIC DIAGRAM OF THE RESEARCH BOILER (1,000 lb/h Steam)

preheated by a natural gas flame prior to CWM combustion testing and provides a source of radiant heat to help support the CWM flame.

CWM is gravity fed from a day tank with 500 lb capacity to a Moyno progressive cavity pump. From the pump the fuel passes through a 1/64" screen to remove oversized material and is introduced into the nozzle. Pulverized coal is fed from a two foot diameter hopper to a venturi via a 1.5-inch diameter screw feeder. The pulverized coal is entrained into an annular section which surrounds the CWM nozzle. The feed rate of pulverized coal is monitored by a load cell.

A gas-fired combustion air preheater supplies over 300,000 Btu/h to preheat the air up to 400°F. The preheated combustion air (secondary air) passes through a conventional swirl ring several inches in front of the gas distribution ring, both of which are 8 inches in diameter. A small portion of unheated primary air is fed to an annulus surrounding the CWM nozzle. This air serves to insulate the nozzle and fuel line from the hot secondary air and prevents overheating of the fuel line which can lead to plugging. Preheated tertiary air is introduced through four tangential ports in the quarl.

The products of combustion are monitored at the economizer exit with a complete analytical package consisting of online O_2, CO_2, CO, NO_x, and SO_2 analyzers. Flue gases are cooled to below 500°F in an economizer prior to passing into a bag filter. Ash samples were taken from the ash hoppers in the convective portion of the boiler and the baghouse.

The quarl section of the boiler was modified to allow for greater flexibility in air staging, controlling air flows, and monitoring air flow rates. Originally the quarl had single pipes mounted at 90 degree angles to allow for the staging of the combustion air by the introduction of tertiary air. The tertiary air could be jetted and balanced to produce greater swirl and a tighter flame. Schematic diagrams of the modified quarl and the arrangement of air staging are given in Figures 3-3 and 3-4. The amount of air admitted into each zone was varied during pulverized coal combustion and cofiring CWM and pulverized coal. Tests were conducted using 20% excess air. During cofiring of CWM and pulverized coal, a CWM atomizer was inserted into the central portion of the burner. The products of combustion are monitored at the exit of the radiant section of the boiler and the inlet to the economizer with a complete analytical package consisting of online O_2, CO_2, CO, NO_x, and SO_2 analyzers.

Prior to each test, the quarl is heated using natural gas to 1,000°F. At this temperature, pulverized coal is gradually introduced while simultaneously reducing the natural gas feed rate. The quarl was further preheated to 1,400°F at which time CWM was admitted into the boiler at the target feed rate equivalent to 20% of the total thermal input. A

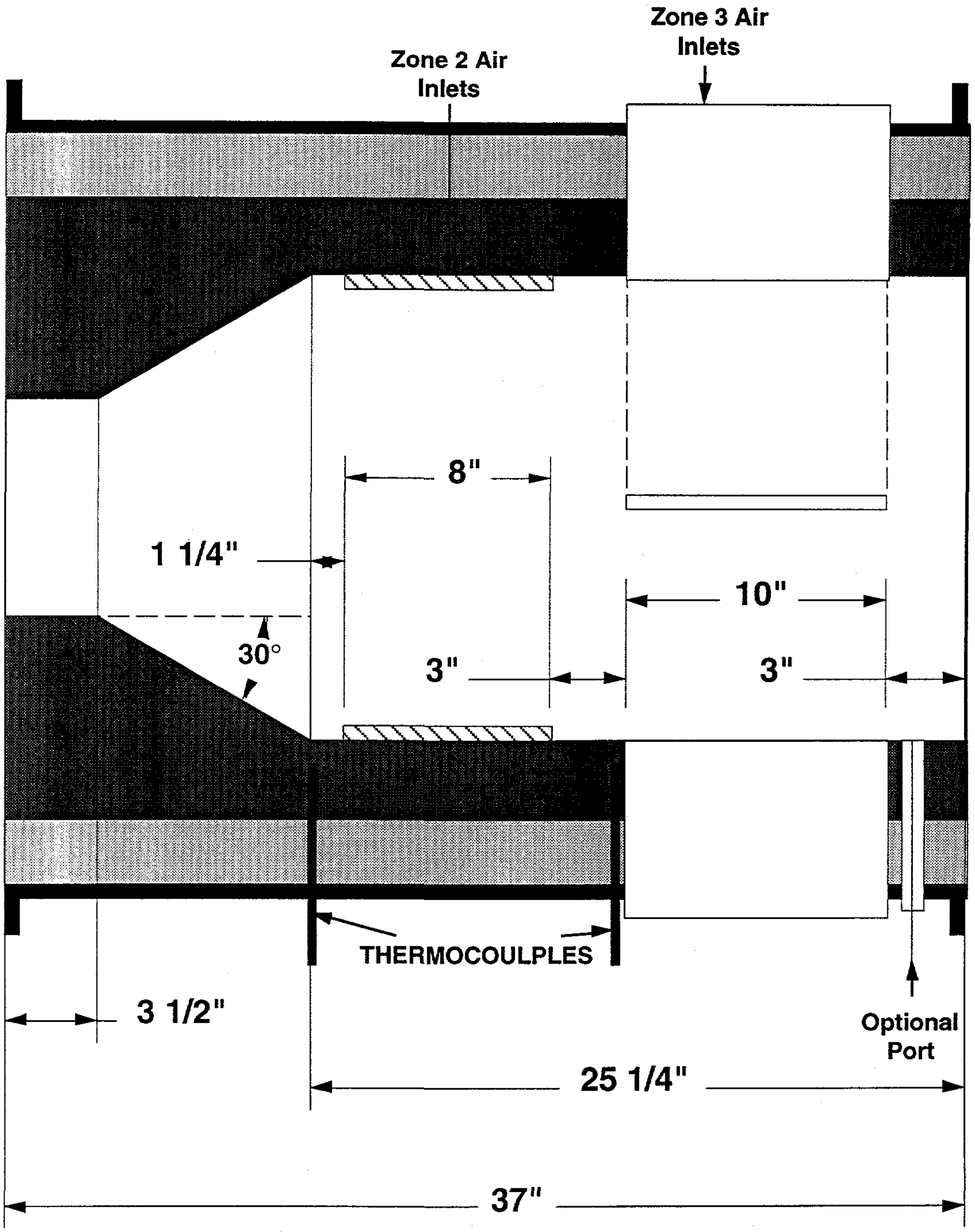


Figure 3-3. SCHEMATIC DIAGRAM OF THE QUARL (side view)

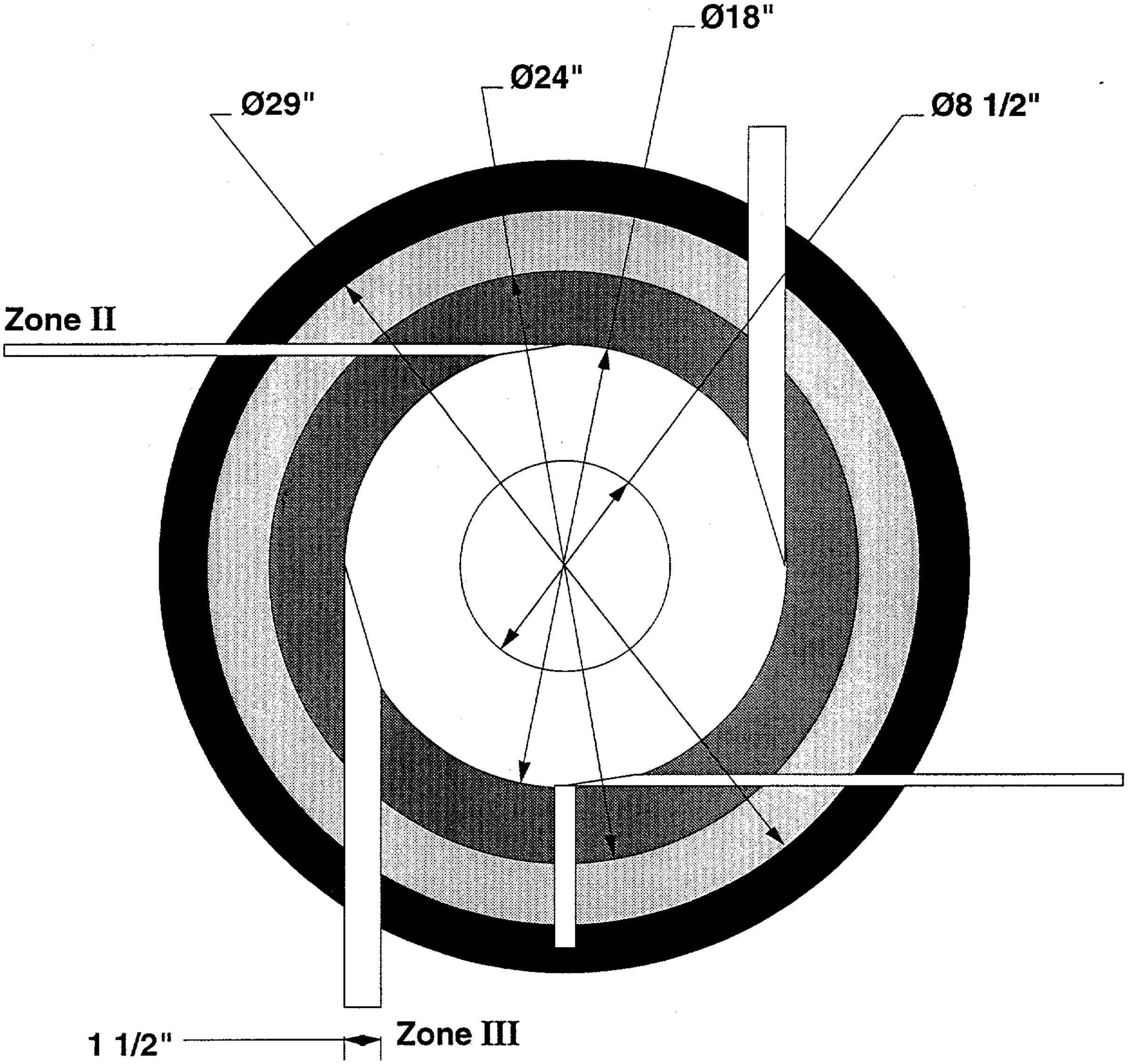


Figure 3-4. SCHEMATIC DIAGRAM OF THE QUARL (end view)

firing rate of 1.8 MM Btu/h was used during each test. Ash samples were collected from hoppers located in the convective pass of the boiler and the baghouse.

Changes in the distribution of air between Zones 1, 2, and 3 and atomizing air were made during pulverized coal and cofiring tests to determine the relative effect on NO_X levels measured in the flue gas and on combustion efficiency. Depending upon the air flow rates, the percent of the total combustion air supplied to each zone was different. Zone 1 air was introduced through an annular pipe around the fuel feed line, and accounted for 32 to 65% of the total combustion air. Zone 2 air enters the quarl tangentially and accounted for 15 to 20% of the total air. Zone 3 air also enters the quarl tangentially and accounted for up to 36% of the total combustion air. Flue gas composition, system pressures and temperatures, and air flow rates were monitored every 30 seconds during each test run. The data were then averaged for each test run.

3.5.2 Test Results

A series of tests was performed to determine the effect of air staging on NO_X emissions. By reducing the amount of air introduced at Zones 1 and 2 the fuel-rich zone can be increased thereby creating a substoichiometric zone that inhibits the conversion of nitrogen intermediates to NO_X. The remainder of the air required for combustion is then introduced downstream, in Zone 3, to allow the fuel to complete the combustion process. The carbon burnout measured when firing pulverized coal and cofiring CWM with pulverized coal did not vary significantly. The carbon burnout of the samples taken from the baghouse and convective pass hoppers averaged 97 and 91%, respectively.

Figure 3-5 shows the average NO_X levels as a function of the percent of combustion air supplied in Zone 3 during pulverized coal combustion tests. NO_X emissions were reduced by 46.2% as the percentage of combustion air supplied at Zone 3 increased from 0 to 28%. Figure 3-6 shows the average NO_X levels as a function of the percent of combustion air supplied in Zone 3 during cofiring combustion tests. NO_X emissions were reduced by 24% as the percentage of combustion air supplied at Zone 3 increased from 28 to 36.5%.

Tests were also conducted to determine the effect of atomizing air on NO_X emissions. During cofiring, approximately 6% of the total combustion air is used for atomization. Typically during combustion of pulverized coal, the transport air makes up 1 to 2% of the total combustion air. However, it was necessary to introduce air down the center of the quarl where the CWM atomizer is located during the cofire tests to prevent deposition of burning particles on the swirler vanes. The deposition is believed to be a result of the increased recirculation within the quarl as a result of the quarl design and air

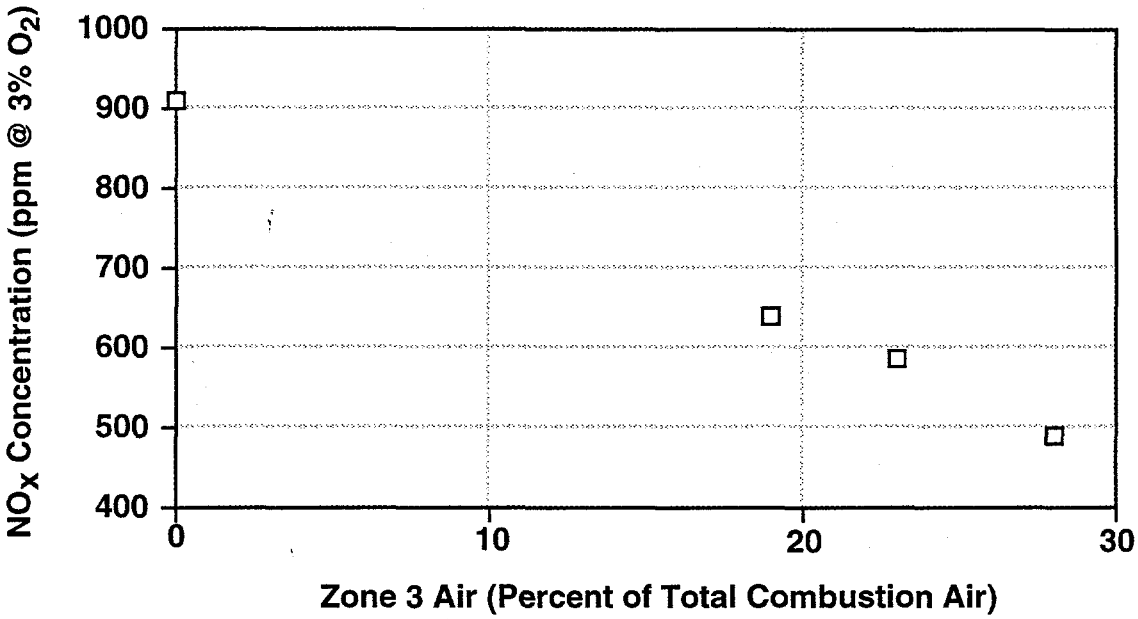


Figure 3-5. NO_X CONCENTRATION IN THE FLUE GAS (corrected to 3% O_2) AS A FUNCTION OF ZONE 3 AIR DURING PULVERIZED COAL TESTING

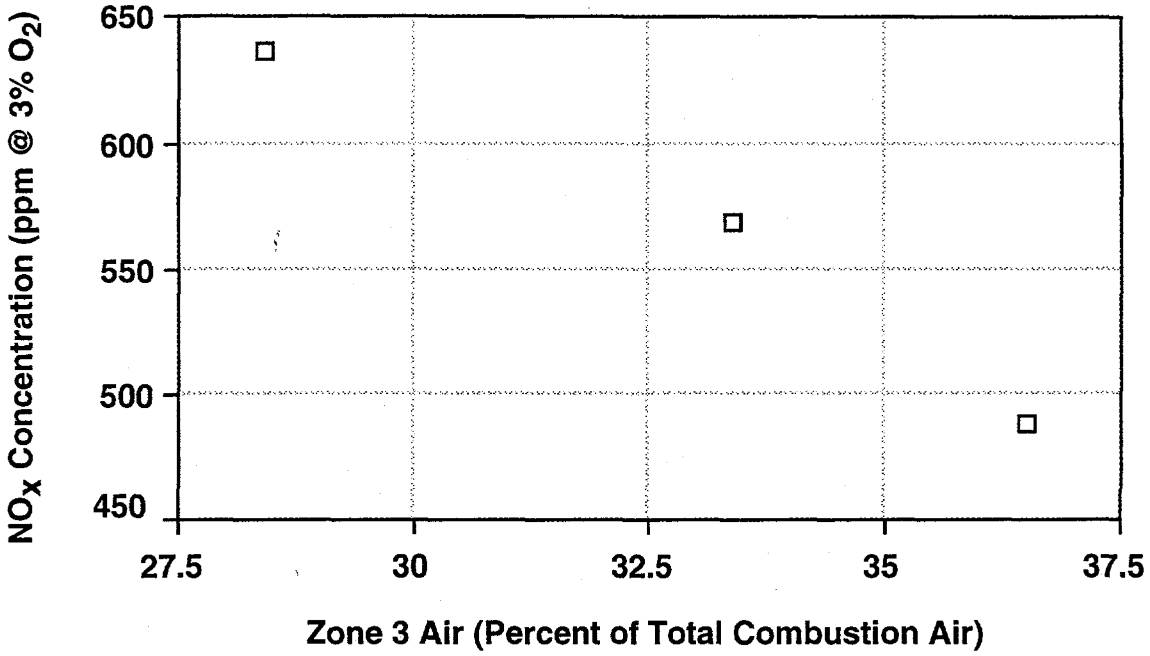


Figure 3-6. NO_X CONCENTRATION IN THE FLUE GAS (corrected to 3% O_2) AS A FUNCTION OF ZONE 3 AIR WHEN COFIRING PULVERIZED COAL AND COAL-WATER SLURRY FUEL

flow patterns. The burning char deposits resulted in the oxidation of the swirler. Over a one hour period, the swirler degraded to the point of forcing the shutdown of the unit.

NO_X emissions were found to be sensitive to the presence and amount of atomization air introduced into the boiler. Figure 3-7 shows that NO_X emissions increased significantly as the quantity of atomization air increased. The presence of air injected into the central portion of the coal flame reduces the fuel-rich portion of the flame resulting in lower conversion of NO_X to N_2. Under cofiring conditions, the flow rate of the atomizing air is 110 lb/h. Since NO_X emissions were found to be sensitive to the presence and amount of atomization air introduced into the boiler, the same amount of atomizing air was used during the pulverized coal tests. The atomizing air also prevented deposits from forming on the swirler.

The introduction of atomizing air at the burner significantly increased NO_X emissions. The increase in NO_X emissions was not the same as the increase in NO_X emissions if the same amount of air was introduced into the boiler at another location. It is possible that the added oxygen in the flame zone could be oxidizing the nitrogen intermediates or that the air is disrupting the substoichiometric recirculation zone. Pulverized coal transport air seemed to also affect NO_X formation. Increased transport air decreased NO_X emissions, contrary to the observation when atomizing air was increased. It is thought that by increasing the pulverized coal transport air, i.e., pulverized coal velocity, the flame front is extended. By extending the flame front the evolved nitrogen intermediates have greater residence time in the fuel-rich zone to be reduced to molecular nitrogen.

3.5.3 Literature Survey on Trace Organic Emissions

A literature search on trace organic emissions from coal fired boilers was completed. Particular attention was paid to the formation and/or release of polycyclic organic matter (POM). More specifically, a subgroup of POM called polycyclic aromatic hydrocarbons (PAHs) was the subject of the search. PAHs include naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, benzo[ghi]perylene, dibenz[a,h]anthracene and indeno[1,2,3-cd]pyrene. Based on the search, little to no detectable amounts of these species have been found in flue gas streams of seven utility boilers investigated by the DOE. However, with decreasing boiler size, the emissions of these species were reported to increase due to an increase in the surface to volume ratio of industrial scale boilers. This is due to a decrease in the peak temperature in the boiler. Similar observations were also reported, particularly an increase in the PAHs emissions, in the case of fluidized bed boilers which operate at 800-950°C.

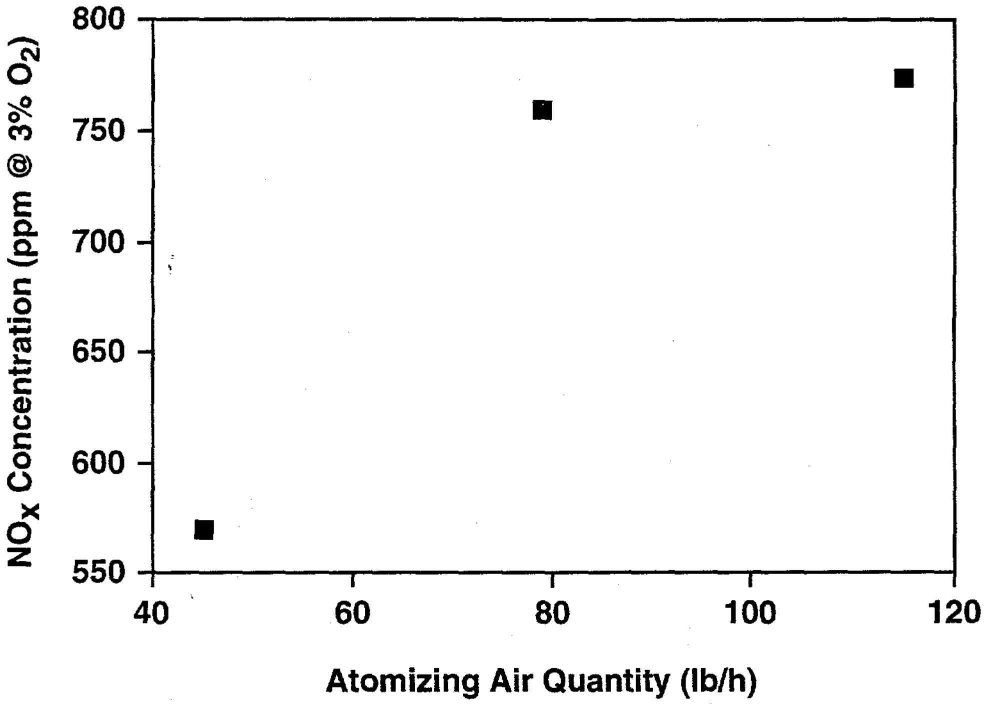


Figure 3-7. NO_X EMISSIONS (corrected to 3% oxygen in the flue gas) AS A FUNCTION OF ATOMIZING AIR QUANTITY

Lower temperatures favor the formation of PAHs. In industrial scale boilers, due to high surface area to volume ratio, temperatures are observed to be low.

