PENNSSTATE

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

Semiannual Technical Progress Report for the Period 03/28/1997 to 09/27/1997

By

Bruce G. Miller, Sharon Falcone Miller, Joel L. Morrison, Sarma V. Pisupati, Alan W. Scaroni,
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Carnegie Mellon University

January 6, 1998

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

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By
The Consortium for Coal-Water Slurry Fuel Technology
The Pennsylvania State University
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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 developing technologies which can potentially decrease 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

Phase I was completed on November 1, 1995.

PHASE II

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

Emissions reductions investigations included performing pilot-scale air toxics (i.e., trace elements and volatile organic compounds) testing and evaluating a ceramic filtering device on the demonstration boiler. Also, a sodium bicarbonate duct injection system was installed on the demonstration boiler.

An economic analysis was conducted which investigated the benefits of decreased dependence on imported oil by using new coal combustion technologies.

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

PHASE III

Work in Phase III focused on coal preparation studies, pilot-scale NO_x reduction studies, economic analyses of coal use, and evaluation of deeply-cleaned coal as boiler fuel.

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

The evaluation of deeply-cleaned coal as boiler fuel included receiving three cleaned coals from Cyprus-Amax.

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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 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. 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 (The Energy Institute, Mineral Processing Section, Department of Energy, Environmental, and Mineral Economics, Fuel Science Program, and Polymer Science Program), Energy and Environmental Research Corporation (EER), AMAX Research and Development Center, ABB Combustion Engineering, Inc., 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 expands upon emissions reduction strategies through the use of deeply-cleaned coals as a means for reducing air toxics. 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 and AMAX Research and Development Center. This task involved 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 Energy Institute 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 The Energy Institute'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 Energy, Environmental, and Mineral Economics and Energy Institute 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 (Davidson et al., 1991). 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
- Subtask 1.8 Conduct NO_x Reduction Study
- Subtask 1.9 Evaluate BioLime as a SO₂/NO_x Reduction Strategy

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 Atomization Study

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 SO₂, NO_x, fine particulate matter (<10 μm), and air toxics (volatile organic compounds and trace metals). Post-combustion and during-combustion

technologies to reduce SO₂ 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 recently added to the program. 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 focus 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 original objectives of Phase III were 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. Since the initial development of the program's statements of work (Phases I through III), there has been a change in military boiler plant operating philosophy. This, coupled with recent developments in cofiring technologies and DOE coal preparation programs, necessitates the revision of the Phase III statement of work. Consequently, the Phase III work has been revised by eliminating coal-based fuel/waste cofiring and stoker combustion performance analysis and evaluation, and focusing these efforts toward evaluating deeply-cleaned coals as industrial boiler fuels, and investigating fundamental, pilot-scale, and demonstration-scale emissions reduction strategies. The revised Phase III consists of five tasks as 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. Emissions Reduction
 - Subtask 2.1 SO₂ Reduction
 - Subtask 2.2 NO_x Reduction
 - Subtask 2.3 Study of VOC and Trace Element Production, Reduction, and Capture
- Task 3. Economic Evaluation
 - Subtask 3.1 Cost and Market Penetration of Coal-Based Fuel Technologies
 - Subtask 3.2 Selection of Incentives for Commercialization of the Coal-Using Technology
 - Subtask 3.3 Community Sensitivity to Coal Fuel Usage
 - Subtask 3.4 Regional Economic Impacts of New Coal Utilization Technologies
 - Subtask 3.5 Economic Analysis of the Defense Department's Fuel Mix
 - Subtask 3.6 Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects
 - Subtask 3.7 Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies
 - Subtask 3.8 Integrate the Analysis
- Task 4. Evaluation of Deeply-Cleaned Coal as Boiler Fuels
 - Subtask 4.1 Modify MCWM Preparation Circuit
 - Subtask 4.2 Fuels Characterization
 - Subtask 4.3 Pilot-Scale Combustion Tests
 - Subtask 4.4 Demonstration-Scale Combustion Tests

Task 5. Final Report

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 is on fine-coal processing for the production of high-quality, micronized coal for dry coal and coal-water mixture (CWM) applications.

Task 2: Task 2 is a continuation of the emissions reduction work started in Phase II, and involves fundamental studies, pilot-scale investigations, and full-scale demonstrations. The low-temperature NO_x reduction catalyst identified in Phase II will be tested at the pilot and demonstration scale. The effect of coal cleaning, particulate removal devices, and boiler operating conditions on air toxics emissions from coal-fired industrial boilers will also be investigated.

Task 3: The activities in Task 3 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 is being determined and a national energy portfolio constructed.