Therefore, in the under this subtask of this Phase of the program, emphasis will be placed on PAH formation and emissions.

An extensive literature search is ongoing on the analytical procedures used for sampling and analysis of the PAHs from the flue gas streams. Software has been purchased to aid in finding appropriate standard methods (if available) for many different sampling and analysis techniques. EPA publication SW-846 has been purchased along with a subscription service which provides updates on emerging approved standard methods. Many professionals with a wealth of experience in the field of stationary source sampling and analysis have been contacted and their advice has been solicited.

3.5.4 Evaluate the GC/MS Equipment and Upgradation

Some of the GC/MS equipment to be used is available on campus in the Fuel Science Program. An evaluation of the methods and auxiliaries is being made to identify the additional columns that need to be procured to accomplish the planned study.

3.5.5 Procurement of Method 5 Apparatus and Auxiliaries

An EPA Modified Method 5 sampling train will be utilized in sample collection. Samples from the flue gas stream will be collected prior to and after the baghouse. Appropriate extractions will be performed on the samples and the target compounds will be analyzed using High Resolution Gas Chromatography (HRGC) coupled with either Low or High Resolution Mass Spectrometry (LRMS or HRMS). Equipment under this task will be procured for the test program by the end of June, 1996.

3.6 Subtask 1.6 Conduct Trace Element Study

The objective of Subtask 1.6 is to characterize trace element emissions from coal-fired industrial boilers. Work started on this subtask during this reporting period and the activities that were conducted included starting a literature search on trace element emissions from coal-fired boilers, specifically from utility-scale boilers. In addition work started on identifying the necessary sampling equipment and the appropriate analytical techniques, determining the quantity of samples to be analyzed, and identifying the laboratories for analyzing the samples.

During the next reporting period, the literature review will be completed, the sampling equipment procured, the analytical techniques identified, and the laboratories selected.

3.7 Subtask 1.7 Conduct Nitrogen Occurrence Study

No work was conducted during this reporting period.

4.0 PHASE II, TASK 2: COAL PREPARATION/UTILIZATION

Activities in Phase II, Task 2 primarily focused on preparing the final report. Phase II activities, Subtasks 1 through 9 (See Section 1.0 for a listing of the subtasks) were previously completed and the final report is being prepared. However, during this reporting period, a subcontract was issued to Carnegie Mellon University to study the fundamental behavior of atomization. Details of the study are presented in Section 4.1.

4.1 Subtask 2.10 Conduct Atomization Study

The additives typically used in coal-water slurry fuels will be examined for their influence on the rheology and atomization characteristics. A subcontract was issued to Carnegie Mellon University (CMU). Dr. Norman Chiger, who is the principal investigator at CMU, has expertise and equipment for measuring extensional viscosity and aerodynamics of the burner region. CMU will be examining the influence of stabilizers on the rheology and atomization. The Combustion Laboratory at Penn State will be preparing the slurries with and without stabilizers for CMU studies and will also examine the influence on the combustion behavior by burning them in a down-fired combustor.

5.0 PHASE II, TASK 3 ENGINEERING DESIGN AND COST; AND ECONOMIC ANALYSIS

Phase II, Task 3 has been completed except for Subtasks 3.6 regional economic impacts, 3.10 engineering design, and 3.11 integration of analysis. Activities in Phase II, Task 3 focused on preparing the final report for the remainder of the subtasks.

5.1 Subtask 3.6 Determination of Regional Economic Impacts

5.1.1 Introduction

In previous work, an optimization-type market penetration model was developed that found the total market in a single region for boiler retrofit technology. This type of market penetration model was based upon a partial equilibrium structure toward which the market share of the new technology (boiler retrofits) would trend. A limitation of this type of model is that gathering the necessary data to derive results for the entire state of Pennsylvania is problematic and simple extrapolation based on the relative numbers of water-tube boilers may not yield acceptable estimates. An alternative approach that was taken is to simplify the optimization model, making a few assumptions in the process, and then build a market penetration model using data already in-hand from a previously compiled census of Pennsylvania water tube boilers. It was found that at an 8% interest rate the state-wide impacts of the boiler retrofit technology could be as much as 237 boiler retrofits, requiring 1.3 B$ of capital, fuel savings of 41.1 M$ per year and 2,890 thousand tons of additional coal consumption per year.

5.1.2 Pennsylvania Market Penetration Model Description

Review of the Regional Optimization Market Penetration Model

The previous market penetration model utilized an optimization, linear programming framework. The approach was to use a transportation model that considers the costs to produce the boiler retrofit fuel, the costs to transport MCWSF to the retrofitted boilers, and the capital, and operation and maintenance (O&M) costs of retrofitting. The transportation model framework minimized the cost to boiler owners given the location of each boiler, and its individual characteristics, and the location of each possible source of MCWSF. The decision to retrofit was assumed to be made if the total casts of retrofitting are less than the costs to continue firing oil or gas. The model considered was a partial equilibrium analysis since it is assumed that there are no substitution effects on oil or natural gas prices due to their displacement by MCWSF. Another assumption is that there would be no increase or decrease of the boiler utilization due to displacing the utilization of other types of boilers that may be in use at a site. A producer may own several different types of boilers at a single site and choose to operate the ones that provides the greatest competitive advantage at a particular point in time.

One of the key features of this model was that it recognized that the production of fuels at each supply point is subject to economies of scale. That is, the per unit cost of MCWSF production fell as production at a single supply point was increased.

Description of the Pennsylvania Market Penetration Model

Attempting to gather the data necessary to implement the regional market penetration model described above on a state-wide basis would have been extremely difficult. Instead, a model that included all potential Pennsylvania boiler retrofit candidates was constructed using a few simplifying assumptions that on an aggregate basis should describe the likely state-wide market penetration of the boiler retrofit technology.

The basic structure of the state-wide model is the same as the regional model. Namely, that the decision to retrofit is assumed to be made if the total casts of retrofitting are less than the costs to continue firing oil or gas. Assumptions are then made that would allow developing reasonable results at an aggregated state level. One set of assumptions involves setting a single price for MCWSF fuel supply to each boiler. This is accomplished by assuming that each boiler being evaluated in the model is equidistant from a supply point providing MCWSF at a fixed price. Another assumption made is that each boiler is operated identically to achieve the same utilization rate. To complete the model, each boiler's capacity in MMBtu/hr was estimated from the allowed working pressure.

The transportation costs for MCWSF were determined through consultation with a local hauler of mine wastes using Department of Transportation (DOT) approved tank trucks[6].

The fixed \$/MMBtu cost is related to the fixed amount of time both the driver and tanker truck are required to spend to complete unloading of the fuel at the site. This fixed cost is included with the other fixed costs for operating the boiler with MCWSF. The variable costs are expressed as \$/MMBtu per mile.

The capital cost of the retrofit technology has been estimated by EER for the Crane site's 25.2 MMBtu/hr boiler (EER, 1995). The standard method for scaling capital costs is to use the power factor method (see for example, Addy, 1994[7]). The power factor reflects the economies of scale in construction which for boiler plants is usually taken as 0.75.

Anecdotal evidence exists that a portion of the cost estimate for converting the 25.2 MMBtu/hr Crane boiler is not subject to scaling for boilers as large as 100 MMBtu/hr[8]. Given this information, a cost model was initially postulated that assumed that the 25.2 MMBtu/hr capital cost to retrofit is subject to a graduated increasing percentage of costs subject to scaling. This approach yielded a linear cost curve. Refinements to this approach were made by incorporating more detailed information concerning how the individual cost components scale with increasing boiler size. Figure 5-1 shows the result of this work in estimating the total capital requirement (TCR) necessary to implement the boiler retrofit. It can be observed from the TCR curve shown in the figure that the retrofit TCR increases at nearly a linear rate through much of the range of boiler sizes.

Census of Pennsylvania Industrial Boilers

The chief problem with developing a market penetration model is that the population of boilers numbers in the tens of thousands. Gathering and analyzing detailed information on this many boilers would be a formidable task. The approach taken in the regional model was to narrow the model space to include only those regions that have both a large industrial base and a significant coal industry already in place. The observation that the initial market for boiler retrofits is likely to be concentrated in a small area to allow economies of scale in fuel supply to be realized substantiated this approach.

The effort to define the model space thus began by obtaining a current census database of industrial and commercial boilers located in Pennsylvania. The census was based upon data collected by the Pennsylvania Department of Labor & Industry (DL&I) and includes only those boilers that have been in active use within the past two years.

The data provided by the DL&I were classified as to the particular type of boiler, or boilers, in use at each location. This allowed for a 'first-pass' sifting of the database to isolate a subset of boilers for further analysis that included only water tube boilers. A summary of the boiler census by boiler type is:

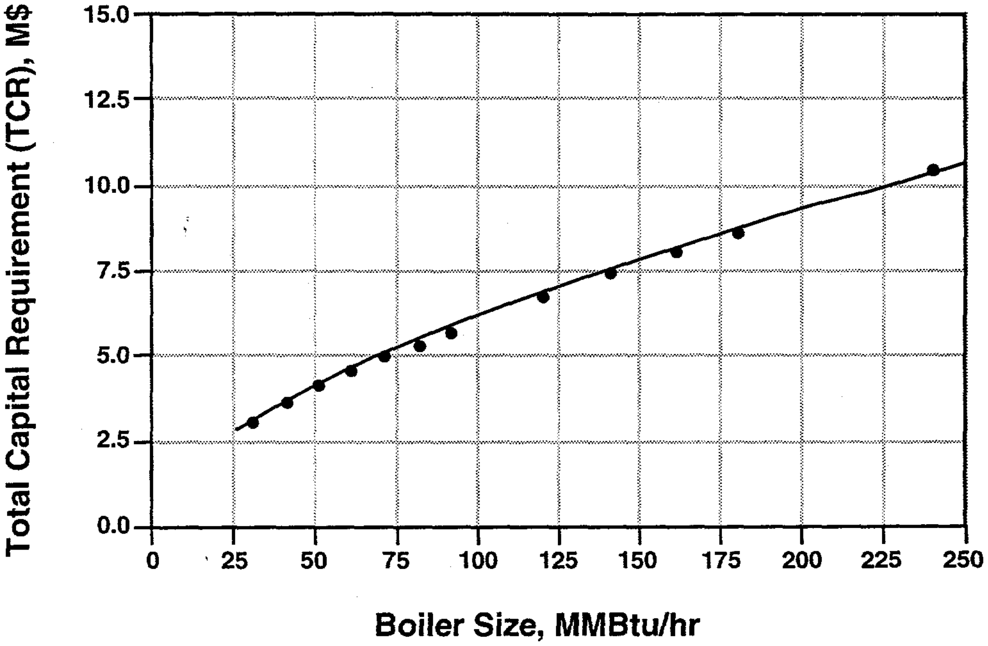


Figure 5-1. TOTAL CAPITAL REQUIREMENT VERSUS BOILER SIZE

Boiler Type	Count	%
Cast Iron	30,760	46.4
Fire Tube	12,093	18.3
Water Tube	6,936	10.5
Electric	4,228	6.4
Other	12,245	18.5
Total	66,262	100.0

There are 6,936 boilers are of water tube design. Figure 5-2 shows a spatial distribution of all the water tube boilers in Pennsylvania by three-digit zip code region.

In modeling the market penetration at the state-wide level the boiler census was revisited. First, all boilers under 200 allowable working pressure (AWP) were found to be too small to technically carry out the retrofit. Second, boiler capacity was estimated and all boilers over 200,000 Btu/hr in size were eliminated as being larger than the maximum size to be retrofitted using the technology. This screening resulted in winnowing the sample down to a total of 950 boilers.

5.1.3 Pennsylvania Market Penetration Model Results

Using base assumptions, there are 237 boiler retrofits are profitable to undertake out of the 950 boilers considered. This number of retrofits requires 1.3 B$ of capital and results in an estimated fuel savings of 41.1 M$ per year and 2,890 thousand tons of additional coal consumption per year.

At interest rates of 16 percent and higher no boiler retrofits would be implemented. The results are also sensitive to boiler utilization. No retrofits would be attempted at 20 percent utilization while all 950 boilers would be retrofitted at 60 percent utilization. Boiler utilization also greatly effects the retrofit savings and coal consumption levels. With regards to differential fuel cost (DFC), a minimum of $2.00 per MMBtu must be attained before any boilers can be retrofitted with a DFC of $3.80 per MMBtu resulting in all boilers being retrofitted.

Regional Economic Benefits of Decreased Dependence on Imported Oil: The Case of New Coal Combustion Technologies

Many policymakers have extolled the benefits of decreased reliance on imported oil. The gains would stem from lowering expected losses from potential embargoes and other political actions that cause shortages or price spikes. In addition, there would be gains from the positive economic stimulus of increased domestic production of energy resources. These would include not only direct output and employment impacts in domestic energy industries, but also general equilibrium effects by way of the stimulus to other sectors. Of

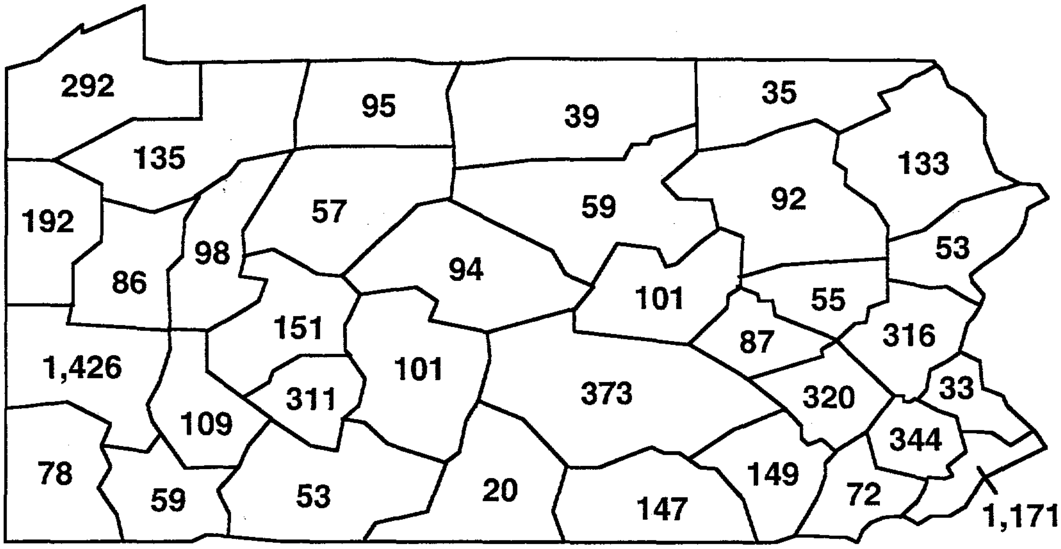


Figure 5-2. PENNSYLVANIA WATER TUBE BOILERS BY 3-DIGIT ZIP CODE REGION

course, the gains would be relatively greater in those regions providing the domestic energy substitutes.

In place of foreign oil, there are several domestic alternatives. For example, the U.S. has more energy in coal than the Middle East has in oil reserves. Moreover, recent advances in technology hold the promise of burning coal more efficiently, thereby lowering its cost and pollution emissions. In addition, there are a range of renewable resource options whose technological development is progressing as well.

Estimates of the value of the "security premium" on imported oil have dropped in recent years. The adjustments are based on revisions of estimates of the actual macroeconomic shocks associated with the Arab oil embargo and Iranian revolution. Also noted is the fact that while the U.S. is now importing as large a percentage of oil as before the embargo about (45%), most of these imports are from countries considered friendly to the U.S. or at least are politically stable.

Even if the security issue wanes, however, the economic stimulus from increased domestic energy production remains. But just how significant is it? 1.0% of GNP, 0.1%, of GNP or some infinitesimal amount. Even the 0.1% figure represents $7 billion of value added and nearly 150 thousand jobs.

The purpose of this chapter is to measure the economic stimulus effect of replacing foreign oil with domestic energy resources. Specifically, a computable general equilibrium model will be employed to examine the widespread adoption of coal-fired industrial boilers in Pennsylvania. Although the impacts in the state of Pennsylvania are likely to be higher than most other parts of the U.S., and therefore represent an upward bound for generalization purposes, they are indicative of the extent of potential benefits from oil imports substitution policies.

Note that if we assume an economy is already in equilibrium, the existing pattern of international trade would be optimal, and any import substitution policy would imply a decrease in economic activity. However, the factor that makes the opposite outcome possible is the development of a new technology that lowers the effective price of coal vis-a-vis imported oil.

5.2 Subtask 3.10 Engineering Design

No work was conducted.

5.3 Subtask 3.11 Integration of Analyses

Work continued integrating the analyses.

6.0 PHASE II, TASK 4 FINAL REPORT/SUBMISSION OF DESIGN PACKAGE

Work in preparing the final report continued. Tasks 2 (except for Subtask 2.10) and 3 (except for Subtask 3.10) have been completed.

7.0 PHASE III, TASK 1 COAL PREPARATION/UTILIZATION

7.1 Subtask 1.1 Particle Size Control

7.1.1 Attrition Milling

Tests are being conducted to evaluate the breakage characteristics of coarse coal particles in an attrition device. As discussed in the previous report, these particles function as grinding media for much smaller coal particles but at the same time produce fine particles by self-breakage. Therefore, in a continuous operation, the "media" in the mill decrease with time and need to be replenished on a regular basis. Figure 7-1 shows the disappearance plots for the 16x20 mesh fractions for 3 three different coals agitated in a stirred-media mill. It can be seen that the disappearance rate is bigger with higher solids concentration and softer coals. However, it is clear that the process is non-first order. The self-breakage process appears to be fast in the first short period of time and then slows down leaving about 80% of the original fraction in the original sizes even after 64 minutes of grinding.

It can be postulated that the high initial breakage rates are caused by chipping of irregularities from the lumps, leaving more rounded material which then abrades slowly. Similar trends have been observed in the autogenous milling of rocks. However, in those systems, the disappearance of media from the original size is quite rapid because a significant weight of media is lost by chipping and disintegrative fracture resulting from tumbling and falling of big heavy rocks. In attrition milling, it appears that chipping and fracture are less significant with abrasion being the predominant breakage mechanism.

Figure 7-2, in which the size distributions of media are shown at various times, supports this observation. It can be seen that the curves are almost flat in the finer size range, and are translated upward by an increase in the percentage of -400 mesh material. This indicates that media breakage in the stirred-media mill does not produce any particles in the intermediate size range but produces only very fine particles, which is the abrasion phenomenon. This simplifies the mathematical modeling of the attrition process, since it allows us to assume that all fragments are smaller than some very fine size and the history of the fragments does not have to be followed.

The treatment of abrasion is simple if we assume that the rate of abrasion of a particle follows a linear wear law

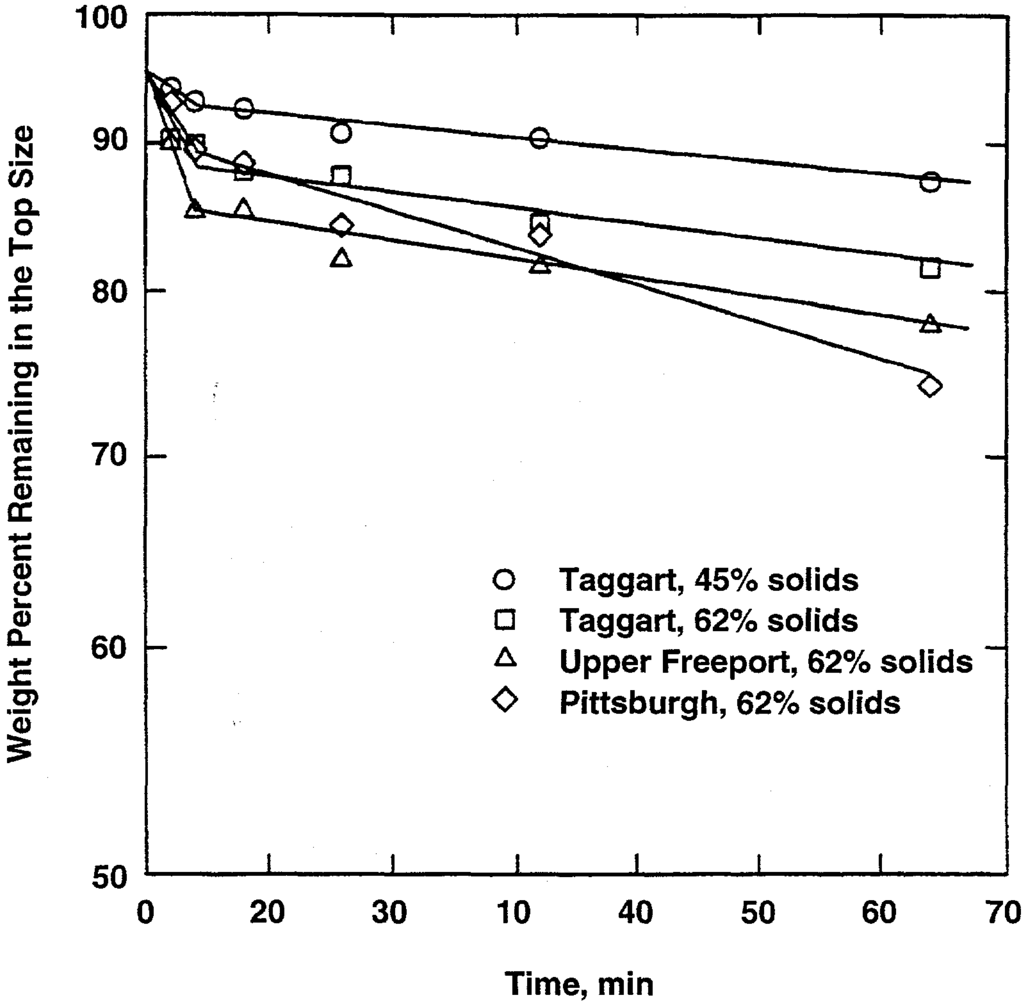


Figure 7-1. DISAPPEARANCE PLOTS FOR COARSE COAL (16 x 20 mesh) "MEDIA" IN ATTRITION GRINDING

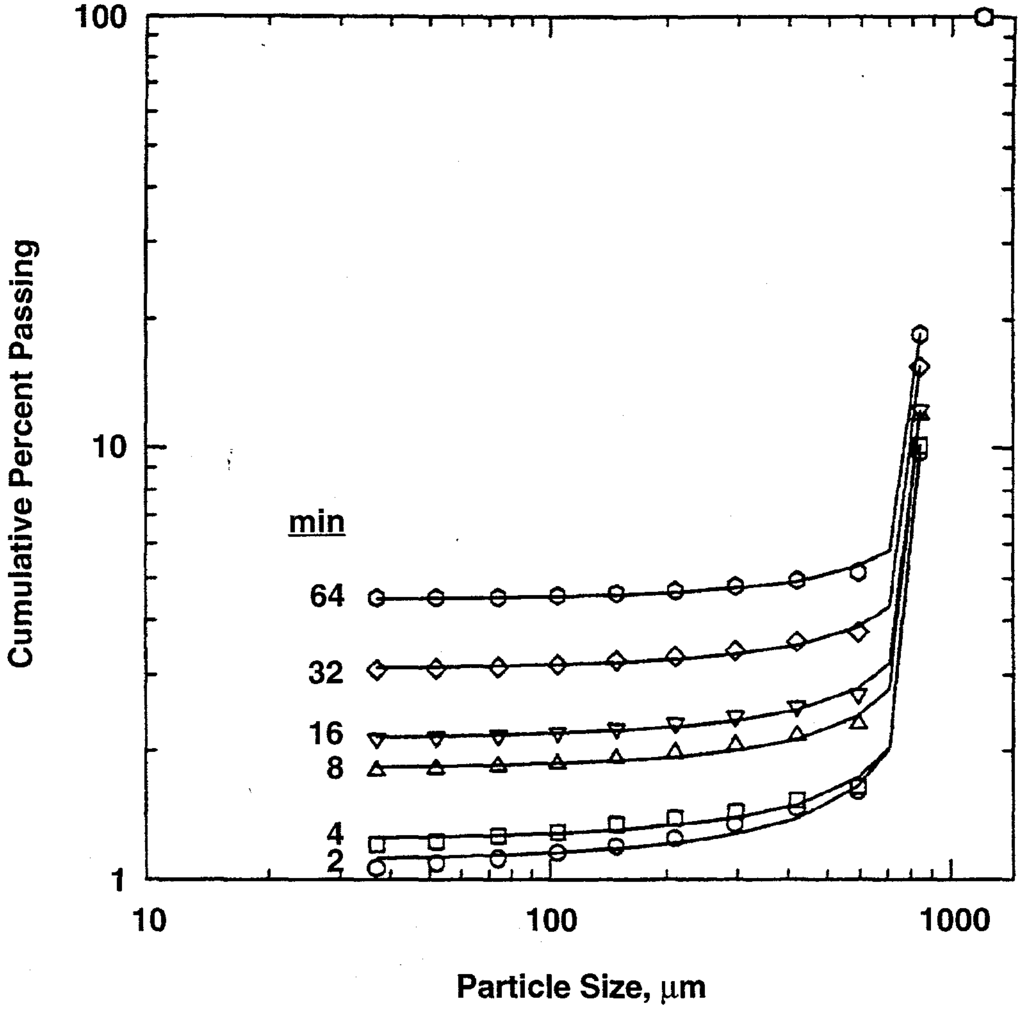


Figure 7-2. VARIATION IN "MEDIA" SIZE DISTRIBUTION WITH GRINDING TIME IN ATTRITION MILLING

$$-\frac{dx}{dt} = k \tag{7-1}$$

where the linear wear rate k is the rate of decrease of the equivalent spherical diameter x with time. If k is not a function of x and t, the particle diameter after wearing for time t in the mill is

$$x(t) = x_o - kt \tag{7-2}$$

where x_o is the initial particle size.
In the form of cumulative mass fraction this becomes

$$P(x,t) = \begin{Bmatrix} 1.0 \\ 1-(\xi/x)^3{}_0 \end{Bmatrix} \begin{matrix} x \geq \xi \\ \xi \geq x \end{matrix} \tag{7-3}$$

where $\xi/x_o = 1-kt/x_o$.

If the feed size distribution is P(x,0), Equation 7-3 becomes

$$P(x,t) = \int_0^{x^*_o} 1.0 \; dP\,(x_o,0) + \int_{x^*_o?}^{x_{max}} \left[1.0-(1-kt/x_o)^3\right] dP(x_o,0) \tag{7-4}$$

where $x^*_o = x+kt$ and $x+kt \leq x_{max}$. Thus,

$$P(x,t) = \begin{Bmatrix} 1-\displaystyle\int_{x+kt}^{x_{max}} \left[1-(1-kt/x_o)^3\right] dP(x_o,0) \\ 1 \end{Bmatrix} \begin{matrix} 0 \leq x+kt \leq x_{max} \\ x+kt \geq x_{max} \end{matrix} \tag{7-5}$$

For example, for a simple feed size distribution of $P(x,0)=(x/x_{max})^{\alpha}$, Equation 7-5 yields

$$P(x,t) = 1-\alpha\left[\begin{matrix} \left(\frac{1}{\alpha} - \frac{3kt}{(\alpha-1)x_{max}} + \frac{3k^2t^2}{(\alpha-1)x^2_{max}} + \frac{3\,k^3t^3}{(\alpha-1)x^3_{max}}\right) - \\ \left(\frac{x+kt}{x_{max}}\right)^3 \left(\frac{1}{\alpha} - \frac{3kt}{(\alpha-1)\,(x+kt)} + \frac{3k^2t^2}{(\alpha-1)\,(x+kt)^2} + \frac{3\,k^3t^3}{(\alpha-1)\,(x+kt)^3}\right) \end{matrix}\right] \tag{7-6}$$

Figure 7-3 shows results for a feed size distribution with α=8.6 within a $\sqrt{2}$ size interval and k=0.43. It can be seen that the general trend agrees well with the experimental values, although the data points do not exactly match each other. This can be attributed to several factors: 1) poor estimation of the linear wear rate, 2) the wear rate is not constant with time but decreases with time as seen in Figure 7-1, and 3) the feed size distribution is not a simple power function. Further analysis, taking these factors into account, is in progress.

7.2 Subtask 1.2 Physical Separations

7.2.1 Dense-Medium Separation

The baseline testing of the continuous, solid-bowl centrifuge for dense-medium separations was completed. The test variables included bowl and scroll speeds, weir height, relative density of the medium, medium-to-coal ratio, and feed rate. Minus 100 mesh Upper Freeport seam coal was used for all tests. Table 7-1 summarizes the operating conditions and results for selected tests.

For each test, samples of the clean coal (weir overflow) and refuse (scroll discharge) streams were taken. Each sample was wet screened to remove the -500 mesh material, and the 100x500 mesh coal was analyzed. The clean coal yield of the 100x500 mesh material was calculated by ash balance. Float-sink analyses were done on selected samples from which the partition values were calculated. These data where plotted to produce the corresponding partition curves from which the characteristic performance parameters -- relative density of separation, ρ_{50}, and probable error, E_p -- were derived.

Figure 7-4 shows the partition curves obtained for several main drive (bowl) speeds, with all other conditions constant. As seen, the best separation, based on the lowest probable error, was obtained for the middle bowl speed of 800 rpm (test 16). The relative density of separation was also the lowest at this condition. At the highest speed (3200 rpm), both the E_p and ρ_{50} values were higher (test 17). Because there is a lack of coal in this relative density range, the yield and corresponding ash values were similar. However, for the bowl speed of 600 rpm (test 15), the higher relative density of separation produced a slightly higher yield (92% versus 90%) but with a much higher clean coal ash content (7.7% versus 6.4%).

Overall, the ρ_{50} values were much higher than the relative density of the medium (1.3). This can be attributed, in part, to the weir setting that was used. For these tests, the minimum weir setting was used, which gave the shallowest pond depth. Hence the probability that a larger amount of material would exit to the overflow stream was higher, as reflected in the higher ρ_{50} values.

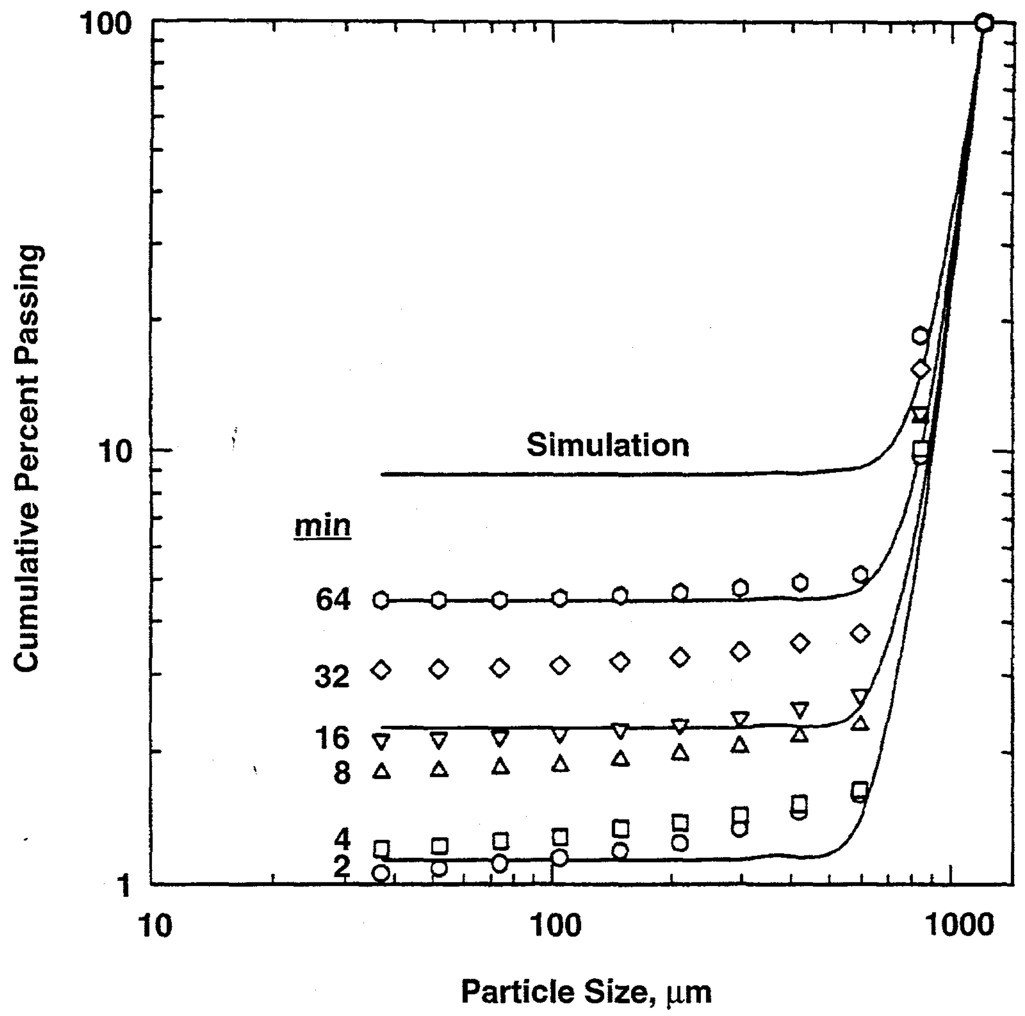


Figure 7-3. SIMULATION OF MEDIA SIZE DISTRIBUTION BASED ON CONSTANT WEAR RATE MODEL

Table 7-1 Summary of the Operating Conditions and Test Results for the Solid-Bowl Centrifuge

Test	Feed Rate, L/min	Relative Density	Medium-to-Coal	Weir Height*	Main Speed, rpm	Scroll Speed, rpm	Yield, %	Clean Coal Ash, %	Refuse Ash, %
1	11.4	1.3	20:1	4	500	300	56.4	8.4	15.5
2	11.4	1.3	20:1	4	700	300	69.4	6.1	23.7
3	11.4	1.3	20:1	4	800	300	66.2	6.0	22.2
4	11.4	1.3	20:1	4	900	300	62.9	6.8	19.5
5	11.4	1.3	20:1	4	1000	300	43.1	6.1	15.6
6	11.4	1.3	20:1	4	800	500	64.8	8.2	17.5
7	11.4	1.3	20:1	4	800	700	55.8	8.9	14.8
8	9.5	1.3	20:1	4	700	300	24.7	6.4	13.2
9	13.2	1.3	20:1	4	700	300	37.6	6.6	14.5
10	15.1	1.3	20:1	4	700	300	53.0	7.2	16.4
11	11.4	1.3	15:1	4	800	300	38.8	6.5	14.7
12	11.4	1.3	10:1	4	800	300	39.9	6.3	14.3
13	11.4	1.5	20:1	4	800	300	70.7	6.7	23.0
14	11.4	1.6	20:1	4	1200	300	45.9	5.8	16.4
15	11.4	1.3	20:1	1	600	300	92.3	7.7	57.7
16	11.4	1.3	20:1	1	800	300	89.4	6.0	58.1
17	11.4	1.3	20:1	1	3200	300	90.2	6.4	58.7
18	11.4	1.2	20:1	1	800	300	80.3	5.3	37.3
19	11.4	1.25	20:1	1	800	300	82.0	6.0	37.0
20	11.4	1.15	20:1	1	800	300	0.0	-	-
21	11.4	1.3	10:1	1	800	300	85.3	5.6	46.0
22	11.4	1.25	10:1	1	800	300	85.0	5.8	44.0

1 = shallowest pond depth; 4 = deepest pond depth

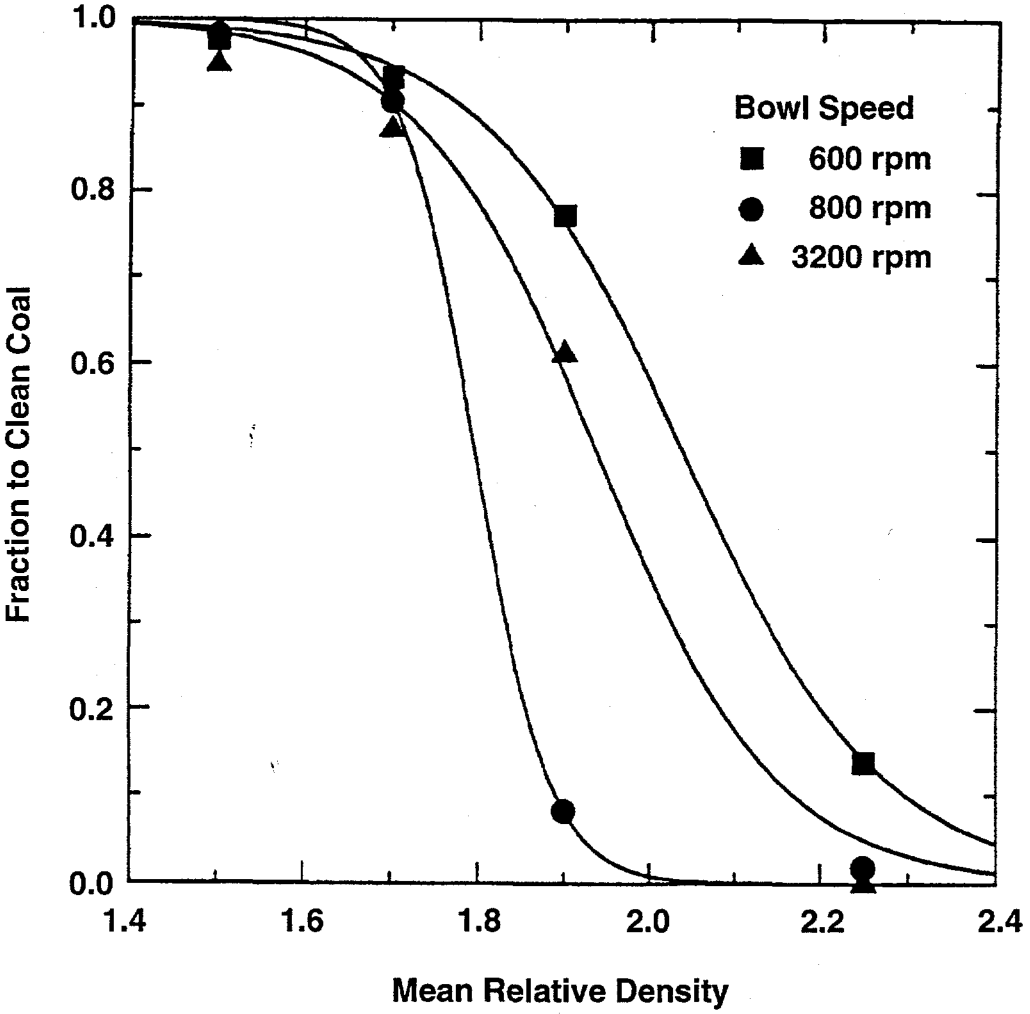


Figure 7-4. **EFFECT OF MAIN DRIVE SPEED ON THE PARTITION CURVES WHEN SEPARATING 100 x 500 MESH UPPER FREEPORT SEAM COAL IN THE SOLID-BOWL CENTRIFUGE**

(600 rpm (test 15): E_p=0.13, ρ_{50}=2.04; 800 rpm (test 16): E_p=0.05, ρ_{50}=1.80; 3200 rpm (test 17): E_p=0.12, ρ_{50}=1.94)

A theoretical analysis of the separation phenomena from a phenomenological point-of-view is being investigated using a hindered settling model. This will provide additional information on the relationships among the various test variables.

7.2.2 Magnetic Fluid Separation

Magnetic-fluid testing of the modified Frantz separator continued. Testing of the unit for centrifugal separations was initiated. A Dynawhirlpool-type separator, which was designed to fit between the pole pieces of the electromagnet, was constructed out of Plexiglas. A schematic of the flow circuit is shown in Figure 7-5. This device was selected over a hydrocyclone for several reasons. Since this unit consists only of a cylindrical portion, the design of the magnet poles would be simpler. Also, the design lends itself to staging whereby the clean coal leaving the first device could be injected directly into a second separator. The second unit would be operated at a lower density by using a weaker magnetic field. Thus a two stage separation, producing a high quality clean coal, a lower quality middling, and a refuse fraction, could be obtained using the same fluid. This approach is similar to the Tri-Flo separator, which uses a magnetite or ferrosilicon-based system as opposed to a magnetic fluid.

Unlike a hydrocyclone, two feed ports are used in a Dynawhirlpool separator. The feed coal enters at the top of the device, along with a portion of the medium (Figure 7-5). The remaining medium enters the separator tangentially, near the bottom of the device. This imparts the desired flow pattern in the separator to produce the necessary centrifugal force for separation. The refuse is driven outward and is carried up the separator wall where it exits tangentially near the top of the device. The clean coal is driven inward and exits at the bottom of the device.

For the test circuit, the coal was fed to the unit from a vibrating feeder. The magnetic fluid was pumped from a sump and was split prior to entering the separator. Approximately 15% of the fluid was combined with the feed coal, with the remaining fluid entering the medium inlet. The concentration of the feed coal was around 2% solids by weight. The product streams were directed into filter bags where the coal was collected. The filtrate was recovered and recirculated through the circuit, providing a continuous operation.

Initially, a 1.30 relative density zinc bromide solution was used as the separating medium to validate the operation of the device. Upper Freeport seam coal (28x32 mesh) was passed through the device and the products were collected. Approximately 60% of the coal reported to the overflow (clean coal) stream. In comparison, no coal reported to the overflow stream when only water was used as the separating medium, as was expected. This demonstrated that density separations were possible in this unit.

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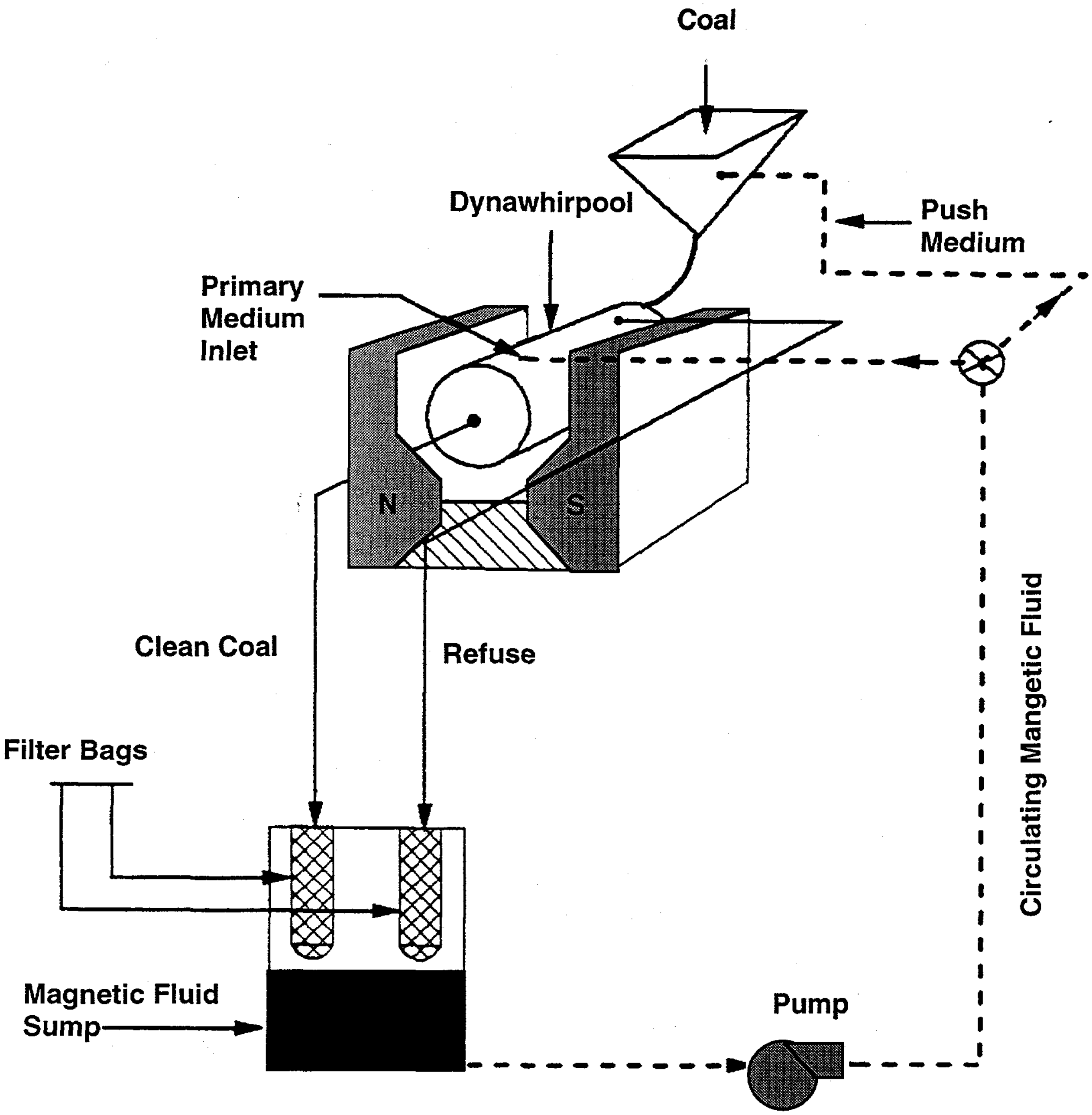

Figure 7-5. MAGNETIC FLUID SEPARATOR TEST CIRCUIT

Tests were then run using the magnetic fluid as the separating medium, along with the 28x32 mesh Upper Freeport seam coal. In all cases, no separation occurred, and all the coal reported to the refuse stream. The same results were obtained even when the concentrated magnetic fluid was used at maximum field strength. The addition of the centrifugal acceleration negated the buoyancy effect created by the magnetic fluid. To counteract this effect, a stronger magnetic field is needed, which cannot be obtained with the Frantz electromagnet. Hence, additional testing using this particular design will not be possible.