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

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, and 5 are presented in Sections 7.0, 8.0, 9.0, 10.0, and 11.0, respectively. Section 12.0 discusses miscellaneous activities that were conducted. Activities planned for the next semiannual period are listed in Section 13.0. References and acknowledgments are contained in Sections 14.0 and 15.0, 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

Phase I has been completed and the final report was submitted on January 31, 1997.

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 SO₂, NO_x, fine particulate matter (<10 µm), and air toxics (volatile organic compounds and trace metals).

3.1 Subtask 1.1 Evaluation of Emissions Reduction Strategies

Subtask 1.1 was previously completed.

3.2 Subtask 1.2 Install System on the Demonstration Boiler

Subtask 1.2 was completed during this reporting period. An SO₂ reduction system and a ceramic filter chamber were installed on the demonstration boiler to reduce SO₂ emissions, and remove ultrafine particulate and increase the particulate collection efficiency, respectively. The SO₂ reduction system and a ceramic filter chamber are discussed in Sections 2.2.1 and 2.2.2, respectively. Details of the demonstration boiler system and micronizing coal system have been discussed elsewhere (Miller et al., 1997).

3.2.1 SO₂ Reduction System

A sodium duct injection system, which consists 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, was installed during this reporting period. A roof and siding were also installed on the system to protect the equipment from

Figure 1-1. DOD PHASE II MILES

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

Figure 1-2. DOD PHASE III MILEST

ONE SCHEDULE

Task 3. Economic Evaluation

Subtask 3.1 - Cost and Market Penetration of Coal-Based Fuel Technologies

Subtask 3.2 - Selection of Incentives for Commercialization of the Coal Using Technology

Subtask 3.3 - Community Sensitivity of Coal Fuel Usage

Subtask 3.4 - Regional-National Economic Impacts of New Coal Utilization Technologies

Subtask 3.5 - Economic Analysis of the Defense Department's Fuel Mix

Subtask 3.6 - Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects

Subtask 3.7 - Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies

Subtask 3.8 - Integration of Economic Analysis

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1997

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Table 1-1. Phase II. Milestone Description

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
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	07/01/96
Subtask 1.2, No. 2	Complete installation of system	09/30/97	09/30/97
Subtask 1.3. Evaluate Emissions Reduction System			
Subtask 1.3, No. 1	Shakedown system	10/31/97	
Subtask 1.3, No. 2	Complete system evaluation	12/31/97	
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	04/01/96
Subtask 1.4, No. 7	Develop catalyst characterization database	06/15/96	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	08/31/97	08/31/97
Subtask 1.5, No. 4	Procurement of Method 5 apparatus and auxiliaries	10/31/96	10/31/96
Subtask 1.5, No. 5	Shakedown of the sampling procedures	01/31/97	01/31/97
Subtask 1.5, No. 6	Conduct test program and analyze samples	12/31/97	
Subtask 1.5, No. 7	Analysis of the results	01/31/98	
Subtask 1.6. Conduct Trace Element Study			
Subtask 1.6, No. 1	Conduct literature survey on trace element emissions and analysis techniques	11/30/96	03/01/97
Subtask 1.6, No. 2	Procure sampling equipment	02/28/97	02/28/97
Subtask 1.6, No. 3	Shake down sampling procedure	04/30/97	04/30/97
Subtask 1.6, No. 4	Characterize emissions from industrial boiler	07/31/97	06/30/97
Subtask 1.6, No. 5	Analysis of results	10/31/97	
Subtask 1.7. Study Nitrogen Containing Groups in Coal			
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

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 1.7, No. 4	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. 5	Complete acetylation portion of derivitization work	09/30/97	09/30/97
Subtask 1.7, No. 6	Complete data analysis of derivitization work	10/31/97	
Subtask 1.7, No. 7	Complete low-temperature ashing of a range of coals and model polymer systems	12/31/97	
Subtask 1.7, No. 8	Establish methodology of methylation work	12/31/97	
Subtask 1.7, No. 9	Complete analysis of samples for methylation work	03/31/98	
Subtask 1.7, No. 10	Complete FTIR quantitative analysis of low-temperature ashes	03/31/98	
Subtask 1.8. Conduct NO_x Reduction Study			
Subtask 1.8, No. 1	Complete tests in the down-fired combustor	12/31/97	
Subtask 1.8, No. 2	Complete analysis of results	03/31/98	
Subtask 1.9. Evaluate BioLime as a SO_2/NO_x Reduction Strategy			
Subtask 1.9, No.1	Establish baseline reburn limits with BioLime	12/31/97	
Subtask 1.9, No.2	Establish operating limits for BioLime operating limits	03/31/98	
Subtask 1.9, No.3	Complete pilot-scale testing of wood feedstock with High NO_x Retention Formula	06/30/98	
Subtask 1.9, No.4	Complete fundamental study of predominant mechanism	08/31/98	
Subtask 1.9, No.5	Complete scale up of BioLime injection technology	08/31/98	
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
Subtask 2.3, No. 6	Initiate micronized coal classification studies	04/30/95	03/31/95
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

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
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
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	03/31/98	
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		12/31/96	12/31/96
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		03/31/98	
Task 4. Final Report		09/30/98	

Table 1-2. Phase III. Milestone Description

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
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	01/31/98	
Subtask 1.1, No. 5	Initiate investigation of an integrated grinding/cleaning circuit	12/31/97	
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	06/30/97	09/30/97
Subtask 1.2, No. 5	Initiate testing of integrated centrifugal/flotation system	01/31/98	
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	08/31/97	08/31/97
Subtask 1.4 Dry Processing			
Subtask 1.4, No. 1	Complete deagglomeration testing using the batch triboelectrostatic separator	01/31/97	03/15/97
Subtask 1.4, No. 2	Complete baseline testing of continuous triboelectrostatic separator unit	05/31/96	08/31/96
Subtask 1.4, No. 3	Initiate investigation of alternative approaches to charging/deagglomeration	12/31/96	12/31/96
Subtask 1.4, No. 4	Complete preliminary testing of integrated grinding and triboelectrostatic separator unit	11/30/96	11/30/96

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
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. Emissions Reduction			
Subtask 2.1. SO₂ Reduction			
Subtask 2.1, No. 1	Evaluate SO ₂ reduction system in coordination with NO _x reduction system	07/01/98	
Subtask 2.2. NO_x Reduction			
Subtask 2.2, No. 1	Complete preliminary pilot-scale SCR testing firing natural gas	12/31/96	12/31/96
Subtask 2.2, No. 2	Design pilot-scale SCR tests for NO _x reduction system	04/01/97	04/01/97
Subtask 2.2, No. 3	Perform pilot-scale tests of SCR NO _x reduction system	11/30/97	
Subtask 2.2, No. 4	Design selective catalytic NO _x reduction system	01/31/98	
Subtask 2.2, No. 5	Design demonstration boiler modifications for SCR NO _x reduction system	04/01/98	
Subtask 2.2, No. 6	Modify demonstration boiler system for SCR NO _x reduction system	09/30/98	
Subtask 2.2, No. 7	Complete testing of SCR NO _x reduction system	12/31/98	
Subtask 2.2, No. 8	Modify demonstration boiler system for BioLime SO ₂ /NO _x reduction system	02/01/99	
Subtask 2.2, No. 9	Complete testing of BioLime reduction system	04/01/99	
Subtask 2.3. Study VOC and Trace Element Production, Reduction, and Capture			
Subtask 2.3, No. 1	Complete pilot-scale testing of deeply-cleaned coals	06/30/99	
Subtask 2.3, No. 2	Complete demonstration-scale testing of deeply-cleaned coals	10/01/98	
Task 3. Economic Evaluation			
Subtask 3.1. Cost and Market Penetration of Coal-Based Fuel Technologies			
Subtask 3.1, No. 1	Complete study of cost and market penetration of coal-based fuel technologies	06/01/95	09/27/95
Subtask 3.2. Selection of Incentives for Commercialization of the Coal Using Technology			
Subtask 3.2, No. 1	Complete selection of incentives for commercialization of the coal-using technology	09/27/95	09/27/95