However, theoretical and experimental mapping of the magnetic field has been initiated. Through the use of finite element analysis, it should be possible to design the appropriate magnet that is compatible with the Dynawhirlpool separator. Work in this area is continuing.

7.3 Subtask 1.3 Surface-Based Separation Processes

Continuous flotation experiments were carried out in our 0.076 m x 3.55 m pilot flotation column. Pressure sensors were mounted at varying axial locations. The output from these sensors was fed to a computer. The desired hydrostatic head in the column (measure of the liquid level) was set using the pressure sensor located at the bottom of the column, and was regulated by the tailings pump. A detailed description of the column with other ancillary instrumentation has been provided in a previous report[9]

The flotation experiments were carried out using - 100 mesh Lower Kittanning seam coal. 100 liters of a 5 wt. % coal slurry was prepared. The required amount of frother was added directly to the slurry in the reservoir. Except where indicated, the frother used was methyl-iso-butyl-carbinol, MIBC. The feed was introduced into the column at the desired flow rate with the air turned off. When the desired hydrostatic head in the column was attained, aeration was turned on. Collection of timed froth and tailings samples were initiated the moment the froth overflowed the cell lip. For the froth samples, collection was over 30 sec and 1 minute intervals for the first minute and remainder of the experimental run respectively, while for the tailings stream, sampling was over 10 s, 15 s, 20 s, 30 s or 40 s intervals. In order to facilitate froth sample removal in the column, a water ring spray was installed on the outer periphery of the cell lip. For all the experiments reported here, the wash water addition rate was fixed at 1.2 liters per minute. This mode of operation was selected in order to minimize the time required to attain steady state conditions in the column (see Figure 7-6).

The initial studies were carried out with the column equipped with a Mott porous gas sparger. In these experiments, the slurry feed was introduced into the column at varying inlet positions from the gas distributor. With these experiments, the effect of

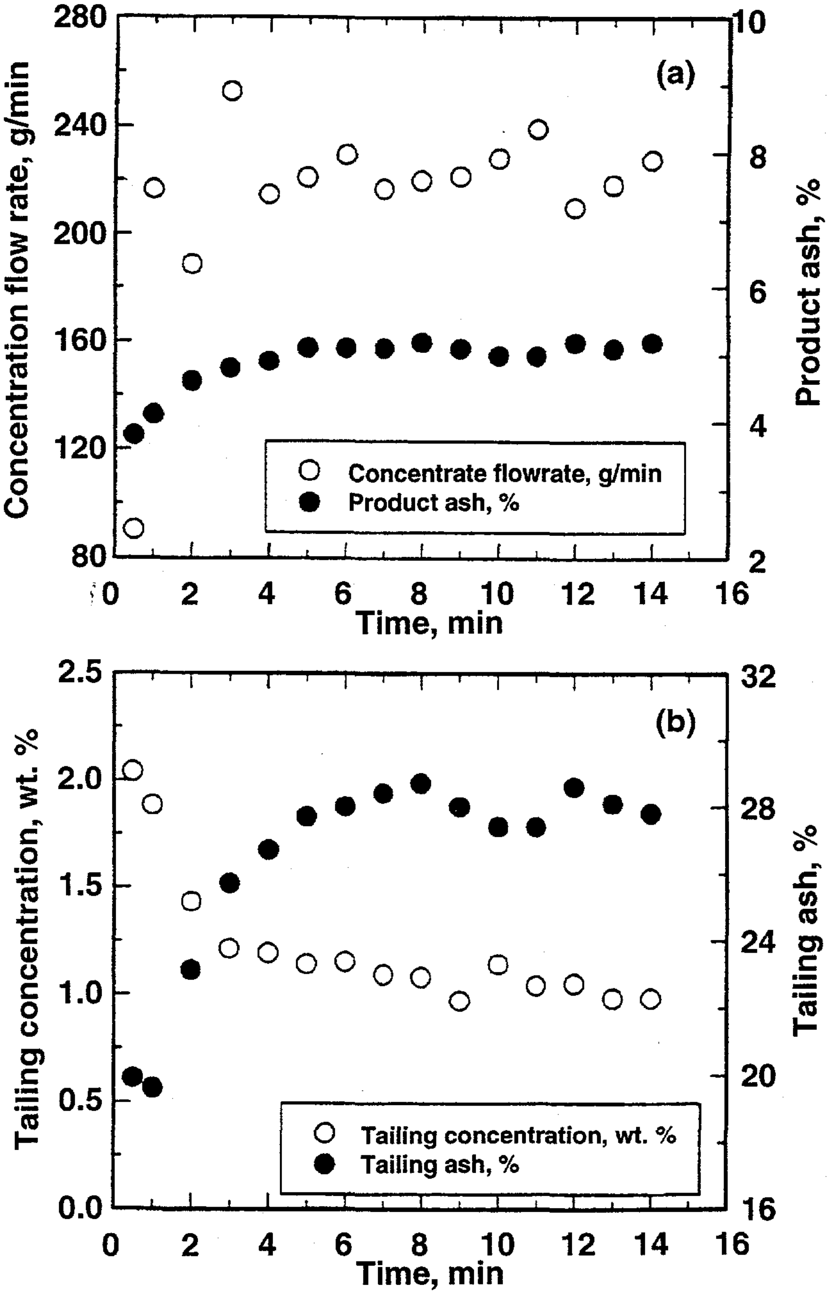

Figure 7-6 TRANSIENT FLOTATION RESPONSE (a) CONCENTRATE FLOW RATE AND GRADE, (b) TAILINGS FLOW RATE AND GRADE

recovery zone height on yield (and concentrate production rate) was determined. Additional experiments were also carried out at varying slurry concentrations. In order to evaluate the effectiveness of a novel vortactor bubble generator in fine coal cleaning, additional experiments were carried out in which the Mott sparger was replaced by the vortactor described in the last progress report[2]. In these experiments, the slurry feed and air were brought into intimate contact in the vortactor chamber where the pressure was set at 138 kPa. The slurry-air mixture was also introduced into the column at two axial locations to provide a preliminary evaluation of the effect of recovery zone height.

The froth and tailings samples were filtered, dried and weighed. For the tailings samples, the amount of water was also measured in order to determine the tailings flow rate at any given time interval, and the per cent solids in the tailings stream. All of these values were used to determine the attainment of steady state in the experiments.

7.3.1 Results and Discussion

Figure 7-7 shows the effect of recovery zone height on yield and product ash content. These tests were carried out at a superficial gas velocity of 0.022 m/s (air flow rate of 6 liters per minute). While the yield was largely independent of the recovery zone height, the ash content increased with decreasing recovery zone* height. The results show the yield was largely independent of the recovery zone height. This observation is consistent with the experimental and theoretical results of Bensley et al.[10] and Ityokumbul[11], respectively. However, the effect of feed location on product ash was more pronounced. With the exception of the lowest feed location, the product ash was fairly constant and in the range expected for the observed yields. By contrast, Bensley et al.[10] reported that the product ash increased as the feed location was raised. While the reasons for this are not entirely clear, it is noted that wash water was only employed in Penn State's studies. With wash water addition, entrainment of fine refuse is suppressed.

The effect of solid concentration on the yield, concentrate flowrate, and product ash was determined at an air flow rate of 3 liters per minute. In these experiments, the feed solid flow rate varied from 139 g/min (2.5% slurry) to 585 g/min (10% slurry) and the results are shown in Figure 7-8. The results show that the yield and product ash content decrease with increasing feed solid concentration. With the exception of the 2.5 wt. % feed, the bubble surface appears to be limiting in these tests (see Figure 7-8a). Under bubble surface limiting conditions, the competition for the available surface clearly favors the more hydrophobic material (cleanest product). Thus, the product ash content decreased from 5.76 % to less than 3.2% at the high solid feed rates. Since the project objective called for a 5% ash product, operation of the column under surface limiting conditions is not recommended.

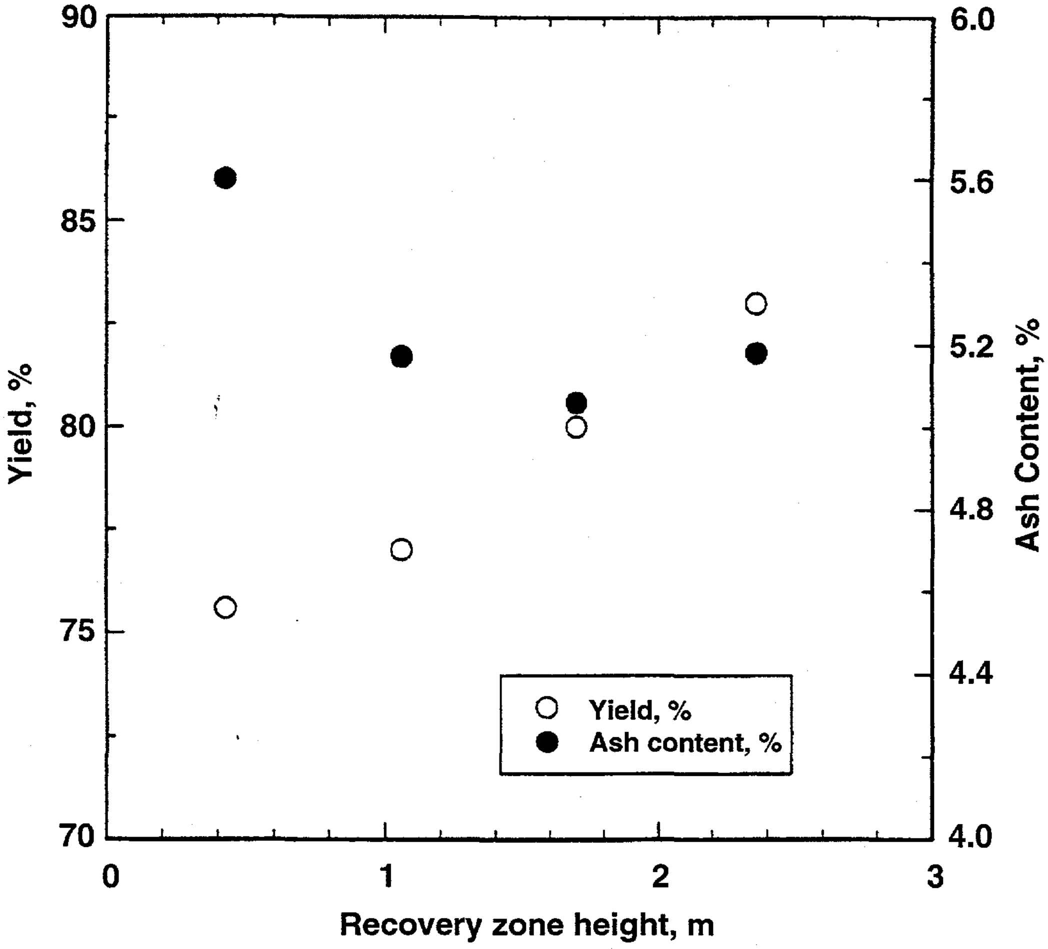

Figure 7-7. VARIATION OF CLEAN COAL YIELD AS GRADE WITH RECOVERY ZONE HEIGHT (air flow rate = 6 lpm)

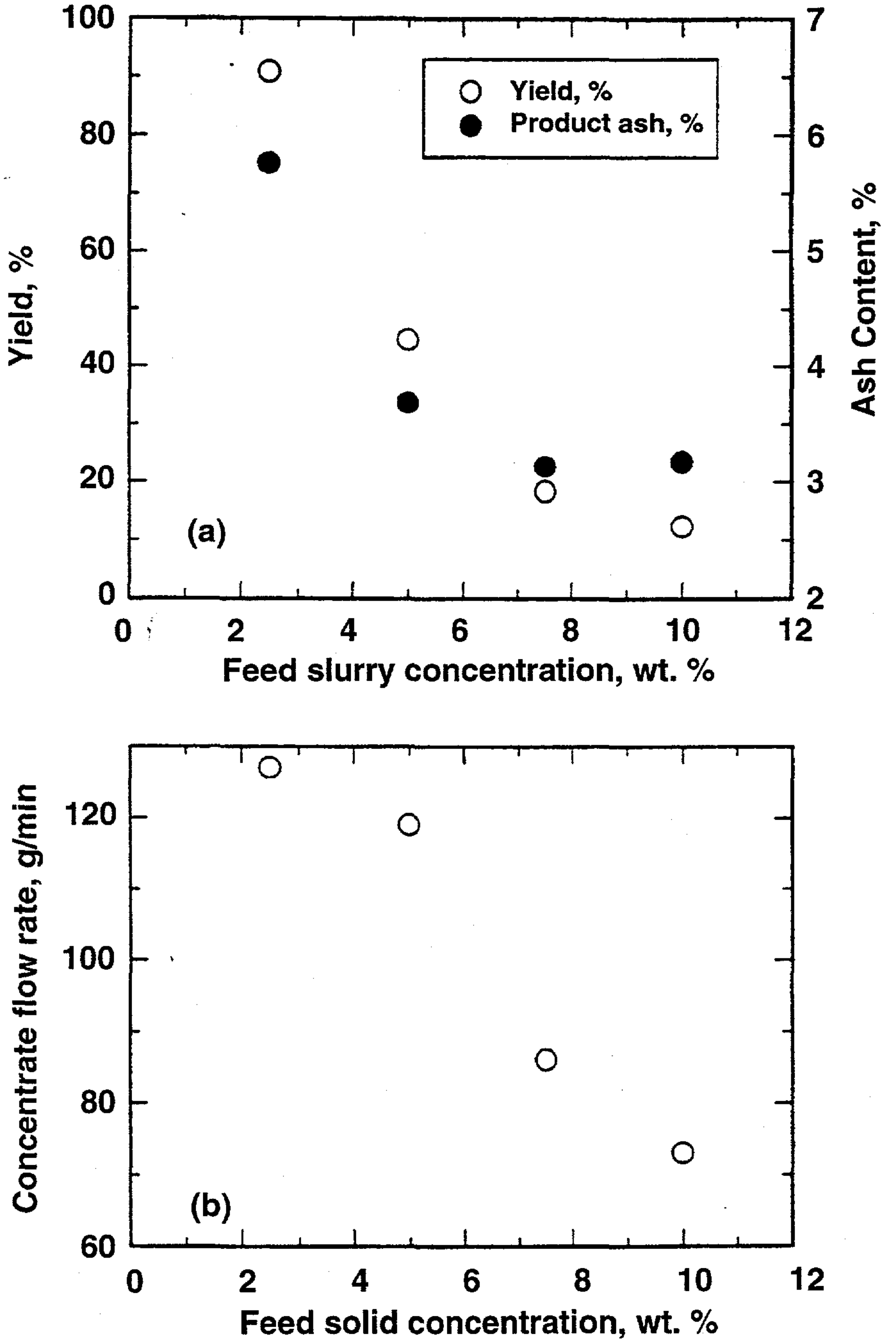

Figure 7-8. EFFECT OF FEED SOLID CONCENTRATION ON FLOTATION RESPONSE (a) CLEAN COAL YIELD AND GRADE (b) CONCENTRATE FLOW RATE (air flow rate = 3 lpm)

The variation of the concentrate flow rate with feed solid concentration is shown in Figure 7-8b. In general, the concentrate flow rate decreased with increasing feed solid concentration, with the decrease being more pronounced at solid concentrations exceeding 5 wt. %. At these high solid concentrations, we observed a stable froth in the collected tailings samples. This observation suggests that excessively tall flotation columns may not be particularly suited for cleaning duties as overloaded bubbles may lack the buoyancy to reach the froth phase, thus resulting in a lowering of the concentrate production rate. A similar observation was reported by Szatkowski and Freyberger[12] and King et al.[13] with single bubble loading.

The variation of clean coal yield and product grade with air flow rate is shown in Figure 7-9. These tests were carried out using a 5 wt. % feed slurry. The results show that the yield, concentrate flow rate and product ash content increased with air flow rate. This trend is expected since the available bubble surface increases with air flow rate. For solid feed rate in the range 240-320 g/min, it appears that conditions of free flotation are encountered at air flow rates above 4.5 lpm. This is consistent with our earlier observation on the presence of air bubbles in the tailing samples collected at low air flow rates. Since the project objective calls for the production of clean coal with an ash content of 5%, our results suggest that a single column flotation stage is sufficient for the beneficiation of Type II coal, at a yield of 66-80%.

The Mott porous sparger used in the studies reported above was replaced with the Vortactor. Table 7-2 shows the preliminary results obtained with the Vortactor bubble generator. The results show that flotation performance (yield, product ash and concentrate flow rate) was independent of feed location. This observation is consistent with the results obtained with the Mott sparger. However, since there is no bulk transport of feed material above the inlet point, the results suggest that particle-bubble attachment is rather fast and takes place in the contact chamber and/or feed line.

Increasing the air flow rate from 2 lpm to 6 lpm increased the yield, concentrate flowrate to the levels obtained with the Mott porous sparger. However, end product ash was considerably higher. The reasons for the higher ash content observed with the Vortactor bubble generator at an air flowrate of 6 lpm are not entirely clear at the present time. However, our gas hold-up data suggests that the column operating conditions did not favor adequate drainage of the froth. This observation is partially supported by the unusually high ash content of the coarser size fractions (i.e. +140 mesh and -140+200 mesh fractions). The results obtained with an air flowrate of 2 lpm clearly show that increasing the recovery zone height (i.e. lowering the feed inlet point) did not have any

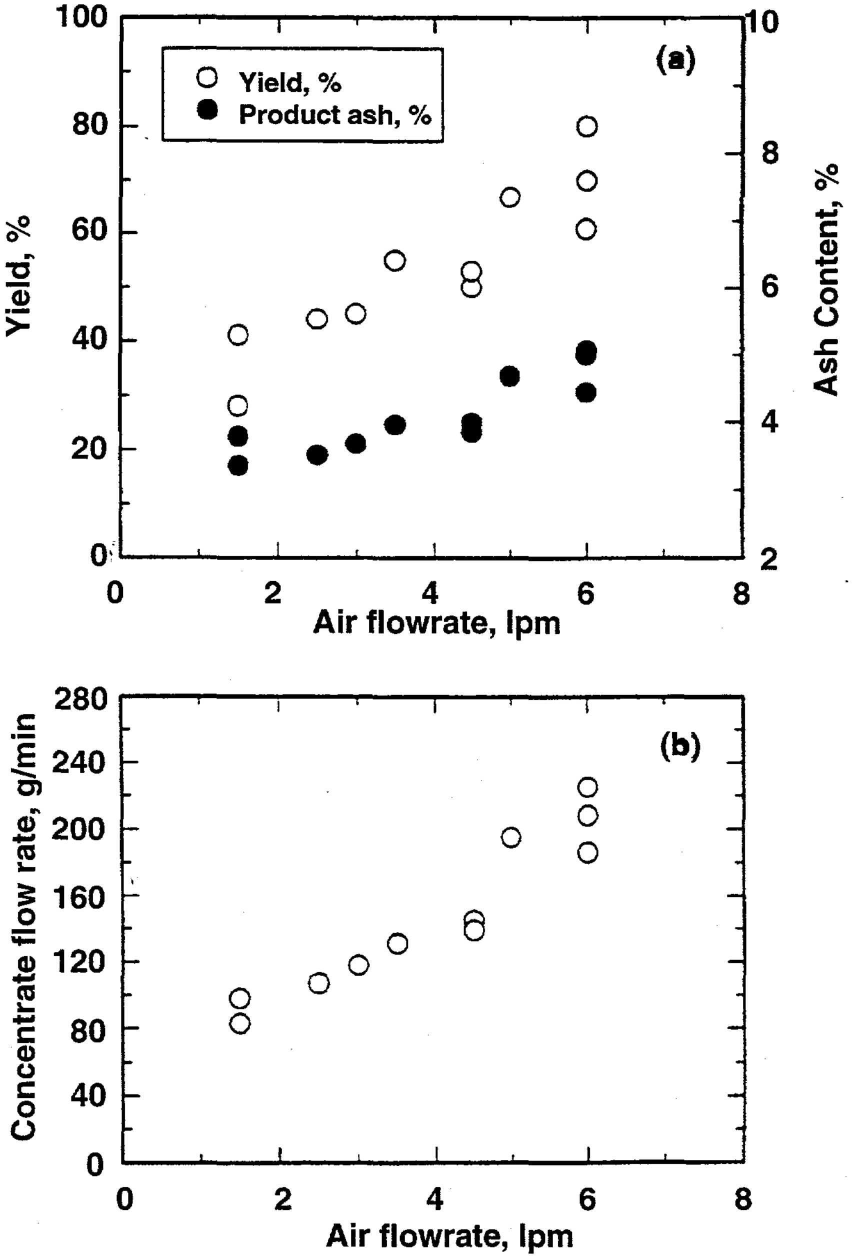

Figure 7-9. EFFECT OF FEED SOLID RATE ON (a) CLEAN COAL YIELD AND GRADE, (b) CONCENTRATE FLOW RATE (feed solid concentration = 5 wt. %)

Table 7-2. Preliminary Evaluation of Vortactor Bubble Generation in Fine Coal Cleaning

Air flowrate (liters/min)	Feed inlet[a] (m)	Yield (%)	Product Ash (wt. %)	Concentrate flowrate (g/min)
2	0.43	46.6	3.77	110
2	1.70	42.1	3.62	110
6[b]	1.70	70.1	5.40	181

[a] Distance from the bottom of the column

[b] The pulverizer used for coal preparation broke down and the coal preparation procedure was changed.

effect on the yield and concentrate flow rate. As indicated with the Mott porous sparger, this observation would suggest that tall columns are not required for fine coal flotation.