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 3.3. Community Sensitivity to Coal Fuel Usage			
Subtask 3.3, No. 1	Complete evaluation of community sensitivity to coal fuel usage	12/31/96	
Subtask 3.4 Regional Economic Impacts of New Coal Utilization Technologies			
Subtask 3.4, No. 1	Complete study of regional economic impacts of new coal utilization technologies	06/01/96	06/01/96
Subtask 3.5 Economic Analysis of the Defense Department's Fuel Mix			
Subtask 3.5, No. 1	Complete economic analysis of the defense department's fuel mix	09/27/95	06/30/95
Subtask 3.6 Constructing a National Energy Portfolio which Minimizes Energy Price Shock Effects			
Subtask 3.6, No. 1	Complete construction of a national energy portfolio which minimizes energy price shock effects	06/01/96	06/01/96
Subtask 3.7 Proposed Research on the Coal Markets and their Impact on Coal-Based Fuel Technologies			
Subtask 3.7, No. 1	Complete research on the coal markets and their impact on coal-based fuel technologies	09/27/95	09/27/95
Subtask 3.8 Integrate the Analysis			
Subtask 3.8, No.1	Complete integration of the analysis	03/31/98	
Task 4. Evaluation of Deeply-Cleaned Coals as Boiler Fuels			
Subtask 4.1 Modify MCWM Preparation Circuit			
Subtask 4.1, No. 1	Complete modifications to MCWM preparation circuit	04/01/97	03/01/97
Subtask 4.2 Fuels Characterization			
Subtask 4.2, No. 1	Complete fuels characterization	01/01/98	
Subtask 4.3 Pilot-Scale Combustion Tests			
Subtask 4.3, No. 1	Complete pilot-scale testing of deeply-cleaned coals	06/30/99	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 4.4 Demonstration-Scale Combustion Tests			
Subtask 4.4, No. 1	Complete demonstration-scale testing of deeply-cleaned coals	10/01/98	
Task 5. Final Report/Submission of Design Package		12/31/99	

the weather. Approval was received from the Pennsylvania Department of Environmental Protection to use the system.

3.2.2 Ceramic Filter Chamber

Construction of the ceramic filter chamber was completed during the previous reporting period. Shakedown and operation of the system were conducted during this reporting period. The ceramic filter chamber was installed adjacent to the existing baghouse and is capable of filtering the entire flue gas stream. The system has been engineered such that the flue gas stream can be passed through either the baghouse or ceramic filter. Schematic diagrams of the new system and details of the ceramic filter chamber were given in previous semiannual reports (Miller et al., 1996a,b). A generalized schematic diagram of the interior of the ceramic filter chamber showing the baffles and filters is given Figure 3-1.

3.3 Subtask 1.3 Evaluate Emissions Reduction Systems

Evaluation of the ceramic filter system began during this reporting period. Evaluation of the SO₂ reduction system will begin during the next reporting period after the initial characterization of the ceramic filter system is completed.

3.3.1 Ceramic Filter System Shakedown

Shakedown of the ceramic filter system was completed during this reporting period. Shakedown was performed while firing the boiler on natural gas to ensure proper dirty side gas management prior to introducing fly ash into the system. The primary objective of the shakedown period, which occurred during March and April 1997, was to ensure that there was sufficient compressed air flow and filter face pressure when backpulsing the filters to clean them. The air flow and face pressure recommended by CeraMem Separations, Inc., the manufacturer of the filters, is ~1,600 scfm per filter and 3 to 4 psig, respectively.

Shakedown activities included systematically modifying the blowtubes in order to provide the proper compressed air flow and pressure to the face of the clean-side of the filters. The blowtubes are 3" in diameter and are located above the venturis which are, in turn, mounted on the face of the clean side of the filters. Figure 3-2 is a side view showing four of the filter/ venturi/ blowtube/ valve combinations. In addition, Figure 3-2 shows the locations of two ports on one of the venturis where pressure readings were collected. The system has 80 filters located in two sections which each section comprised of 10 rows of 4 filters (see Figure 3-1). Each blowtube has one opening/ nozzle located above the venture for a total of four nozzles on each blowtube. When cleaning the filters, one blowtube (4 of 80 filters) at a time is backpulsed. Controls for the cleaning cycle allow for varying the pulse time (time compressed air is introduced into the venturi) from 50 ms to 180 ms, and

Figure 3-1. INTERIOR OF THE CERAMIC FILTER CHAMBER SHOWING BAFFLES AND FILTERS

Figure 3-2. SIDE VIEW OF ONE ROW OF CERAMIC FILTERS WITH VENTURIS, BLOWTUBE, AND NOZZLES

the cycle time (time between pulses from tube to the next) from rapid succession to ~1.75 minutes between pulses.

The blowtubes were originally installed with 1/2" holes for directing the nozzle of compressed air into the venturi. They resulted in only ~1,070 cfm of compressed air flow at a filter face pressure of ~1 psig. The diameter of the holes was increased from 1/2 to 3/4 to 13/16 to 1 to 1 1/4" with the compressed air flow and filter face pressure measured at each hole diameter. The compressed air flow increased to ~1,900 cfm exiting the blowtube with a hole diameter of 1 1/4"; however, the peak filter face pressure was 1.6 psig with an 1" hole and decreased to below 1.6" with the 1 1/4" hole. There was a concern that insufficient air was entering the venturi with the increased spray angle; therefore, an 1 1/4" nozzle was welded onto the blowtube with an increase in the filter face pressure to ~1.7 psig observed. The nozzle length was then increased to 3-4" which resulted in the air flow being directed into the throat of the venturi. The resulting face filter pressure was 4.2 to 4.6 psig. Consequently, nipples 1 1/4" in diameter and 3-4" long were welded over each of the holes in the blowtubes.