7.3.2 Overall Evaluation

In order to determine the optimum conditions for the processing of the Lower Kittanning seam coal, the yield index is plotted as a function of the ash rejection for all the tests carried out in the present study (see Figure 7-10). The results show that the optimum conditions will give a yield index of about 45-48% at an ash rejection of 60%. These optimum conditions will give a clean coal yield of 75 - 80% with an ash content in the range 4.8 - 5.1 %.

The operational parameter that affects the product grade is the gas hold-up in the froth phase. For effective removal of fine refuse the use of wash water has proven successful. However, our results also show that a well-drained froth having gas hold-up of 55-70% was necessary for achieving target grades (see Figure 7-11). Since the objective of the current study is to produce a clean coal product with an ash content of less than 5%, our results show that this can be done in a single stage of column flotation. The processing conditions necessary for achieving these target objectives are:

- air flow rate of 6 liters per minute
- solid feed rate 240-280 g/min, and
- froth phase gas hold-up of at least 50%.

7.3.3 Conclusion

These results suggest that flotation columns may not be effective for cleaning duties (where bubble surface area is limiting), except where a high value product is to be produced. Since the project objective called for a 5% ash product, operation of the column under bubble surface limiting conditions are not recommended. For optimum results in fine coal cleaning, the feed solid concentration should not exceed 5 wt. %.

7.4 Subtask 1.4 Dry Processing

Preliminary testing of an integrated grinding/separator circuit was initiated. A Holmes high-speed pulverizer was used for size reduction in combination with the batch triboelectrostatic separator. The Holmes pulverizer was used to prepare the -100 mesh coal that was used in the previous triboelectrostatic separation tests. However, in those cases, the pulverized coal was stored under argon for up to several weeks prior to tribocharging and separation. In this case, the coal was used directly after size reduction.

Nominal -28 mesh Upper Freeport seam coal was fed to the pulverizer. As the coal passed through the device, it was pulverized by rotating steel hammers. A stainless steel screen, having nominal 0.2 mm openings, was used to produce a product of

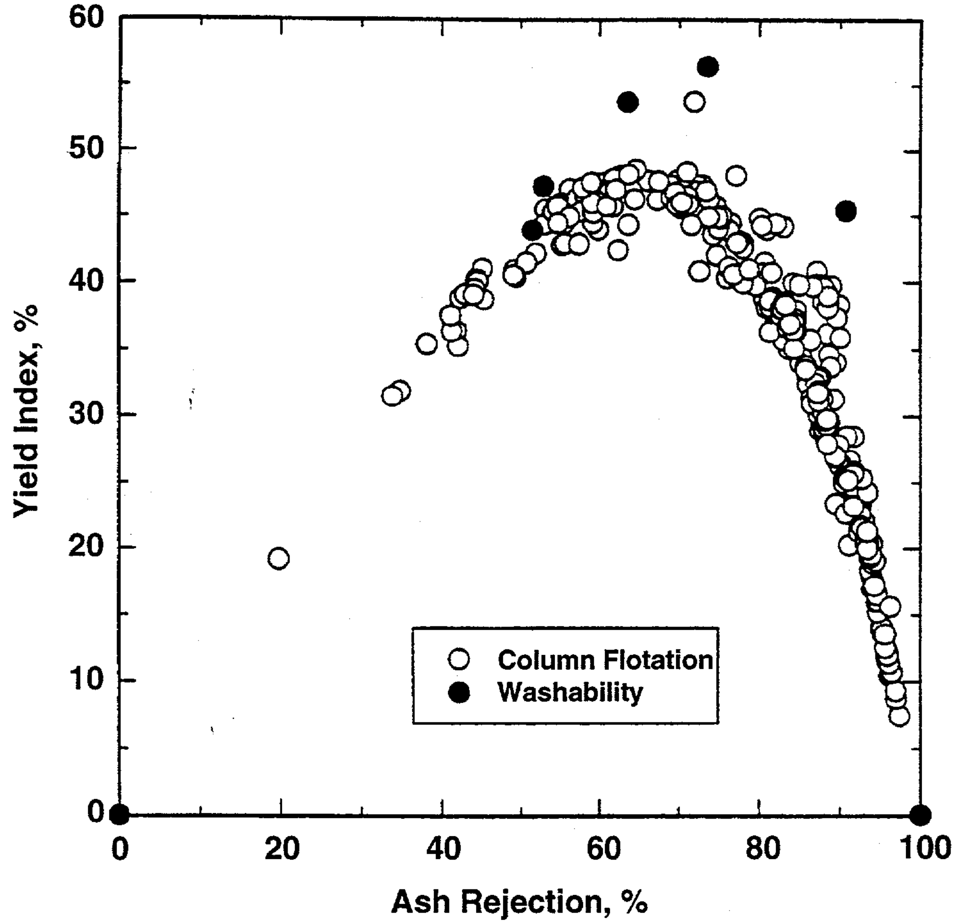

Figure 7-10. COMPARISON OF COLUMN FLOTATION AND WASHABILITY RESULTS

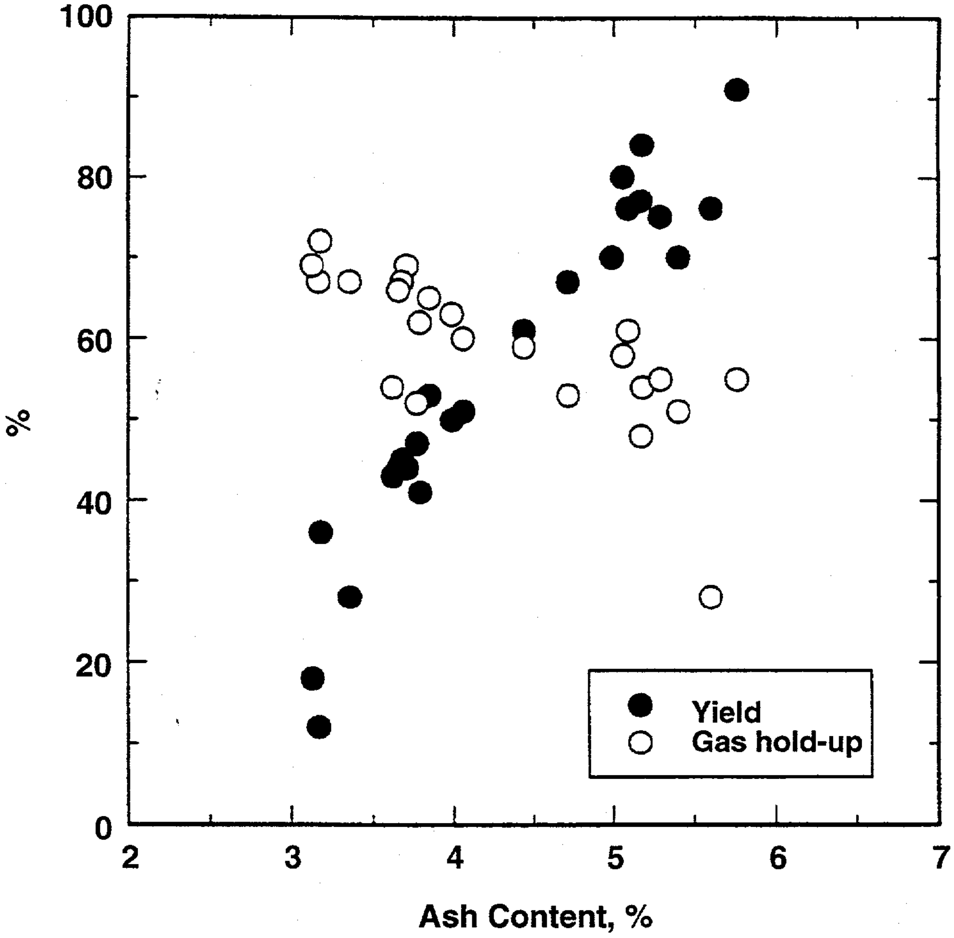

Figure 7-11. VARIATION OF CLEAN COAL YIELD AND GRADE ON GAS HOLD-UP IN THE FROTH PHASE

approximately -100 mesh. Contact with the hammers and screen provided the opportunity for tribocharging the coal.

In order to provide a direct feed to the separator, the collection bin was removed and a funnel was attached to the pulverizer discharge. The funnel discharge was placed over the venturi feeder of the batch electrostatic separator, which had the in-line tribocharger removed. Nitrogen was used as the transport medium. As in the previous tests, the solids were separated and collected along the copper plates. Upon completion of the test, the material was removed in increments along each plate. Each sample was weighed to determine the incremental yield. Ash and total sulfur analyses were performed on each sample. These results are plotted in Figure 7-12.

As seen, the overall yield was about 55% for an ash content of about 4%. The clean coal sulfur content was about 1%. As was found in the previous tests, the lowest and highest ash fractions were obtained near the feed end of the separator.

7.5 Subtask 1.5 Stabilization of Coal-Water Mixtures

Subtask 1.5 was completed during the previous reporting period.

8.0 PHASE III, TASK 2 STOKER COMBUSTION PERFORMANCE ANALYSIS AND EVALUATION

8.1 Subtask 2.1 Determine DOD Stoker Operability and Emissions

No work was conducted in Subtask 2.1.

8.2 Subtask 2.2 Conduct Field Test of a DOD Stoker

No work was conducted in Subtask 2.2.

8.3 Subtask 2.3 Provide Performance Improvement Analysis to DOD

No work was conducted in Subtask 2.3.

8.4 Subtask 2.4 Evaluate Pilot-Scale Stoker Retrofit Combustion

No work was conducted in Subtask 2.4.

8.5 Subtask 2.5 Perform Engineering Design of a Stoker Retrofit

No work was conducted in Subtask 2.5.

9.0 PHASE III, TASK 3 EMISSIONS REDUCTION

9.1 Subtask 3.1 Demonstrate Advanced Pollution Control System

No work was conducted in Subtask 3.1.

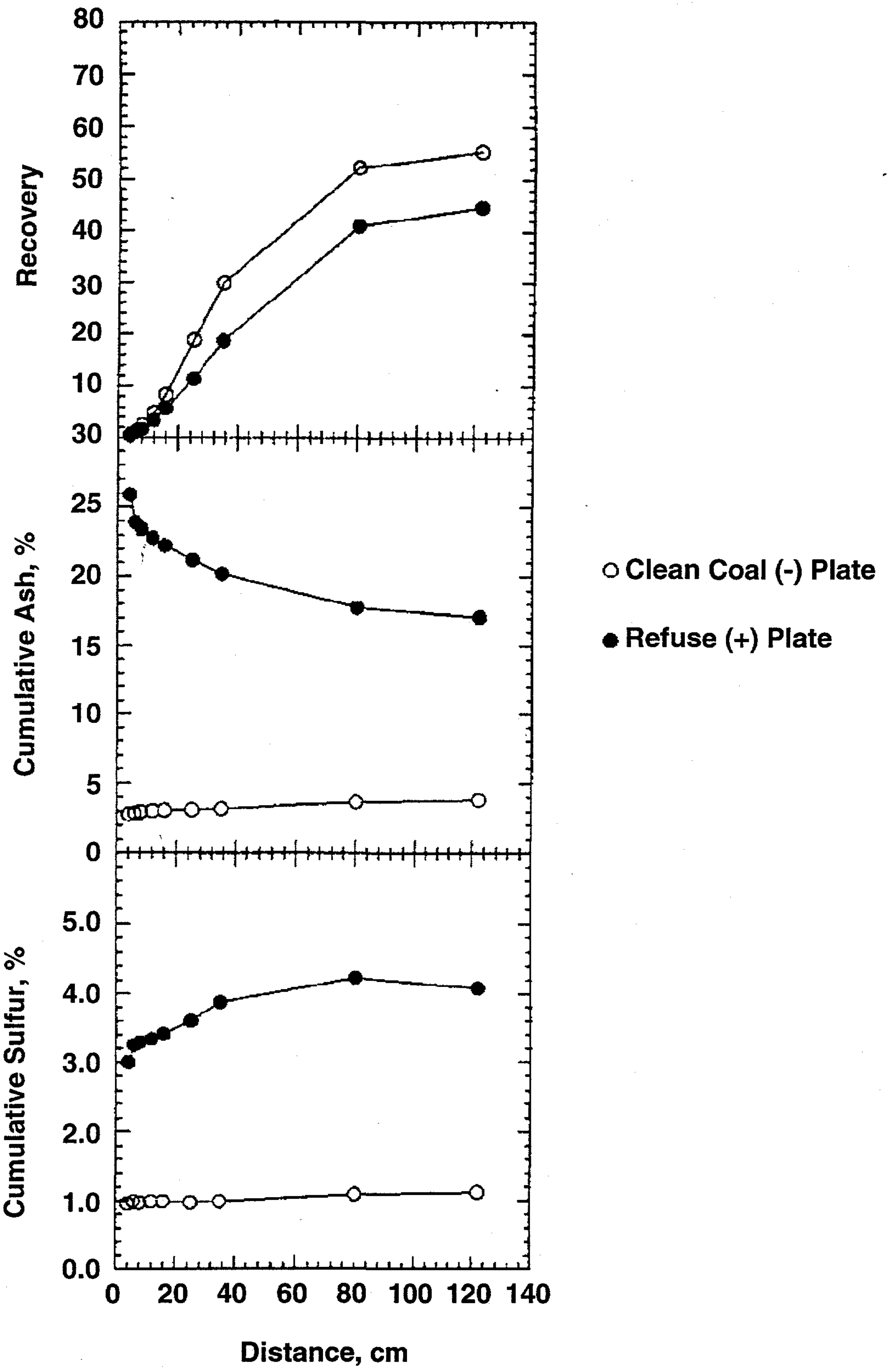

Figure 7-12. RESULTS FOR THE INTEGRATED PULVERIZER/ELECTROSTATIC SEPARATOR CIRCUIT

9.2 Subtask 3.2 Evaluate Carbon Dioxide Mitigation and Heavy Metal Removal in a Slipstream System

No work was conducted in Subtask 3.2.

9.3 Subtask 3.3 Study VOC and Trace Metal Occurrence and Capture

No work was conducted in Subtask 3.3.

10.0 PHASE III, TASK 4 COAL-BASED FUEL WASTE COFIRING

10.1 Subtask 4.1 Coal Fines Combustion

No work was conducted in Subtask 4.1.

10.2 Subtask 4.2 Coal/Rocket Propellant Cofiring

No work was conducted in Subtask 4.2.

11.0 PHASE III, TASK 5 ECONOMIC ANALYSIS

11.1 Subtask 5.1 Cost and Market Penetration of Coal-Based Fuel Technologies

Subtask 5.1 was previously completed.

11.2 Subtask 5.2 Selection of Incentives for Commercialization of the Coal Using Technology

11.2.1 Motivation and Aim of the Study

As the results of Phase II indicate there are social, economic and political benefits of substituting clean burning coal-based fuels for oil and gas. A heavy reliance on imported oil makes the United States vulnerable to price shocks, i.e. periods of increased price volatility, and disruptions in the supply of oil. Clearly, price shocks and disruptions in supply may have significant economic and political effects in the U.S. As previous studies document the infamous oil embargo of 1973-1974 by OPEC resulted in approximately a 2% rise in unemployment and a 2% increase in the rate of inflation.

The world has been witnessing a downtrend in oil prices, on average, since 1989; nevertheless due to the concentrated political and highly volatile nature of the oil market, it is not an easy task to predict how oil prices would fare over the next decades. On the other hand, coal prices have been exhibiting one of the smallest price fluctuations in energy markets over the last one and a half decades. This consistent and statistically significant difference in the volatilities of the two price series, oil and coal prices, may be viewed to indicate that there are advantages of switching to a coal-based technology from a oil-based one for risk management purposes.

Subtasks 4.1 and 4.2 of Phase II addressed the question of estimating the net costs of this technology switch at the firm level. They estimate the magnitude of the gross costs and benefits associated with the suggested retrofitting. As it is remarked in Subtask 4.1, the "success (of the new technology) will most likely be achieved through those technologies that can achieve the margin of economic viability by reducing capital costs and not through 'serendipitous' changes in oil price alone." This finding clearly shows that even though there may be significant advantages in substituting clean-burning coal-based fuels for oil and gas at the macroeconomic level, at the microeconomic level, e.g. firm level, the costs of retrofitting are considerably high for individual firms, so that managers may be tempted to decide against it. Consequently, in the conclusion of Subtask 4.1, it is suggested that "those technologies that can reach that marginal level of viability could make their market entry by highlighting fuel flexibility as quantified by option pricing methods." Even though there exist undeniable benefits -in terms of options- by adopting the new technology, due to the complex nature of the problem at hand and lack of data it is not possible to come up with an estimate of an option value for this "technological investment". Thus, Subtasks 4.1 and 4.2 provide us with net cost figures which are based on the discounted cash flow technique.

This subtask starts with the premise that the new coal-using technologies offer significant macroeconomic benefits in terms of fuel price differentials and managerial, economic and political options (some of which are to be quantified by a further study) and that the sum of positive externalities outweigh the negative externalities which are associated with the differential environmental damage and so forth. As it was evidenced by previous research, the adoption of the coal-based technology, i.e. the investment in the new technology, has a significant cost component attached to it, which may induce the managers at the firm level to be hesitant or even unwilling to undertake it. Thus, recognizing the net positive externalities, the government may decide that it is appropriate to offer incentives for firms, which have a potential use for it, to facilitate the use and commercialization of the new technology.

Economic and financial incentives in general, and those provided to manufacturing enterprises in particular, have become accepted tools for the implementation of preferred government policies. These incentives not only affect the size of investments, but also alter the basic parameters of design and operation of industrial firms. However, the combined result of implemented incentives and particularly, the quantitative decision about the choice of the incentives has not been analyzed in depth in the literature.

Typical examples of government incentives which are employed as policy tools are: investment tax credits, reduced or no-interest loans, capital subsidies and tax incentives through accelerated depreciation. These policy tools have been subject to academic research at several occasions, recently: for instance, the discussions on the effectiveness of tax rates on business investment by Feldstein[14] and Chirinko[15], the debate on the impact of investment tax credit on investment behavior and value of the firm by Auerbach and Kotlikoff[16], Feldstein[17], Auerbach[18] and Lyon[19] can be mentioned as examples of research involving assessment of effectiveness of these tools in achieving objectives set forth by the government.

The studies conducted on the effectiveness of the policy tools mentioned above remain highly macroeconomics oriented and have little to say about the consequences of them in a given sector, or sub-sector in a given economy. This deficiency was addressed in two sector-oriented studies: Cone[20] and more recently, Rose and Mor[21].

Nevertheless, all previous studies attempted to estimate the impact of incentives by using aggregate market data and have ignored the response generated by the economic agents operating in those markets: the firms. This study, therefore, is aimed at filling that gap in the literature and focuses on the microeconomic responses generated by the firms to the incentives. The subtask examines firm-specific data on firms which are potential customers of the new coal-using technology where the optimal incentive or combination of incentives is determined based on the empirically estimated reactions of firms.

A careful inspection of the government incentives mentioned above reveals that they are designed at fostering projects with different characteristics. In other words, one incentive may be optimal with projects with characteristic "A", whereas another may be of choice if the project has characteristic "B". For example, tax incentives, such as direct tax cuts, accelerated depreciation and so forth, can be thought to be more effective on projects which require a big initial capital outlay. On the other hand, reduced or no-interest loans are more useful on projects which are highly sensitive to interest rate fluctuations in the market, e.g. due to the nature of their cash flow stream.

Modern finance theory has shown that, under realistic assumptions, project selection and project financing decisions are not independent from the current financial attributes of the firm. In other words, risk exposure of firms becomes crucial in project selection and financing decisions: the same project can be regarded as profitable and desirable by one firm and not so by another.

The switch to a new technology can be thought as an investment in technology, and thus an "investment project" by itself. The importance of this is self-explanatory: if firms are given incentives, regardless of their financial and operational risk exposures, the result may be suboptimal or even off the policy target set forth by the government in some cases. The distortion of prices and the market mechanism may even produce undesirable outcomes in those industries: for instance generous capital subsidies may induce the firms to take projects with an -otherwise- unacceptable levels of risk exposure.

In sum, devising a government incentive scheme which aims at widespread commercialization of the new coal-using technology is a complex task: on the one hand, a miscalculation or negligence of firm characteristics and behavior may lead to suboptimal or even unwanted outcomes. On the other hand, calculation of the optimal mix of incentives presents another challenge for the policy makers. This subtask will address both of these issues by taking individual firm characteristics into consideration in assessing the optimal strategy which should be implemented by the government.

11.2.2 Data

A list of 6,823 water tube boiler locations in the Commonwealth of Pennsylvania was generated from a database obtained from the Pennsylvania Department of Labor and Industry (PDL&I). Consequently, these locations were cross referenced against the names of publicly traded corporations or their subsidiaries for the entire United States. This cross reference revealed 128 corporations, or their subsidiaries with have water tube boiler locations in the Commonwealth of Pennsylvania.

The latest and past one, three and five year annual financial statements, i.e. income statements and balance sheets, and key financial and operating ratios for the aforementioned 128 corporations were obtained from a CD-ROM provided by the Compact Disclosure Database Company. A closer inspection of the individual characteristics of these boilers revealed the result that only 63 firms (and subsidiaries), some with multiple boiler locations, fit into the category of boilers which the new technology is developed for.

Based on the balance sheets and income statements the following financial ratios are calculated according to their standard definitions: quick ratio (acid test), i.e. (current assets - inventory)/current liabilities, current ratio, i.e. currents assets/current liabilities , net sales/cash, net sales/working capital, net sales/current assets, net sales/assets, total liabilities/total assets (D/A), liabilities/equity (D/E), total net income/net sales, measure of operating leverage (MOL), i.e. percentage change in EBIT per one percent change in sales), measure of financial leverage (MFL), i.e. percentage change in net income per one percent change in EBIT, and finally, measure of total leverage (MTL), i.e. MOL multiplied by MFL.

The data about the new coal-based technology costs are taken from Subtasks 4.1 and 4.2 of Phase II. Similarly, boiler-specific costs and benefits are estimated using the same algorithm which is utilized in the aforementioned sections. The data was then tabulated and organized into a convenient format to facilitate quantitative analysis of the impacts of various government incentives for commercialization of the new technology. For given levels of boiler capacity the switch in technology is treated as a real investment and the net return on investment is calculated. A list of firms included in this study is presented in Table 11-1. Tables 11-2 and 11-3 display some selected balance sheet items and calculated financial ratios for the firms in the sample.