3.3.2 Ceramic Filter Evaluation

Evaluation of the system has started and includes ~400 hours of operation.

Parameters that are either currently being monitored/ measured or will be measured include:

- 1) Pressure drop history of the ceramic filter chamber. This includes monitoring both the pressure drop across the chamber as a function of hours of firing coal as well as the pressure drop recovery (i.e., return to a baseline value). The pressure drop, when firing natural gas at 12 million (MM) Btu/h at 4% O₂ and 400 acfm of transfer air, is measured prior to firing coal at the beginning of a day of operation (normal operation consists of either one or two 8-hour shifts of operation) and after coal feed has been terminated and purged from the coal feed lines;
- 2) Periodic checks on the filter face pressure and flow;
- 3) Stack particulate emissions (i.e., dust loadings) measured by EPA Method 5;
- 4) Ceramic filter chamber particulate collection efficiency (determined by EPA Method 5 dust loading measurements on the filter chamber inlet and outlet);
- 5) Ceramic filter chamber fine particulate (i.e., PM₁₀ and PM_{2.5}) and condensable particulate matter (CPM) emissions measured by EPA Methods 201A (PM₁₀), modified 201A (PM_{2.5}), and 202 (CPM);
- 6) Ceramic filter chamber fine particulate collection efficiency;
- 7) Particle size distribution of the fine particulate collected at the ceramic filter chamber inlet and outlet; and

- 8) Comparison of particulate emissions and collection efficiency of the ceramic filter chamber with the fabric filter baghouse.

Items #1 through 4 were conducted during this reporting period and are reported herein. Item #5 was started; however, the results are preliminary and are not reported. In addition, no testing was performed on Items #6 through 8 during this reporting period. Items #5 through 8 will be completed during the next reporting period.

Ceramic Filter Pressure Drop History

The pressure drop of the ceramic filter chamber was monitored as part of the system evaluation. This included monitoring both the pressure drop as a function of hours firing coal in addition to the pressure drop recovery (i.e., return to a baseline value) when firing natural gas. The pressure drop is recorded using a computerized data acquisition system (DAS) and by taking manual readings.

The typical operating procedure of the boiler is:

- 1) Preheat the boiler system while firing natural gas at a rate of 12 MM Btu/h until the ceramic filter chamber outlet temperature is $\sim 300^{\circ}\text{F}$;
- 2) Record the chamber pressure drop when the chamber inlet temperature is $\sim 340^{\circ}\text{F}$ when firing natural gas at 12 MM Btu/h at 4% O_2 and with a transfer air flow of 400 cfm;
- 3) Transition from natural gas to micronized coal by reducing the quantity of natural gas in increments while simultaneously increasing the micronized coal feed. The total firing rate is slowly increased from 12 MM Btu/h (when firing 100% natural gas) to ~ 16.5 MM Btu/h. When the firing ratio is 12.5 MM Btu/h micronized coal and 4 MM Btu/h natural gas, the natural gas valve is closed. The coal feed is then increased until the desired firing rate, which is typically 15 MM Btu/h, is reached;
- 4) The system is allowed to stabilize then the DAS begins recording (data points are recorded every 30 seconds) and manual readings are taken every half hour. The boiler is typically operated 8 to 16 hours per day which results in 5 to 12 hours of steady-state operation;
- 5) Upon conclusion of testing, the coal feed is turned off, the coal feed line is purged of coal (by leaving the transfer fan on), and the natural gas rate is increased until the firing rate is 12 MM Btu/h. After the lines are purged, the ceramic filter chamber pressure drop is recorded at the 12 MM Btu/h firing rate with 4% O_2 and a transfer air flow of 400 cfm; and

- 6) A series of rapid filter cleanings (i.e., the time between pulses is set to the minimum value for a few minutes) is conducted prior to shutting the boiler down.

Ceramic Filter Chamber Pressure Drop When Firing Coal

Figure 3-3 is a plot of the ceramic filter chamber pressure drop as a function of firing coal from April 28, 1997 to October 2, 1997. The data points are the manual readings taken every half hour. Over this time period, approximately 420 hours of coal-fired operation was obtained.

The data in Figure 3-3 exhibit four regions of performance. In the first region, from 0 to ~100 hours of coal-fired operation, the filters are being seasoned and the pressure drop increases from ~3.5 to between 6 and 7" W.C. (water column). The pressure drop then remains in the 6 to 7" W.C. range for the next ~160 hours (Run Hour 260) with a slight increasing trend (Region 2). At Run Hour 260, the pressure drop begins to increase more rapidly over the next 70 hours until it reaches ~8" W.C. (Region 3). The pressure drop then unexplainably drops to slightly below 7" W.C. and fluctuates between 6.5 and 8" W.C. (Region 4).

The behavior of the ceramic filter system observed in the first two regions was as expected. The pressure drop was expected to increase as the filters came to steady state with respect to fly ash being deposited in the filters. Not all the fly ash that is captured will be removed from the filters during backpulsing.

The second region was one of relatively steady-state performance, with the pressure drop ranging from ~6 to 7" W.C. This observed ceramic filter pressure drop was less than the design pressure drop of 8 to 10" W.C. (for a flue gas flow of ~8,150 acfm, which was the baghouse design flow) at 400 °F. However, the actual flue gas flow is ~6,500 to 7,000 acfm rather than 8,150 acfm; therefore, the lower pressure drop was expected.

Pressure drop readings that are significantly higher than those around them (e.g., at Run Hours 100 and 120) tend to be the result from sootblowing the convective chamber of the boiler. This is better observed in Figures 3-4 through 3-11 which are plots of the pressure drop as a function of firing coal for every 50 hours of operation showing the sootblowing events. The pressure drop significantly increases when the sootblower is operated because a large quantity of steam is introduced into the system and, to a lesser extent, ash deposits from the boiler are transported to the ceramic filter chamber.

The relatively rapid increase in pressure drop in Region 3 is unexplained at this time as is the decrease in pressure drop at Run Hour 330. The pressure drop exhibited a fairly wide range in Region 4 varying from ~6.5 to 8" W.C. Additional operating time will be obtained during the next reporting period to see if the pressure drop has stabilized.

Figure 3-3. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FROM APRIL 28, 1997 THROUGH OCTOBER 20, 1997

Figure 3-4. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 0 TO 50

Figure 3-5. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 50 TO 100

Figure 3-6. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 100 TO 150

Figure 3-7. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 150 TO 200

Figure 3-8. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 200 TO 250

Figure 3-9. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 250 TO 300

Figure 3-10. CERAMIC FILTER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 300 TO 350

Figure 3-11. CERAMIC FILTER CHAMBER PRESSURE DROP AS A FUNCTION OF TIME FIRING COAL FOR RUN HOURS 350 TO 400

Ceramic Filter Chamber Pressure Drop When Firing Natural Gas

There was concern that fly ash may be building up in the filters when the pressure drop was observed to increase in Region 3. Tests were then conducted to determine if the pressure drop returned to a baseline value when firing natural gas. Table 3-1 lists the results from the pressure drop recovery tests. The pressure drop was recorded when preheating the system firing natural gas prior to firing micronized coal. The chamber pressure drop was recorded when the chamber inlet temperature reached ~340°F, when firing natural gas at 12 MM Btu/h at 4% O₂, and with a transfer air flow of 400 cfm. Similarly, when testing was completed, the coal feed was turned off, the coal feed line was purged of coal (by leaving the transfer fan on), and the natural gas rate was increased until the firing rate reached 12 MM Btu/h. After the lines were purged, the ceramic filter chamber pressure drop was recorded at a firing rate of 12 MM Btu/h with 4% O₂ and a transfer air flow of 400 cfm.

As can be seen from the tests conducted prior to firing coal (which correspond to run hours after Run Hour 332), the pressure drop is relatively constant and is between 5.8 and 6.0" W.C. This indicates that the filters appear to be cleaning with no appreciable material remaining in the filters. These tests will be continued during the next reporting period, along with tests measuring the pressure drop across the chamber with the induced and forced draft fans operating (prior to firing natural gas).

There was more variability observed during the tests conducted after coal was fired and the boiler was firing natural gas. This appears to be due to the range in flue gas temperatures after coal testing.

Ceramic Filter Face Pressure and Compressed Air Flow When Backpulsing

Periodic tests were conducted on the ceramic filter face pressure and compressed air flow when backpulsing to ensure that they were adequate for cleaning. These checks showed that the face pressure and air flows are within CeraMem Separations, Inc. recommended ranges.

Stack Particulate Emissions and Ceramic Filter Collection Efficiency

A series of EPA Method 5 particulate emissions tests were conducted to determine the dust loadings and collection efficiency of the ceramic filter. The preliminary results from the testing, which were conducted in July and September 1997, are summarized in Table 3-2. For comparison, Table 3-2 also contains the results from Method 5 testing that was performed on the fabric filter baghouse, when the site was commissioned in order to obtain an operating permit from the Pennsylvania Department of Environmental Protection.