11.2.3 Methodology

In order to assess firms' responsiveness to alternative incentives and financial ratios the following regression equation is estimated:

$$y_i = \alpha + \sum_j \beta_j Z_{ji} + \varepsilon_i \qquad (11\text{-}1)$$

where y_i stands for the net income of the i-th firm, α is a constant, Z_j is the j-th vector of the Z-matrix which includes the explanatory variables, and finally β_j is the estimated coefficient of Z_j and ε_i is a white-noise error term. The Z_j matrix includes variables such as, cost of goods sold, research and development expenses, fixed costs, depreciation, interest expenses, taxes, measures of financial, operational and total leverages, and other aforementioned financial ratios, e.g. debt-equity ratio, current ratio, quick ratio, etc.

In order to determine the explanatory variables in the model, in the regression equation, a stepwise regression procedure is applied. Stepwise regression can adopt a forward selection criterion, where variables are added to the model sequentially until none of the remaining would have t-statistics with a P-value (significance level) smaller than a threshold value. Alternatively, it can also adopt a backward criterion, where starting from the full set of regressors, variables are deleted sequentially as long as their t-statistics produce a P-value larger than a threshold value. In this study, variables are added to the model sequentially; at each stage in this forward selection procedure, the backward selection algorithm is run to delete variables which now have small t-statistics.

It is known that ordinary least squares (OLS) provides a consistent estimator for β in the regression model $Y = X\beta + u$ in a large number of settings where the standard assumption that the residuals satisfy: $V = E(uu') = \sigma^2 I$. If this assumption is violated and the form of V is known, it may be possible to obtain a more efficient estimator by some form of generalized least squares (GLS). However, in certain cases, GLS for serially correlated residuals produces inconsistent parameter estimates (See: Hayashi and Sims,[22]). Moreover, in the case of heteroscedasticity, it may not always be clear what form V should take. Hansen[23] and others show that it is possible to compute consistent estimators for the covariance matrix of estimators in a wide range of situations using a procedure that imposes little structure upon matrix V. An alternative method for calculating consistent covariance matrices for the estimated coefficients is provided by Newey and West (1987). Hence, to assure the reliability of the reported test statistics of estimated coefficients the regressions are performed with Newey and West method.

Table 11-1. List of Firms Included in the Sample

[illegible]
- ACF INDUSTRIES INC
- ALCAN ALUMINUM LTD
- ALCOA INTERNATIONAL HOLDINGS COMPANY
- ALLEGHENY LUDLUM CORP
- ALLIED SIGNAL INC
- ALUMINUM CO OF AMERICA
- AMERICAN HOME PRODUCTS CORP
- ANGELICA CORP
- ARCO CHEMICAL CO
- ARMCO INC
- ASHLAND OIL INC
- AT&T CORP
- BEATRICE FOODS INC
- BETHLEHEM STEEL CORP
- BETZ LABORATORIES INC
- BORDEN INC
- CABOT CORP
- CARBIDE GRAPHITE GROUP INC
- CATERPILLAR INC
- CHEVRON CORP
- CONSOLIDATED CIGAR CORP NEW JERSEY
- EXXON CORP
- GENCORP INC
- GENERAL ELECTRIC CO
- GENERAL SIGNAL CORP
- GUILFORD MILLS INC
- H J HEINZ CO
- HANOVER FOODS CORP
- HERCULES INC
- INDSPEC CHEMICAL CORP
- J&L SPECIALTY STEEL INC
- KRAFT GENERAL FOODS INC
- LTV STEEL CO INC
- LUKENS INC
- MASLAND CORP
- MERCK & CO INC
- MINNESOTA MINING & MANUFACTURING
- NATIONAL GYPSUM CO
- OCCIDENTAL PETROLEUM CORP
- PPG INDUSTRIES INC
- PROCTER & GAMBLE CO
- RHONE POULENC SA
- ROHM & HAAS CO
- SEARS ROEBUCK & CO
- SMITHKLINE BEECHAM PLC
- SONOCO PRODUCTS CO
- SPS TECHNOLOGIES INC
- ST JOE PAPER CO
- TEMPLE INLAND INC
- USX CORP
- VALSPAR CORP
- WARNER LAMBERT CO
- WEST PENN POWER CO
- WESTINGHOUSE ELECTRIC CORP
- WESTVACO CORP
- WITCO CORP
- YORK INTERNATIONAL CORP

Table 11-2. Selected Items from the Balance Sheets of Included Firms

COMPANY NAME	TOT CUR ASSETS	TOTAL ASSETS	INCOME TAXES	CURRENT LIABILITY	TOTAL LIABILITY	COMMON STOCK	RETAINED EARNINGS	TOT LIAB-NET WORTH
ACF INDUSTRIES INC	640,603.00	1,706,454.00	8,336.00	469,213.00	1,388,925.00	76,573.00	(18,453.00)	1,706,454.00
ALCAN ALUMINIUM LTD	2,402,000.00	9,810,000.00	16,000.00	1,335,000.00	5,291,000.00	1,183,000.00	2,813,000.00	9,810,000.00
ALCOA INTL HOLDINGS COMPANY	1,111,800.00	3,872,600.00	181,900.00	571,700.00	1,243,500.00	0.00	1,827,800.00	3,872,600.00
ALLEGHENY LUDLUM CORP	469,788.00	1,174,049.00	20,634.00	210,877.00	770,627.00	7,288.00	152,258.00	1,174,049.00
ALLIED SIGNAL INC	4,567,000.00	10,829,000.00	0.00	3,489,000.00	8,439,000.00	358,000.00	1,023,000.00	10,829,000.00
ALUMINUM CO OF AMERICA	3,702,500.00	11,596,900.00	0.00	2,092,900.00	6,623,900.00	88,800.00	2,946,100.00	11,596,900.00
AMERICAN HOME PRODUCTS CORP	4,807,684.00	7,687,353.00	171,404.00	1,584,411.00	3,612,235.00	103,442.00	2,884,244.00	7,687,353.00
ANGELICA CORP	210,255.00	332,861.00	5,530.00	53,067.00	140,868.00	9,448.00	190,301.00	332,861.00
ARCO CHEMICAL CO	943,000.00	3,502,000.00	28,000.00	487,000.00	1,803,000.00	100,000.00	703,000.00	3,502,000.00
ARMCO INC	625,400.00	1,904,700.00	0.00	353,000.00	2,208,100.00	1,000.00	(1,450,300.00)	1,904,700.00
ASHLAND OIL INC	1,973,001.00	5,551,817.00	41,560.00	1,618,913.00	4,097,023.00	60,022.00	1,008,264.00	5,551,817.00
AT&T CORP	29,738,000.00	60,766,000.00	0.00	25,334,000.00	46,334,000.00	1,352,000.00	857,000.00	60,766,000.00
BEATRICE FOODS INC	137,062.00	655,641.00	4,157.00	113,772.00	491,942.00	155,140.00	4,226.00	655,641.00
BETHLEHEM STEEL CORP	1,591,100.00	5,876,700.00	0.00	914,200.00	5,180,100.00	93,400.00	(939,900.00)	5,876,700.00
BETZ LABORATORIES INC	208,635.00	521,129.00	6,838.00	92,041.00	221,810.00	3,365.00	394,726.00	521,129.00
BORDEN INC	1,290,200.00	3,871,700.00	56,500.00	1,371,500.00	3,117,000.00	121,900.00	835,100.00	3,871,700.00
CABOT CORP	544,206.00	1,489,473.00	26,314.00	354,221.00	1,047,200.00	33,887.00	861,803.00	1,489,473.00
CARBIDE GRAPHITE GROUP INC	102,693.00	171,870.00	213.00	32,665.00	115,314.00	70.00	42,869.00	171,870.00
CATERPILLAR INC	6,071,000.00	14,807,000.00	111,000.00	4,671,000.00	12,608,000.00	835,000.00	1,234,000.00	14,807,000.00
CHEVRON CORP	8,682,000.00	34,736,000.00	782,000.00	10,606,000.00	20,739,000.00	1,069,000.00	13,955,000.00	34,736,000.00
CONSOLIDATED CIGAR CORP NEW JERSEY	49,748.00	205,906.00	0.00	15,771.00	173,027.00	1.00	2,879.00	205,906.00
EXXON CORP	14,859,000.00	84,145,000.00	2,359,000.00	18,590,000.00	46,958,000.00	2,822,000.00	49,365,000.00	84,145,000.00
GENCORP INC	430,000.00	1,164,000.00	14,000.00	341,000.00	929,000.00	3,000.00	229,000.00	1,164,000.00
GENERAL ELECTRIC CO	195,240,000.00	251,506,000.00	0.00	178,638,000.00	224,026,000.00	584,000.00	28,613,000.00	251,506,000.00
GENERAL SIGNAL CORP	594,545.00	1,224,841.00	7,385.00	325,848.00	699,655.00	77,082.00	583,099.00	1,224,841.00
GUILFORD MILLS INC	248,638.00	506,742.00	0.00	96,644.00	287,003.00	393.00	244,066.00	506,742.00
H J HEINZ CO	2,291,530.00	6,381,146.00	130,535.00	1,692,362.00	4,042,595.00	71,850.00	3,633,385.00	6,381,146.00
HANOVER FOODS CORP	73,013.00	124,646.00	1,092.00	50,734.00	81,656.00	21,042.00	26,371.00	124,646.00
HERCULES INC	1,226,523.00	3,161,961.00	0.00	884,211.00	1,793,754.00	31,198.00	1,955,005.00	3,161,961.00
INDSPEC CHEMICAL CORP	32,269.00	237,125.00	0.00	23,571.00	230,874.00	1.00	8.00	237,125.00
J&L SPECIALTY STEEL INC	209,384.00	626,038.00	165.00	99,120.00	358,522.00	387.00	(36,959.00)	626,038.00

KRAFT GENERAL FOODS INC	6,982,000.00	32,669,000.00	428,000.00	6,577,000.00	18,602,000.00	0.00	1,529,000.00	32,669,000.00
LTV STEEL CO INC	1,350,900.00	4,584,100.00	0.00	716,600.00	8,399,500.00	100.00	(5,239,100.00)	4,584,100.00
LUKENS INC	307,739.00	817,178.00	0.00	161,705.00	550,424.00	158.00	193,977.00	817,178.00
MASLAND CORP	101,924.00	203,774.00	0.00	79,629.00	129,503.00	132.00	34,755.00	203,774.00
MERCK & CO INC	5,734,600.00	19,927,500.00	1,430,400.00	5,895,700.00	8,761,400.00	4,576,500.00	9,393,200.00	19,927,500.00
MINNESOTA MINING & MANUFACTURING	6,363,000.00	12,197,000.00	290,000.00	3,282,000.00	5,685,000.00	6,512,000.00	0.00	12,197,000.00
NATIONAL GYPSUM CO	196,480.00	774,340.00	10,868.00	67,144.00	1,428,135.00	1.00	(744,195.00)	774,340.00
OCCIDENTAL PETROLEUM CORP	1,934,000.00	17,123,000.00	110,000.00	2,048,000.00	13,152,000.00	61,000.00	(1,883,000.00)	17,123,000.00
PPG INDUSTRIES INC	2,025,900.00	5,651,500.00	4,700.00	1,281,000.00	3,126,500.00	242,100.00	3,436,800.00	5,651,500.00
PROCTER & GAMBLE CO	9,988,000	25,535,000	0	8,040,000	16,703,000	684,000	7,496,000	25,535,000
RHONE POULENC SA	41,813,000.00	114,481,000.00	0.00	31,492,000.00	64,730,000.00	6,271,000.00	13,155,000.00	114,481,000.00
ROHM & HAAS CO	1,200,000.00	3,524,000.00	3,000.00	701,000.00	2,012,000.00	197,000.00	1,444,000.00	3,524,000.00
SEARS ROEBUCK & CO	25,549,800.00	90,807,800.00	0.00	57,290,200.00	76,809,700.00	293,800.00	8,162,800.00	90,807,800.00
SMITHKLINE BEECHAM PLC	3,393,000.00	5,438,000.00	0.00	2,178,000.00	3,608,000.00	335,000.00	831,000.00	5,438,000.00
SONOCO PRODUCTS CO	513,110.00	1,707,125.00	3,071.00	303,178.00	918,761.00	7,175.00	623,500.00	1,707,125.00
SPS TECHNOLOGIES INC	161,010.00	285,979.00	646.00	66,527.00	183,152.00	6,362.00	60,516.00	285,979.00
ST JOE PAPER CO	283,856.00	1,491,271.00	2,737.00	93,399.00	348,940.00	8,714.00	851,511.00	1,491,271.00
TARKETT INTERNATIONAL GMBH	13,048.00	13,048.00	0.00	12,998.00	12,998.00	50.00	0.00	13,048.00
TEMPLE INLAND INC	4,671,243.00	11,959,260.00	0.00	9,021,256.00	10,259,080.00	61,390.00	1,482,093.00	11,959,260.00
USX CORP	3,180,000.00	17,374,000.00	0.00	3,334,000.00	13,510,000.00	366,000.00	(831,000.00)	17,374,000.00
VALSPAR CORP	197,480.00	336,798.00	11,412.00	113,481.00	140,280.00	13,330.00	223,483.00	336,798.00
WARNER LAMBERT CO	2,218,700.00	4,828,100.00	180,300.00	2,015,900.00	3,438,500.00	160,300.00	2,287,700.00	4,828,100.00
WEST PENN POWER CO	229,283.00	2,544,763.00	11,533.00	184,109.00	1,501,086.00	425,994.00	412,288.00	2,544,763.00
WESTINGHOUSE ELECTRIC CORP	4,774,000.00	10,553,000.00	0.00	3,925,000.00	9,474,000.00	393,000.00	1,401,000.00	10,553,000.00
WESTVACO CORP	609,284.00	3,927,837.00	15,574.00	365,325.00	2,103,849.00	545,166.00	1,294,130.00	3,927,837.00
WITCO CORP	792,573.00	1,838,998.00	0.00	341,338.00	1,125,583.00	254,089.00	488,241.00	1,838,998.00
YORK INTERNATIONAL CORP	702,775.00	1,335,181.00	35,072.00	521,699.00	878,214.00	188.00	36,227.00	1,335,181.00

Table 11-3. Selected Financial Ratios for the Firms in the Sample

COMPANY NAME	QUICK RATIO	CURRENT RATIO	LIABILITY/EQUITY	INCOME/SALES	INCOME/ASSETS	INCOME/EQUITY
ACF INDUSTRIES INC	1.24	1.37	4.37	(0.05)	(0.01)	(0.06)
ALCAN ALUMINIUM LTD	0.86	1.80	1.31	(0.01)	(0.01)	(0.03)
ALCOA INTERNATIONAL HOLDINGS COMPANY	1.33	1.94	1.22	0.07	0.05	0.18
ALLEGHENY LUDLUM CORP	0.99	2.23	1.91	0.06	0.06	0.18
ALLIED SIGNAL INC	0.64	1.31	3.53	0.03	0.04	0.17
ALUMINUM CO OF AMERICA	0.90	1.77	3.10	0.00	0.00	0.00
AMERICAN HOME PRODUCTS CORP	2.28	3.03	0.98	0.18	0.19	0.40
ANGELICA CORP	1.32	3.96	0.73	0.03	0.03	0.06
ARCO CHEMICAL CO	1.01	1.94	1.24	0.07	0.06	0.15
ARMCO INC	0.99	1.77	(4.34)	(0.39)	(0.34)	1.26
ASHLAND OIL INC	0.75	1.22	3.53	0.01	0.03	0.12
AT&T CORP	0.94	1.17	3.49	(0.06)	(0.06)	(0.29)
BEATRICE FOODS INC	0.80	1.20	3.01	0.00	0.00	0.01
BETHLEHEM STEEL CORP	0.80	1.74	7.59	(0.06)	(0.05)	(0.39)
BETZ LABORATORIES INC	1.59	2.27	0.75	0.10	0.13	0.22
BORDEN INC	0.32	0.94	(11.86)	(0.11)	(0.16)	2.40
CABOT CORP	0.84	1.54	2.83	0.01	0.01	0.03
CARBIDE GRAPHITE GROUP INC	0.00	3.14	2.24	0.02	0.03	0.11
CATERPILLAR INC	0.79	1.30	5.73	0.06	0.04	0.30
CHEVRON CORP	0.55	0.82	1.48	0.03	0.04	0.09
CONSOLIDATED CIGAR CORP NEW JERSEY	0.78	3.15	5.26	0.03	0.01	0.09
EXXON CORP	0.46	0.80	1.48	0.05	0.06	0.17
GENCORP INC	0.55	1.26	3.95	0.02	0.04	0.18
GENERAL ELECTRIC CO	1.07	1.09	9.27	0.07	0.02	0.18
GENERAL SIGNAL CORP	0.79	1.82	1.33	0.02	0.03	0.07
GUILFORD MILLS INC	1.56	2.57	1.31	0.04	0.06	0.13
H J HEINZ CO	0.56	1.35	1.73	0.09	0.09	0.26
HANOVER FOODS CORP	0.49	1.44	1.94	0.03	0.05	0.15
HERCULES INC	0.83	1.39	1.31	(0.01)	(0.01)	(0.02)
INDSPEC CHEMICAL CORP	0.71	1.37	36.93	0.00	0.00	0.00

J&L SPECIALTY STEEL INC	0.68	2.11	1.34	0.03	0.03	0.07
KRAFT GENERAL FOODS INC	0.54	1.06	1.32	0.02	0.02	0.05
LTV STEEL CO INC	0.00	1.89	(2.20)	(0.08)	(0.06)	0.07
LUKENS INC	0.78	1.90	2.35	(0.06)	(0.06)	(0.21)
MASLAND CORP	0.84	1.28	2.06	0.05	0.10	0.33
MERCK & CO INC	0.62	0.97	0.99	0.21	0.11	0.24
MINNESOTA MINING & MANUFACTURING	1.00	1.94	0.87	0.09	0.10	0.19
NATIONAL GYPSUM CO	1.99	2.93	(2.18)	(0.15)	(0.09)	0.11
OCCIDENTAL PETROLEUM CORP	0.34	0.94	3.90	0.03	0.02	0.08
PPG INDUSTRIES INC	0.87	1.58	1.29	0.00	0.00	0.01
PROCTER & GAMBLE CO	0.72	1.24	2.42	0.07	0.09	0.32
RHONE POULENC SA	0.60	1.33	3.19	0.01	0.01	0.05
ROHM & HAAS CO	0.91	1.71	1.63	0.03	0.03	0.09
SEARS ROEBUCK & CO	0.38	0.45	9.89	0.05	0.03	0.31
SMITHKLINE BEECHAM PLC	1.04	1.56	2.08	0.13	0.15	0.47
SONOCO PRODUCTS CO	0.93	1.69	1.49	0.06	0.07	0.19
SPS TECHNOLOGIES INC	0.84	2.42	1.78	(0.10)	(0.11)	(0.30)
ST JOE PAPER CO	2.02	3.04	0.53	0.02	0.01	0.02
TARKETT INTERNATIONAL GMBH	0.00	1.00	259.96	0.00	0.00	0.00
TEMPLE INLAND INC	0.35	0.52	6.03	0.04	0.01	0.07
USX CORP	0.36	0.95	3.60	(0.01)	(0.01)	(0.07)
VALSPAR CORP	0.94	1.74	0.71	0.06	0.12	0.20
WARNER LAMBERT CO	0.66	1.10	2.47	0.06	0.07	0.24
WEST PENN POWER CO	0.64	1.25	1.68	0.09	0.04	0.11
WESTINGHOUSE ELECTRIC CORP	0.51	1.22	9.45	(0.04)	(0.03)	(0.33)
WESTVACO CORP	0.77	1.67	1.15	0.04	0.03	0.06
WITCO CORP	1.53	2.32	1.58	0.01	0.01	0.03
YORK INTERNATIONAL CORP	0.64	1.35	1.92	0.00	0.00	0.01

Once the model is determined and estimated the coefficients can be translated to elasticity measures (at the averages), such that for we obtain the sensitivity of firms' income with respect to one percent change in any of the explanatory variables: for instance the coefficient of the tax variable, once converted into an elasticity, will reveal how firms income will respond to a 1% change in taxes.

The net cost of the technological investment is estimated for each particular boiler in the sample; the framework which is developed in Subtasks 4.1 and 4.2 of Phase II is utilized for this task. The net cost is divided by the current income of the firm in order to express the necessary increase in income in percentage points.

Consequently, the ratio of the percentage increase in income -which is necessary to induce the firms to adopt the new technology- to the elasticity of income to explanatory variables (incentives) reveals the amount of percentage change in incentive variables. Next, these percentage increases necessary to induce the desired change are converted into Dollar amounts. The relationship between the induced change in income and the required amount of incentives is expressed as the "rate of return" of the incentive. Similarly, the variance-covariance matrix of estimated coefficients is employed to calculate the "standard deviations" and "correlation matrix" of incentives.

The financial theory of investments is based on the assumption that the essential characteristics of individual investment opportunities and portfolios are captured by information about their expected rate of return and the standard deviation of the return, i.e. the first two moments of the rate of return on the investment. Accordingly, any individual project or combination of projects, i.e. portfolios, can be represented in the "mean-variance (or standard deviation)" space. Modern portfolio theory suggests that individual investment opportunities (or portfolios) can be combined into (further) portfolios. Depending on the risk-return characteristics of the original investment opportunities (portfolios) and their correlation structure, by repeating this process, the investors will end up with a set of portfolios which cannot be dominated by any other combination of portfolios. This set of portfolios is termed as "the efficient frontier" (see Figure 11-1). In the absence of a risk-free investment opportunity, the optimal portfolio of choice for the investors will be determined by their "risk tolerance" and it will be a point which is located on the efficient frontier. If, on the other hand, a risk-free investment alternative is allowed in the model, then portfolio theory suggests that -irrespective of their attitude towards risk- it is in the best interest of all investors to hold a combination of the "market portfolio" (M in Figure 11-1) and the risk-free asset: the market portfolio is simply the point of tangency of a ray to the efficient frontier which originates from the point of risk-free rate of return (RF in Figure 11-1) on the y-axis which measures the return.

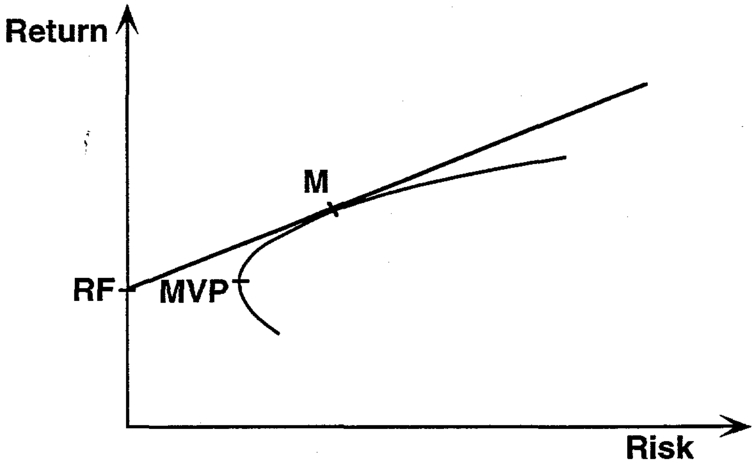

Figure 11-1. EFFICIENT FRONTIER AND THE MARKET PORTFOLIO

Once the incentives can be expressed in their first two moments, i.e. mean and variance, the standard Markowitz mean-variance portfolio analysis can be applied to the present context. Accordingly, one is able to determine: (i) the combination of incentives which would require the least amount of risk-taking possible at the expense of a low return the minimum-variance portfolio, i.e. the minimum-variance portfolio (MVP in Figure 11-1), (ii) the efficient frontier, i.e. the set of combinations of portfolios which stochastically dominate others in terms of their moments, and finally, (iii) given the rate of return on a risk-free investment opportunity (real or financial), one can also calculate the optimal combination of incentives to induce the desired outcome, i.e. point M in Figure 11-1. In other words, the portfolio theory provides a useful decision-making tool in determining the optimal mix of incentives.

The risk-free rate of return in the present context can be understood as the ratio of the increase in firms' revenues (in terms of dollars) per dollar of incentives offered. For example, if the government were to pay *directly* for the costs of technological switch, the amount of increase in firms' revenues (or reduction in their costs) would be exactly equal to the amount of transfer. Thus, in such an event, the risk-free rate of return is simply equal to zero. Clearly, based on familiar welfare-(or profit-) maximization motives, one may suggest that the risk-free rate of return, in our context, ought to be set at a positive rate by the government. On the other hand, if there are significant positive externalities attached to the project, even moderate negative returns may be acceptable from the point of welfare maximization, and the government. In this study we take the conservative approach and consider only non-negative risk-free rates of return, e.g. 0%, 3% and 5%.

11.2.4 Empirical Results

As suggested in the previous section, as the first step a stepwise regression equation is estimated in order to determine the correct model to be estimated. For this purpose *all* of the available RHS (right-hand-side) candidates are entered into the model and they are held subject to sequential elimination where P (significance level) is set at 0.20. Out of the entire set of variables the following succeeded to remain in the model: cost of goods sold (COGS), research and development expenses (RDEXP), fixed costs (FIXED), depreciation allowances (DEPR), taxes (TAX), and measure of operating leverage (MOL).

After determining the estimation model is determined, the regression equation is estimated by the method developed in Newey-West[24]. The results of the estimation and the calculated elasticities are reported in Table 11-4: the estimated equation has an R^2 of 0.80 and an adjusted R^2 of 0.76.

Table 11-4. Results of the Regression Equation

Variables	Coefficients	Elasticity	Absolute t-statistics
COGS	-0.0638	-1.1731	3.08
RDEXP	-1.9589	-0.8002	4.14
FIXED	0.0368	0.35265	5.09
DEPR	0.3344	0.20273	2.58
TAX	-2.4695	-1.9847	4.88
MOL	-33923.0837	-	3.06
Constant	273296.7198	-	3.02

Next, the magnitude of costs is calculated which is necessary to induce the desired technological change for each of the boilers in the sample (some firms have multi-boiler sites) using the framework which was developed in Subtasks 4.1 and 4.2 of Phase II. The results about boiler-size, required capital costs and operating and maintenance costs are summarized in Table 11-5.

The firms in sample have boilers of an average size of 54.41 million Btu and total size of 8,868.48 million Btu. The capital costs of retrofitting for all boilers is estimated to be $281,377,853; the operation and maintenance costs(+) / benefits(-) are estimated to be -$31,777,771, which is due to fuel savings. Thus, the total cost of retrofitting all of the boilers in the sample amounts to $249,600,081.

The boiler-specific cost figures are expressed as percentages of firms' net income. This represents the amount which needs to be induced by means of government incentives. We combine this desired increase in firms' income with the calculated elasticities (Table 11-4) -which measure the sensitivity of firms' net income to a one percent change in the value of incentives- to obtain the Dollar amounts of each of the incentives required to generate the desired outcome. The findings are presented in Table 11-6.

The results of the stepwise regression estimation, Tables 11-4 and 11-6 can be summarized as follows: firstly, the findings show that the relationship between interest payments and firms' net incomes are not statistically significant. This result indicates that interest rate-related government incentives, such a reduced or zero-interest loan, will not necessarily induce the desired increase in net income needed for technology adoption.

On the other hand, it is observed that the net income of firms in sample are responsive to fluctuations in the cost of goods sold, the amount paid for research and development expenses, depreciation allowances, and taxes. Finally, Table 11-6 presents the estimated dollar amounts of change needed to induce the desired increase in firms' income, $249,600,081, to induce them to undertake the technological investment at each and every boiler site in the sample. Accordingly, declines in the cost of goods sold, research and development expenses, and tax burdens by $3,912,226,000, $127,418,400 and $101,073,100, respectively and an increase in their depreciation allowances by $746,411,720 will induce an increase in their profits by the targeted amount.

In Table 11-6 the necessary changes are also expressed in terms of "rate of return" in order to obtain an understanding about their effectiveness: this is simply achieved by taking the ratio of the target change in income to the required change in the aforementioned factors and subtracting one from it. Clearly, this approach assumes that there are no externalities (one way or another) attached with any of the incentives under consideration and hence, the "return" of the incentive is measured as the monetary increase in firms'

Table 11-5. Boiler-Specific Costs

Company Name	Boiler Size	Capital Costs	O&M Costs	TOTAL
ACF INDUSTRIES INC	50.0	1,677,521	(175,516)	1,502,005
ALCAN ALUMINUM LTD	5.0	298,310	(12,329)	285,981
ALCOA INTERNATIONAL HOLDINGS COMPANY	60.0	1,923,330	(214,207)	1,709,123
ALCOA INTERNATIONAL HOLDINGS COMPANY	60.0	1,923,330	(214,207)	1,709,123
ALCOA INTERNATIONAL HOLDINGS COMPANY	40.0	1,419,010	(137,333)	1,281,677
ALCOA INTERNATIONAL HOLDINGS COMPANY	40.0	1,419,010	(137,333)	1,281,677
ALLEGHENY LUDLUM CORP	50.0	1,677,521	(175,516)	1,502,005
ALLEGHENY LUDLUM CORP	50.0	1,677,521	(175,516)	1,502,005
ALLEGHENY LUDLUM CORP	36.0	1,311,195	(122,236)	1,188,959
ALLIED SIGNAL INC	60.0	1,923,330	(214,207)	1,709,123
AMERICAN HOME PRODUCTS CORP	20.0	843,748	(63,297)	780,452
AMERICAN HOME PRODUCTS CORP	27.6	1,074,292	(90,953)	983,339
AMERICAN HOME PRODUCTS CORP	125.0	3,335,208	(473,134)	2,862,074
AMERICAN HOME PRODUCTS CORP	125.0	3,335,208	(473,134)	2,862,074
ANGELICA CORP	20.0	843,748	(63,297)	780,452
ARCO CHEMICAL COMPANY	27.6	1,074,292	(90,953)	983,339
ARCO CHEMICAL COMPANY	27.6	1,074,292	(90,953)	983,339
ARMCO INC	30.0	1,143,619	(99,825)	1,043,794
ARMCO INC	30.0	1,143,619	(99,825)	1,043,794
ASHLAND OIL INC	17.0	746,925	(52,613)	694,313
ASHLAND OIL INC	23.0	936,993	(74,124)	862,869
AT&T CORP	60.0	1,923,330	(214,207)	1,709,123
AT&T CORP	60.0	1,923,330	(214,207)	1,709,123
AT&T CORP	30.0	1,143,619	(99,825)	1,043,794
AT&T CORP	60.0	1,923,330	(214,207)	1,709,123
BEATRICE FOODS INC	24.0	967,384	(77,761)	889,623
BEATRICE FOODS INC	24.0	967,384	(77,761)	889,623
BETHLEHEM STEEL CORP	16.0	713,724	(49,088)	664,636
BETHLEHEM STEEL CORP	16.0	713,724	(49,088)	664,636
BETHLEHEM STEEL CORP	16.0	713,724	(49,088)	664,636
BETHLEHEM STEEL CORP	30.0	1,143,619	(99,825)	1,043,794
BETHLEHEM STEEL CORP	30.0	1,143,619	(99,825)	1,043,794
BETHLEHEM STEEL CORP	100.0	2,821,243	(372,384)	2,448,859
BETZ LABORATORIES INC	40.0	1,419,010	(137,333)	1,281,677
BORDEN INC	10.0	501,696	(28,456)	473,240
BORDEN INC	10.0	501,696	(28,456)	473,240
BORDEN INC	25.0	997,460	(81,410)	916,050
CABOT CORP	30.0	1,143,619	(99,825)	1,043,794
CABOT CORP	30.0	1,143,619	(99,825)	1,043,794
CARBON GRAPHITE GROUP INC	50.0	1,677,521	(175,516)	1,502,005
CARBON GRAPHITE GROUP INC	50.0	1,677,521	(175,516)	1,502,005
CATERPILLAR INC	40.0	1,419,010	(137,333)	1,281,677
CHEVRON CORP	25.0	997,460	(81,410)	916,050
CHEVRON CORP	25.0	997,460	(81,410)	916,050
CONSOLIDATED CIGAR CORP NEW JERSEY	150.0	3,823,921	(574,894)	3,249,027
CONSOLIDATED CIGAR CORP NEW JERSEY	150.0	3,823,921	(574,894)	3,249,027
EXXON CORP	35.0	1,283,783	(118,481)	1,165,302
EXXON CORP	35.0	1,283,783	(118,481)	1,165,302
GENCORP INC	60.0	1,923,330	(214,207)	1,709,123
GENCORP INC	60.0	1,923,330	(214,207)	1,709,123

GENERAL ELECTRIC COMPANY	8.5	444,124	(23,480)	420,645
GENERAL ELECTRIC COMPANY	150.0	3,823,921	(574,894)	3,249,027
GENERAL ELECTRIC COMPANY	150.0	3,823,921	(574,894)	3,249,027
GENERAL SIGNAL CORP	30.0	1,143,619	(99,825)	1,043,794
GENERAL SIGNAL CORP	30.0	1,143,619	(99,825)	1,043,794
GUILFORD MILLS INC	5.0	298,650	(12,353)	286,297
GUILFORD MILLS INC	12.0	575,210	(35,220)	539,990
GUILFORD MILLS INC	35.0	1,283,783	(118,481)	1,165,302
H J HEINZ COMPANY	44.0	1,524,158	(152,537)	1,371,621
H J HEINZ COMPANY	44.0	1,524,158	(152,537)	1,371,621
H J HEINZ COMPANY	40.0	1,419,010	(137,333)	1,281,677
H J HEINZ COMPANY	150.0	3,823,921	(574,894)	3,249,027
HANOVER FOODS CORP	34.0	1,256,174	(114,733)	1,141,441
HANOVER FOODS CORP	34.0	1,256,174	(114,733)	1,141,441
HERCULES INC	12.0	575,210	(35,220)	539,990
HERCULES INC	12.0	575,210	(35,220)	539,990
INDSPEC CHEMICAL CORP	40.0	1,419,010	(137,333)	1,281,677
INDSPEC CHEMICAL CORP	40.0	1,419,010	(137,333)	1,281,677
INDSPEC CHEMICAL CORP	50.0	1,677,521	(175,516)	1,502,005
INDSPEC CHEMICAL CORP	50.0	1,677,521	(175,516)	1,502,005
INDSPEC CHEMICAL CORP	100.0	2,821,243	(372,384)	2,448,859
INDSPEC CHEMICAL CORP	150.0	3,823,921	(574,894)	3,249,027
J&L SPECIALTY STEEL INC	40.0	1,419,010	(137,333)	1,281,677
KRAFT GENERAL FOODS INC	50.0	1,677,521	(175,516)	1,502,005
LTV STEEL CO INC	60.0	1,923,330	(214,207)	1,709,123
LTV STEEL CO INC	77.5	2,330,326	(282,843)	2,047,483
LTV STEEL CO INC	77.5	2,330,326	(282,843)	2,047,483
LTV STEEL CO INC	77.5	2,330,326	(282,843)	2,047,483
LTV STEEL CO INC	80.0	2,386,481	(292,728)	2,093,753
LTV STEEL CO INC	80.0	2,386,481	(292,728)	2,093,753
LUKENS INC	18.0	779,641	(56,156)	723,485
LUKENS INC	18.0	779,641	(56,156)	723,485
LUKENS INC	47.5	1,614,212	(165,918)	1,448,295
LUKENS INC	47.5	1,614,212	(165,918)	1,448,295
MACK TRUCKS	55.0	1,801,824	(194,806)	1,607,019
MACK TRUCKS INC	55.0	1,801,824	(194,806)	1,607,019
MACK TRUCKS INC	55.0	1,801,824	(194,806)	1,607,019
MACK TRUCKS INC	55.0	1,801,824	(194,806)	1,607,019
MASLAND CORP	75.0	2,273,717	(272,977)	2,000,740
MASLAND CORP	60.0	1,923,330	(214,207)	1,709,123
MERCK & COMPANY INC	80.0	2,386,481	(292,728)	2,093,753
MERCK & COMPANY INC	80.0	2,386,481	(292,728)	2,093,753
MERCK & COMPANY INC	80.0	2,386,481	(292,728)	2,093,753
MINNESOTA MINING & MANUFACTURING	45.0	1,550,065	(156,353)	1,393,712
NATIONAL GYPSUM CO	53.0	1,752,457	(187,076)	1,565,381
OCCIDENTAL PETROLEUM CORP	60.0	1,923,330	(214,207)	1,709,123
OCCIDENTAL PETROLEUM CORP	100.0	2,821,243	(372,384)	2,448,859
OCCIDENTAL PETROLEUM CORP	100.0	2,821,243	(372,384)	2,448,859
OCCIDENTAL PETROLEUM CORP	100.0	2,821,243	(372,384)	2,448,859
PPG INDUSTRIES INC	40.0	1,419,010	(137,333)	1,281,677
PPG INDUSTRIES INC	50.0	1,677,521	(175,516)	1,502,005
PPG INDUSTRIES INC	50.0	1,677,521	(175,516)	1,502,005
PPG INDUSTRIES INC	125.0	3,335,208	(473,134)	2,862,074
PROCTER & GAMBLE CO	99.0	2,800,057	(368,379)	2,431,678
PROCTER & GAMBLE CO	99.0	2,800,057	(368,379)	2,431,678
RHONE POULENC SA	50.0	1,677,521	(175,516)	1,502,005
RHONE POULENC SA	50.0	1,677,521	(175,516)	1,502,005

RHONE POULENC SA	50.0	1,677,521	(175,516)	1,502,005
RHONE POULENC SA	50.0	1,677,521	(175,516)	1,502,005
RHONE POULENC SA	50.0	1,677,521	(175,516)	1,502,005
RHONE POULENC SA	50.0	1,677,521	(175,516)	1,502,005
ROHM & HAAS COMPANY	30.0	1,143,619	(99,825)	1,043,794
ROHM & HAAS COMPANY	30.0	1,143,619	(99,825)	1,043,794
ROHM & HAAS COMPANY	30.0	1,143,619	(99,825)	1,043,794
ROHM & HAAS COMPANY	110.0	3,030,296	(412,545)	2,617,750
ROHM & HAAS COMPANY	110.0	3,030,296	(412,545)	2,617,750
ROHM & HAAS COMPANY	125.0	3,335,208	(473,134)	2,862,074
ROHM & HAAS COMPANY	125.0	3,335,208	(473,134)	2,862,074
ROHM & HAAS COMPANY	125.0	3,335,208	(473,134)	2,862,074
ROHM & HAAS COMPANY	125.0	3,335,208	(473,134)	2,862,074
ROHM & HAAS COMPANY	125.0	3,335,208	(473,134)	2,862,074
SEARS ROEBUCK & CO	40.0	1,419,010	(137,333)	1,281,677
SEARS ROEBUCK & CO	40.0	1,419,010	(137,333)	1,281,677
SEARS ROEBUCK & CO	40.0	1,419,010	(137,333)	1,281,677
SEARS ROEBUCK & CO	40.0	1,419,010	(137,333)	1,281,677
SMITHKLINE BEECHAM PLC	40.0	1,419,010	(137,333)	1,281,677
SONOCO PRODUCTS COMPANY	80.0	2,386,481	(292,728)	2,093,753
SPS TECHNOLOGIES INC	55.0	1,801,824	(194,806)	1,607,019
SPS TECHNOLOGIES INC	55.0	1,801,824	(194,806)	1,607,019
ST JOE PAPER CO	40.0	1,419,010	(137,333)	1,281,677
ST JOE PAPER CO	40.0	1,419,010	(137,333)	1,281,677
TARKETT INTERNATIONAL GMBH	75.0	2,273,717	(272,977)	2,000,740
TEMPLE INLAND INC	40.0	1,419,010	(137,333)	1,281,677
USX CORP	8.6	449,014	(23,891)	425,123
USX CORP	50.0	1,677,521	(175,516)	1,502,005
USX CORP	50.0	1,677,521	(175,516)	1,502,005
USX CORP	56.0	1,826,339	(198,677)	1,627,662
USX CORP	56.0	1,826,339	(198,677)	1,627,662
USX CORP	60.0	1,923,330	(214,207)	1,709,123
VALSPAR CORP	20.7	865,801	(65,811)	799,990
WARNER LAMBERT COMPANY	27.0	1,056,728	(88,744)	967,984
WARNER LAMBERT COMPANY	30.0	1,143,619	(99,825)	1,043,794
WARNER LAMBERT COMPANY	30.0	1,143,619	(99,825)	1,043,794
WEST PENN POWER COMPANY	32.0	1,200,336	(107,261)	1,093,075
WEST PENN POWER COMPANY	32.0	1,200,336	(107,261)	1,093,075
WESTINGHOUSE ELECTRIC CORP	10.3	514,809	(29,629)	485,179
WESTINGHOUSE ELECTRIC CORP	80.0	2,386,481	(292,728)	2,093,753
WESTINGHOUSE ELECTRIC CORP	20.0	843,748	(63,297)	780,452
WESTINGHOUSE ELECTRIC CORP	20.0	843,748	(63,297)	780,452
WESTINGHOUSE ELECTRIC CORP	20.0	843,748	(63,297)	780,452
WESTVACO CORP	85.0	2,497,495	(312,549)	2,184,946
WESTVACO CORP	85.0	2,497,495	(312,549)	2,184,946
WITCO CORP	50.0	1,677,521	(175,516)	1,502,005
WITCO CORP	50.0	1,677,521	(175,516)	1,502,005
WITCO CORP	60.0	1,923,330	(214,207)	1,709,123
WITCO CORP	60.0	1,923,330	(214,207)	1,709,123
WITCO CORP	60.0	1,923,330	(214,207)	1,709,123
WITCO CORP	65.0	2,042,328	(233,709)	1,808,619
WITCO CORP	65.0	2,042,328	(233,709)	1,808,619
WITCO CORP	75.0	2,273,717	(272,977)	2,000,740
WITCO CORP	90.0	2,606,888	(332,435)	2,274,453
YORK INTERNATIONAL CORP	30.0	1,143,619	(99,825)	1,043,794
YORK INTERNATIONAL CORP	46.0	1,575,828	(160,174)	1,415,654
			SUM =	$ 249,600,082
			AVERAGE =	$ 1,531,289

Table 11-6. Factors and their Effectiveness

Incentive	Amount Needed	Standard Deviation	Rate of Return
Cogs (VAT)	$ 3,912,226,000	2.1%	-93.62%
R&D Subsidy	$ 127,418,400	47.4%	95.9%
Depr.Allowance	$ 746,411,720	13.0%	-66.6%
Tax Cut	$ 101,073,100	50.5%	+146.95%

profits. The results are striking: it turns out that only tax cuts and reductions in research and development expenses provide positive returns. Magnitudes of required changes in cost of goods sold and depreciation allowances exceed the 'benefits', i.e. the increase in firms' profits by a significant amount.

Thus, if one were to choose only one investment, for some reason, the best candidates seem to be tax cuts and subsidies which are specifically aimed at covering research and development expenses. As the empirical findings indicate, in the case of the firms under investigation, interest-related incentives, such as reduced or no-interest loans will not generate the desired outcome. On the other hand, an incentive which will reduce the cost of goods sold or to increase the depreciation allowance is statistically significant on firms' profits, and thus present feasible alternatives. However, analyzing their effectiveness yields the result that they are inferior when compared with the other two alternatives: tax cuts and subsidies extended for research and development.

Nevertheless, someone who is familiar with the benefits of portfolio analysis may wonder whether a combination of these alternatives can yield a superior result. To explore possible benefits from portfolio analysis the reported rates of return (Table 11-7) their volatilities - which are based on the standard errors of estimated coefficients - and the correlation matrix of estimated parameters are utilized to perform a standard, Markowitz type, portfolio analysis.

In the case of two out of the four factors under scrutiny it is relatively obvious how they are linked to a government incentive scheme: depreciation allowances and taxes. It is straightforward to see that an increase in depreciation allowances or a decrease in tax rates works as an incentive for firms. The other two are less obvious: cost of goods sold and research and development taxes. The government can affect the cost of goods sold by means a subsidy/tax which depends on the sales volume. A good example for this scheme is the value-added tax (VAT). An incentive, in the current context, can simply be thought as a negative VAT. Similarly, an incentive through research and development expenses can be imagined as a specific government subsidy which is meant to cover a portion or the entire amount of firm's research and development expenses.

One may argue that introduction of a (negative) VAT-like schedule would require institutional changes, and thus, in the short- to middle-run its feasibility is questionable. Keeping this potential criticism in regard, we simulated the portfolios with and without the COGS (cost of goods sold) variable to account for both possible states of the world.