The tests listed in Table 3-2 are those where reportable data were obtained. Additional activities in August included modifying the sampling locations for ease of

Table 3-1. Ceramic Filter Chamber Pressure Drop and Inlet and Outlet Temperatures When Firing Natural Gas

Date	Prior to Firing Coal			After Firing Coal		
	ΔP ("W.C.)	T _{inlet} (°F)	T _{outlet} (°F)	ΔP ("W.C.)	T _{inlet} (°F)	T _{outlet} (°F)
09/12/97	N.M. ^a	N.M.	N.M.	7.3	379	366
09/16/97	5.7	322	254	N.M.	N.M.	N.M.
09/17/97	5.8	345	290	N.M.	N.M.	N.M.
09/24/97	5.8	N.R. ^b	N.R.	6.3	360	N.R.
09/25/97	N.M.	N.M.	N.M.	6.2	372	360
09/26/97	6.6 ^c	342	300	5.6	358	349
09/29/97	5.9	343	267	N.M.	N.M.	N.M.
09/30/97	5.9	337	270	5.9	342	320
10/01/97	6.0	338	275	6.4	361	348
10/02/97	5.9	335	273	6.3	368	353

^a Not measured

^b Not reported

^c Measured shortly after sootblowing convective section

Table 3-2. Preliminary Summary of EPA Method 5 Testing on the Ceramic Filter Chamber When Firing Middle Kittanning Seam Micronized Coal

Date	Inlet		Outlet		Collection Efficiency (%)
	(grains/dscf ^a)	pounds/MM Btu	(grains/dscf)	pounds/MM Btu	
01/17/92 ^b	4.728	7.660	0.015	0.0247	99.68
07/09/97	2.2791	4.4574			
07/21/97			0.0056	0.0110	99.75 ^c
07/24/97	2.4609	4.6727			
09/03/97 ^d	1.6707	3.4405			
09/08/97	1.6654	3.5274	0.0028	0.0063	99.83
09/12/97	1.2621	2.8657	0.0025	0.0054	99.80
09/22/97			0.0024	0.0051	99.86 ^e
09/23/97	1.7068	3.5947			

^a Grains per dry standard cubic foot of flue gas

^b These tests were performed on the fabric filter baghouse when firing Brookville seam coal-water slurry fuel for the baghouse performance test.

^c Collection efficiency was determined using inlet results from 07/09/97. Due to operational problems encountered in July, both inlet and outlet sampling could not be conducted on the same day.

^d Outlet sample was collected but is not reported because seal on the sampling train was broken. A new coal shipment was received in August which resulted in lower inlet dust loadings for September 1997.

^e Collection efficiency was determined using inlet results from 09/23/97. The boiler shut down during the inlet sampling on 09/22/97 because of a loss in coal feed. The inlet sample was collected the next day.

sampling, and conducting both Methods 5 and 201A (PM₁₀) sampling. However, because of problems encountered during sampling (i.e., inadvertent sootblowing, broken nozzles, broken seals on the sampling train, etc.) the August tests are not reported. In addition, the ceramic filter chamber was opened and inspected in August to see if there was any leakage from the dirty side to the clean side of the chamber. Tests were conducted injecting lime and a fluorescent material to see if there was any leakage at welds, filter gasket seals, or the filters themselves.

The results listed in Table 3-2 are considered preliminary because coal samples are currently being analyzed for calorific value. Coal samples are collected as the tests are conducted and are then analyzed for their composition and heating value. The boiler was fired at ~15 MM Btu/h for each test; however, the exact firing rate, which does not vary much, will be determined after the coals are analyzed and this rate will be used for determining the emissions rate reported as pounds per million Btu. Past operating experience shows that the heating value remains fairly constant for each shipment of coal.

The collection efficiency of the ceramic filters ranged from 99.75 to 99.86% which tended to be better than that of the fabric filters. The tests conducted on the baghouse were done, when the system was new, as part of a performance test to obtain an operating permit when firing Brookville seam coal-water slurry fuel. Additional tests will be conducted during the next reporting period to determine if the collection efficiency of the baghouse has changed after several years of operation and the installation of bags of different composition.