Portfolio return and volatility calculations are performed assuming a wide range of rate of return which varies between 0 and 100 percent. In addition, the characteristics of the minimum variance portfolio are calculated, for both sets of portfolios. Furthermore, the

Table 11-7. The Correlation Matrix of Estimated Coefficients

	RDEXP	DEPR	TAX
VAT(Subsidy)	0.08	-0.28	0.85
R&D Subsidy	1.00	-0.22	0.22
Depr. Allowance	-0.22	1.00	0.08
Tax Cut	0.22	0.08	1.00

tangent of the straight line (ray) originating from the locus of the risk-free return, i.e. the market rate of return, is calculated, as well. According to the theory this is the portfolio that investors of all types of risk aversion would hold to maximize their expected utility.

The results of the portfolio simulations with COGS variable and without it are presented in Tables 11-8 and 11-9, respectively.

These tables (11-8 and 11-9) analyze eleven portfolios based on their return and risk characteristics. The MVP portfolio, in both tables, refers to the minimum-variance portfolio, i.e. the combination of risky assets which generates the portfolio with lowest possible level of riskiness. Portfolios 1-10 stand for portfolios with expected rates of returns varying between 0%, Portfolio 1, and 100%, Portfolio 10. All of the entries are in terms of percentages, and the figures next to the variables simply indicate their portfolio weights. For example, according to Table 11-8, in order to establish an incentive portfolio which generates a rate of return of 0%, the value added tax (subsidy) should have a weight of 7%, research and development subsidies should have a weight of 19.8%, depreciation allowances 56.3% and finally tax incentives 17%: this is a particular mix of risky incentives which are combined into a portfolio which offers exactly a zero percent rate of return, just as a direct subsidy would which is offered to the firm which reimburses all of the costs (of the switch) directly.

A comparison of the results presented in the two tables yields that the risk-return relationship for portfolios 1-10 is not significantly different from each other: for a given rate of return the portfolio volatility seems to be very similar.

In Table 11-8 it is observed that the weights of research and development subsidies and taxes increase as the resulting portfolios allow for more riskiness. The risk is controlled by the combination of VAT(subsidy) and depreciation allowances. It is interesting to note that after a certain level of riskiness the weight of VAT(subsidy) becomes negative, i.e. it suggests that after a certain level of riskiness it is beneficial from a portfolio analysis point of view for the government to introduce a positive value-added tax, which is to be compensated by the increase of depreciation allowances.

In Table 11-9, which excludes the cost of goods (COGS) variable, it is observed that as the expected rate of return increases the research and development subsidies and tax incentives move in opposite directions: the weight of taxes increases and the other one decreases. Depreciation allowances, which counterbalances the other two in riskiness, loses its importance in the portfolio as we allow for more riskiness; its weight becomes larger for portfolios which are exposed to a lesser degree of uncertainty.

Having calculated the risk-return relationships, and weights of each incentive in different portfolio mixes, the next relevant question to focus on is about the location of the

Table 11-8. Risk and Return of Various Portfolios (with COGS)

	MVP	1	2	3	4	5	6	7	8	9	10
VAT	96.2	7	4.2	2.4	-2.1	-11.1	-20.1	-29.1	-38.2	-60.7	-83.3
R&D	1	19.8	20.3	20.7	21.7	23.6	25.5	27.4	29.3	34	38.8
DEPR	6.5	56.3	57.8	58.8	61.3	66.3	71.3	76.4	81.4	94	106.5
TAX	-3.7	17	17.7	18.1	19.1	21.2	23.3	25.4	27.5	32.7	38
Return	-98.9	0	3	5	10	20	30	40	50	75	100
Risk	0.6	15.2	15.7	16	16.8	18.3	19.8	21.4	22.9	26.8	30.6

Table 11-9. Risk and Return of Various Portfolios (without COGS)

	MVP	1	2	3	4	5	6	7	8	9	10
R&D	11.1	19.7	20.3	20.7	21.6	23.5	25.4	27.3	29.1	33.8	38.5
DEPR	87.8	64.1	62.6	61.5	59.0	53.8	48.7	43.6	38.4	25.6	12.8
TAX	1.1	16.1	17.1	17.8	19.4	22.7	25.9	29.2	32.4	40.6	48.7
Return	-46.1	0	3	5	10	20	30	40	50	75	100
Risk	11.5	15.3	15.7	16	16.7	18.4	20.1	21.9	23.8	28.6	33.6

"market portfolio". Recalling from earlier sections, in the presence of a risk-free rate of return, the risk-free rate and the market portfolio span the so-called "capital-market line" which is the locus of efficient and dominant portfolios in the market; accordingly any position on the capital-market line can be achieved by combining the risky market portfolio and the risk-free security.

Under the presumption that the government can with 100% probability achieve its goal of spreading the commercial usage of the new technology by extending direct subsidies, which cover all of the required switching costs, to firms which are willing to undertake the necessary technological investment, the direct subsidy incentive can be regarded as a no-risk, i.e. *risk-free* incentive alternative. Hence, we introduce direct subsidies to the analysis as the risk-free security and solve for the point of tangency to find the market portfolio. In both scenarios, i.e. with and without the COGS variable (Table 11-8 and 11-9, respectively), the optimal tangency portfolio coincides with a portfolio which is formed 100% by the tax incentive.

Furthermore, in order to account for values which are not accounted for by the standard discounted cash flow analysis, such as externalities, option values, and so forth, the rate of return for the risk-free incentive for -3% and -5% is set and the optimal market portfolio is solved under these assumptions. The results, once again depict the 100% tax incentive portfolio as the optimal market portfolio.

In other words, provided that the direct subsidies can be viewed as risk-free, i.e. the government is 100% confident that it can initiate any marginal technological investment behavior in the industry by undertaking all of the necessary cost by its own if it chooses to do so, it is in government's, and all taxpayers' best interest to offer government incentives in the form of tax cuts, only. Furthermore, even if the risk-free incentive, i.e. direct subsidies generate a subzero rate of return, due to externalities, or some other reasons, the result of the analysis remain unaffected: the 100% tax incentive emerges as the optimal portfolio incentive. In sum, the preceding analysis clearly shows that the tax incentives are the most effective incentives the government can offer to induce increases in firms' profits and thus to induce them to adopt the desired technological changes.

11.2.5 Conclusion

This subtask starts from the premise that there are social, political and economic benefits (in market and non-market value) which can be gained by the widespread adoption and commercialization of the new coal-based technology. As some of the previous subtasks have indicated the success, i.e. the adoption, of the new technology will most likely be achieved through measures which reduce capital costs and not through serendipitous changes in oil price alone. Thus, the previous findings can be interpreted as if to indicate that even though the adoption of the new technology may have macroeconomic advantages for the economy, at the microeconomic level, i.e. at the firm level, additional incentives may be needed to induce such an adoption.

Economic and financial incentives have become accepted tools for the implementation for preferred government policies. Typical examples range from investment tax credits, and reduced or zero-interest loans to capital subsidies and direct and indirect (such as accelerated depreciation) tax incentives. The existing studies on the effectiveness of policy incentives, on average, remain highly macroeconomics oriented and have little to say about the consequences in a given sector in the economy.

This study focuses on the microeconomic responses generated by the firms to the incentives. In this subtask we examine firm-specific data about firms which have a potential use for the new technology. The optimal incentive and policy mixes are determined based on empirical estimation of firms' reactions to various factors. It needs to be emphasized that one incentive may be optimal with projects with characteristic "A", whereas another may be more suitable if the project has characteristic "B": for example, tax incentives can be thought to be more effective on projects which require a big initial capital outlay, whereas, reduced or zero-loan incentives may prove to be more useful in the case of projects which are highly sensitive to interest rate fluctuations in the market.

The adoption of the new technology can be viewed as an "investment" in the new technology and thus, tools of modern finance and portfolio theory can be applied to the problem at hand. First, the sensitivity of firms' net income to various factors are estimated. The required increases in firms' income is estimated by adopting a framework developed by Subtasks 4.1 and 4.2. It turns out that, the cost of technology adoption -net of fuel savings benefits- is $ 249,600,082 for all 163 boilers in the sample (or $1,531,289, on average). Consequently, based on the sensitivities, which are expressed in terms of percentage responses to induce a one percent change in income, and the required change in income, the dollar amounts a set of incentives are calculated which are needed to generate the desired outcome. Accordingly, a decline in the cost of goods sold by $ 3,912,226,000, $ 127,418,400 in research and development expenses, $ 101,073,100 in firms' tax burden, or an increase of $ 746,411,720 in firms' depreciation allowances induce the desired increase in the net income of the firms in the sample.

Recognizing that incentives, on average, do not induce the desired outcome with 100% certainty, the benefits of offering the incentives as a portfolio rather than individually are investigated. The effectiveness of incentives is expressed in terms of their rate of return and riskiness. Consequently, the composition of optimal portfolios are calculated for several rates of return ranging from 0-100% and for the minimum risk portfolio. The results are estimated for two different cases: with and without cost-of-goods (COGS) as an incentive variable. Noting that the government can affect the cost of goods sold by imposing a value-added tax or subsidy, one may argue that COGS can be viewed as a possible incentive variable: Table 11-8 presents the optimal portfolios for this case. On the other hand, the introduction of a value-added tax/subsidy scheme can be viewed as technically difficult in the short to medium-term. Thus, alternatively, another set of optimal portfolios are calculated for the same set of returns, excluding the COGS variable (Table 11-9).

It appears that the risk-return relationship is not significantly altered by the inclusion/exclusion of that variable. Both tables reveal the result that for low risk-low return portfolios depreciation incentive has a significant weight in both portfolios; its weight decreases as the portfolios become riskier. In contrast, tax and research & development expense incentives appear to have lower weight for low-risk portfolios, which increases gradually as portfolios are aimed at higher return. In addition, an interesting finding of the analysis is that the firms in the sample are not sensitive to interest-rate based incentives, such as a reduced or zero-rate loan.

Finally, given a risk-free investment opportunity in the economy the 'market portfolio' can be estimated; by theory this is the only risky portfolio, which will be held by all investors, irrespective of their attitude towards risk. If one makes the assumption that direct capital subsidies -which cover the full cost of the technological investment- are literally risk-free in achieving the desired changes, it can be incorporated to the model to estimate the market portfolio which dominates all other risky portfolios in the existence of a risk-free investment opportunity. The direct capital subsidies, by definition, offer a rate of return of 0%. However, to account for externalities and so forth which are not incorporated in the analysis directly. Two negative rates of return of -3% and -5% are allowed for on the risk-free alternative. Notably, the point of tangency in all three cases happens to be a portfolio which consists of only the tax incentive, i.e. the weight of the tax incentive is 100%. This result shows that in the existence of a no-risk opportunity, the tax incentive is the best alternative to offer to the industry to induce an increase in their profits.

It should be added that a precise answer about the *best* incentive portfolio varies depending on the shape of government's indifference curves, which depict information about how the risk-return tradeoff is viewed by the government at various levels of returns. The *best* portfolio is determined simply at the point of tangency between the indifference curves and the efficient frontier which is formed by the combination of the risk-free investment alternative and the market portfolio (or just by the locus of efficient risky portfolios in the absence of a risk-free alternative). Thus, for the selection of the best suitable incentive mix, the findings and results provided by this study will provide valuable insights to the policy makers.

11.3 Subtask 5.3 Community Sensitivity to Coal Fuel Usage

Work accomplished to date includes:

- Conducted preliminary research of current and proposed energy generation facilities, including facilities that were approved for development and projects that were stopped during the permitting process.
- Examined prior work on formation and characterization of subjective risk perceptions and methods for valuation of reductions in risk levels.
- Met with electric power industry executives to learn how electric power utilities and non-utilities identify sites for proposed facilities and how the industry disseminates information to the public regarding proposed facilities.
- Conducted focus groups identifying issues regarding energy generation relevant to lay persons.
    - Impacts identified by participants were categorized into four primary components:
      environmental, economic, aesthetic, and human health impacts.
    - Whether or not an individual's home is "100% electric" influences participants' perception of the need for fossil-fired facilities and for additional capacity, in general.
    - The majority of participants failed to "make the connection" between demand for electricity and the need for fossil-fired electricity generation.
- Designed a preliminary risk perception/contingent valuation survey based upon the focus group discussions and background research. Conducted focus groups, cognitive interviews, and verbal protocols to pretest the first survey draft. Issues that were addressed include:
    - What information changes or influences preexisting perceptions.
    - Respondents' interpretation of key words in the survey such as "risk," "impact," "concern," "likelihood," and "satisfied."
    - Experimented with question formats, such as psychometric scales, to derive quantitative judgments of risk attributes.
    - Tested valuation questions to elicit option prices [WTP/WTA] for data analysis.
- Modeled expected utility framework to develop consistency between economic and psychological theories of risk and uncertainty.

During this reporting period, steady progress has been made on the Community Sensitivity to Coal Fuel Usage component of Phase III. The examination is focusing on the issues of community risk perceptions and responses to planned non-utility generators. These facilities can entail a variety of fuel types which will allow us to examine specific sensitivity to coal versus other fuel types (e.g. oil, natural gas). The primary emphasis has been on developing a contingent valuation survey instrument to measure layperson risk perceptions and how these relate to welfare impacts from different fuel choices. A theoretical model has been developed which will serve as the basis for the data analysis and measurement of welfare impacts. This is included in Appendix A. The following sessions are planned for completing the survey design and implementation:

March 25 - State College - eight subjects in two focus groups to test survey design. This instrument will incorporate all of the components expected to be included in the final survey design.

March 28 and 29 - State College - Four subjects in one-on-one or verbal protocols. These sessions will examine individual's comprehension of the material simulating an actual survey administration.

April 8 - Williamsport - Twenty subjects in three focus groups to examine issues of market size and commodity timing in the survey design. Issues examined here will be considered for incorporation into variants for the final survey design.

April 19 - Altoona - Verbal protocols. Examining revisions of the March 28 survey instrument including possible variants developed based on the Williamsport focus groups.

May 10th - Harrisburg - Survey implementation - 180 subjects (total number of subjects is undetermined at this time and depends on the costs of hiring a firm to recruit subjects and provide a location for survey implementation).

May 10 - June 16 - Data analysis and report writing.

Anticipated completion date: June 16

The data analysis will provide an econometric model of individual willingness to pay as a function of socio-demographic characteristics and of self-reported measures of perceptions of risk. These risk measures will quantify individual's perceptions of the severity, likelihood, and marginal utility associated with environmental, human health, aesthetic/amenity, and economic impacts of energy facilities burning coal.

11.4 Subtask 5.4 Regional Economic Impacts of New Coal Utilization Technologies

No work was conducted in Subtask 5.4.

11.5 Subtask 5.5 Economic Analysis of the Defense Department's Fuel Mix

Subtask 5.5 was previously completed.

11.6 Subtask 5.6 Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects

No work was conducted in Subtask 5.6.

11.7 Subtask 5.7 Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies

Subtask 5.7 was previously completed.

11.8 Subtask 5.8 Integrate the Analysis

Work is continuing in the integration of the analyses.

12.0 PHASE III, TASK 6 FINAL REPORT/SUBMISSION OF DESIGN PACKAGE

No work was conducted on this task.

13.0 MISCELLANEOUS ACTIVITIES

A program review meeting was held at DOE, Pittsburgh Energy Technology Center on January 18, 1996. The meeting primarily focused on discussing the Phase I conclusions, with status reports of Phases II and III given.

14.0 NEXT SEMIANNUAL ACTIVITIES

During the next reporting period, the following will be done:

- Finalize the design for the ceramic filter system;
- Install the ceramic filter system;
- Conduct NO_x catalyst tests;
- Procure Method 5 apparatus and auxiliaries;
- Begin VOC and trace elements studies;
- Prepare the final report for Phase II, Task 2, Coal Preparation/Utilization; (except for the atomization testing in Subtask 2.10);
- Prepare coal-water slurry fuels for Carnegie Mellon University;
- Prepare the final report for Phase II, Task 3, Economic Analysis;
- Complete Phase III, Task 1, Coal Preparation/Utilization; and
- Complete Phase III, Task 5, Economic Analysis.

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APPENDIX A. Linking Subjective Perceptions and Valuation: The Expected Utility Framework

APPENDIX A.

Linking Subjective Perceptions and Valuation: The Expected Utility Framework

Perceived attributes of a risk can be modeled in an expected utility function when an individual faces risky or uncertain future states of the world. Subjective judgments of the probabilities and consequences of a risk are based on four aspects of risk exposure:

1) the individual's familiarity, prior experience, and knowledge of the risk and its consequences,
2) the level of dread the individual associates with exposure to risk,
3) the perceived severity of the risk consequences, and
4) the perceived exposure to the risk in the future period.

These four aspects of an exposure to risk can be combined and are compatible with economic models of expected utility with subjective probabilities. Because the perceived risk attributes enter into the individual's utility function, they necessarily become partial determinants of an individual's marginal WTP/WTA for a change in the risk level exposure. This research is specifically interested in the lay person's *ex ante* marginal willingness to pay to decrease or completely eliminate a particular risk level as a function of that individual's perceptions of the risk's characteristics.[1]

Assume a scenario where individuals are faced with a choice between two power generation projects, a coal (C) fired plant and a natural gas (NG) fired plant. Regardless of fuel choice, an electric power plant will be built, so no uncertainty about a plant's presence exists, *ex ante*. However, because individuals do not know, *ex ante*, either the severity or the probability of risk consequences of the fuel choice, they rely on their subjective perceptions to make utility maximizing decisions. Subjective judgments of the probabilities are assumed to be conditional upon the individual's familiarity and knowledge of the risk and its consequences.[2]

Any actual state of the world is an *ex post* realization of some combination of environmental, human health, and aesthetic/amenity risk components, given the source of the risk (in this case either coal or natural gas electricity generation). Utility (U) is a function of the individual's consumption of a vector of market goods, X, and the human health, environmental, and aesthetic/amenity risk components. For simplicity, assume each project has only an environmental risk component EN, measured by an index of environmental consequences which is an increasing function of environmental damage. At $EN = 0$, the project has no environmental impacts. Thus

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[1] It is widely accepted in the field of welfare economics that the *ex ante* welfare measure is the most appropriate consideration when individuals are uncertain as to future states of the world. An individual's WTP/WTA is independent of the actual realized *ex post* state of the world. See Mitchell and Carson (1989) and Freeman (1993) for discussions of welfare changes under uncertainty.

[2] Results of previous studies have implied that if an individual is more familiar with hazard consequences then they are more likely to perceive that they have a higher probability of being exposed to the hazard (Slovic, 1987). This does not necessarily imply that individuals with pre-existing knowledge or familiarity will perceive risk to be more severe than individuals without previous experience.

$$U = U(X, EN) \qquad \text{where } \frac{\partial U}{\partial X} > 0,\ \frac{\partial U}{\partial EN} < 0.$$

Based on prior experience and information, *y*, the individual will form subjective estimates of the severity of the environmental consequences (item 3 above) and the likelihood of facing such a consequence (item 4). The subjective probability that an individual will face an environmental risk consequence $EN = en$ (which is also subjective) is denoted $\pi_{en}|y$. The level of dread (item 2) is a component of an individual's risk aversion and may be represented as a function of the Arrow-Pratt measure of relative risk aversion and is also dependent on prior experience with the hazard. Thus dread can be characterized with respect to the slope of the individual's utility function.

Individuals make choices to maximize their expected utility. Because of the uncertainty surrounding the risks associated with fuel choice, individuals form an expected utility which is a function of perceived probabilities and attributes. For each fuel choice (C or NG), the individual maximizes expected utility subject to prices, P_X, income *I*, and environmental conditions. For *n* possible environmental consequences, the individual will chooses *X* to maximize expected utility

$$E[U] = \sum_{en=1}^{n} (\pi_{en}|y) U[X, EN_{en}|y] \qquad \text{where } \sum_{en=1}^{n} \pi_{en} = 1.$$

The budget constrained utility maximization problem solves for Marshallian demand functions and the indirect utility function

$$V = \sum_{en=1}^{n} (\pi_{en}|y) v[P_x, I, EN_{en}|y].$$

To reduce or avoid the risks associated with the environmental consequence, an individual may be willing to make an *ex ante* payment. This payment, the individual's willingness to pay or option price, is equal to the income which holds expected utility constant over all possible marginal risk changes. If an individual prefers a natural gas-fired plant to a coal-fired plant, then

$$\overline{V} = \sum_{en=1}^{n} (\pi_{en}^{C}|y) v[P_x, I, EN_{en}^{C}|y] = \sum_{en=1}^{n} (\pi_{en}^{NG}|y) v[P_x, I - WTP, EN_{en}^{NG}|y].$$

This WTP, or option price, represents the change in income that equalizes the individual's expected utility among alternative fuel choices. The value of absolute risk changes could be measured by designing a scenario with a choice between accepting or rejecting a proposed facility.

Environmental conditions with one fuel choice may not occur with another fuel choice. In this case, *n* consequences still exist, although the individual places a zero probability on some depending on the fuel. If two environmental consequences are possible with the coal-fired plant and two with the natural gas plant, then the WTP is derived from

$$
\begin{aligned}
&(\pi^{C}_{en=1}|y)v[P_x, I, EN^{C}_{en=1}|y] + (\pi^{C}_{en=2}|y)v[P_x, I, EN^{C}_{en=2}|y] \\
&\qquad = (\pi^{NG}_{en=3}|y)v[P_x, I-WTP, EN^{NG}_{en=3}|y] + (\pi^{NG}_{en=4}|y)v[P_x, I-WTP, EN^{NG}_{en=4}|y].
\end{aligned}
$$

Solving for WTP derives the individual's valuation for a change in the perceived level of environmental risk between a coal and natural gas plant, holding prices and income constant. The individual's willingness to pay to prevent a coal fired plant will thus be a function of prices P_X, income I, and the individual's subjective perceptions of the probabilities and severity of the consequences, π and *EN*, respectively:

$$WTP = WTP(P_x, I, \pi_i^{C,NG}|y, EN_i^{C,NG}|y).$$

This project will estimate individual's marginal willingness to pay as a function of the level of subjective risk perception in addition to the socio-demographic measures conventionally modeled as determinants of WTP. The above model will be expanded to consider multiple risk consequences, e.g. health hazards and aesthetic/amenity hazards, as well as potential economic benefits such a project would generate. The potential exists to gather comparable data from "experts" to define appropriate levels of objective risk. These could then be compared to layperson's subjective perceptions to estimate the welfare impacts from a divergence between expert and layperson assessment of the risks associated with a facility.

This work could also be extended to examine the determination of individual's perceptions as a function of *y*. This approach is implicit in programs to identify the impact or value of public information efforts and is of considerable importance in risk communication programs. The methodology developed here is likely transferable to a multitude of hazards which may generate welfare impacts based on subjective risk perceptions.