Although the collection efficiency of the ceramic filters is good, it is not as high as the 99.99% that CeraMem Separations, Inc. reports to be achievable. In addition to CeraMem Separations, Inc., individuals from several organizations (i.e., Stanley Miller Energy and Environmental Research Corporation who conducted bench-scale collection tests, and John Vaklyes and Tony Andriola from Fisher-Klosterman Inc. who market collection systems using the filters) claim that the collection efficiency should be higher than that currently achieved. Consequently, the ceramic filter chamber will be opened, the clean side of the plenum checked again for leakage and silicone added on every welded joint and around the filter gaskets before the next series of tests.

Due to boiler operational problems (coal accumulating on the booster fan blades) encountered in July, both inlet and outlet samples could not be collected on the same day. The boiler could only be fired on micronized coal for approximately six hours each day. After the problem was remedied, the boiler could be operated for an unlimited amount of time; therefore, both inlet and outlet tests were conducted in September unless problems with sampling were encountered.

Middle Kittanning seam coal was used for the Method 5 testing firing micronized coal. A new shipment of coal was received in August 1997 which had a similar ash content (~5 wt.%) but resulted in a lower inlet dust loading. Another observation noted was that the inlet dust loadings tended to show an inverse relationship with combustion efficiency, that is, the lower dust loadings were the result of higher combustion efficiency. Combustion efficiencies are affected by the cleanliness of the boiler. They tend to be lower after the ash has been cleaned out of the boiler and will increase as ash deposition and accumulation occurs.

Table 3-3 is a comparison between the emissions results of the fabric filter baghouse and the ceramic filter chamber. In addition, the emissions results of the ceramic filter chamber are compared to the New Source Performance Standards (NSPS) and DOE's LEBS (Low Emissions Boiler System) and HIPPS (High Performance Power Systems) targets. As previously stated, the performance of the ceramic filter chamber is better than the fabric filter baghouse. In addition, the ceramic filter chamber emissions obtained to date meet the NSPS and LEBS target. One objective of the testing, during the next reporting period, is to meet the HIPPS target after ensuring there are no leaks in the system prior to performing additional Method 5 sampling tests.

3.4 Subtask 1.4 Conduct NO_x Emissions Study

Subtask 1.4 is completed.

3.5 Subtask 1.5 Conduct VOC Study

A majority of the 190 species listed in the Clean Air Act Amendments of 1990, including polycyclic aromatic hydrocarbons (PAHs), can be collected by what is generically termed a Modified Method 5 (MM5) sampling train. The train is used to isokinetically collect samples at desired locations in flue gas streams. The collected flue gas stream sample can be separated into solid, condensed liquid and gaseous phases (for PAH determinations, the gaseous phase is not retained or analyzed.). The PAHs of interest are extracted from the collected sample, concentrated, then separated and quantified by gas chromatography/mass spectrometry (GC/MS) techniques. Samples have been collected from Penn State's research boiler and down-fired combustor (DFC).

Test Matrix

The DFC is a 500,000 Btu/h pilot-scale combustor. The first series of tests was conducted to determine the effect of firing rate and excess air on PAH formation. A Middle Kittanning seam coal was pulverized to 80% passing 75 μm (commonly referred to as a pulverized coal, or "PC" grind). The coal was fed into the combustor at two rates: 315,000 Btu/h (designated "low fire") and 425,000 Btu/h (designated "high fire"). The combustion air was fed into the combustor at two rates and monitored as the oxygen concentration in

Table 3-3. Comparison of Ceramic Filter Chamber and Fabric Filter Baghouse Particulate Emissions

	Fabric Filter	Ceramic Filter	NSPS^a	LEBS^b Target	HIPPS^a Target
Dust Loading (gr/dscf)	0.015	0.0024 to 0.0056	--	--	--
Emissions (lb/ MM Btu)	0.025	0.005 to 0.011	0.03	0.01	0.003
Collection Efficiency (%)	99.68	99.75 to 99.86	--	--	--

^a New Source Performance Standards

^b Low Emissions Boiler System

^c High Performance Power System

the flue gas stream. The excess oxygen was held at either 3% (designated "low air") or 5.5% (designated "high air").

The second series of tests investigated the effect of fuel on PAH formation. All fuels in this series of tests were burned at low fire, high air conditions. A Freeport seam uncleaned (As Received; A.R.) and cleaned coal were prepared as PC and burned in the DFC. Additionally, the Middle Kittanning seam coal was retested at these conditions, but with a different temperature profile in the combustor than the earlier test. Finally, the Middle Kittanning seam coal was tested as a CWM in the DFC.

A third series of tests was conducted to see the effect of combustor type on PAH formation. The research boiler is a 2 MM Btu/h A-frame watertube package boiler. The Middle Kittanning seam coal was tested as both PC and CWM in the research boiler.

A summary of the testing that was conducted is:

Furnace Type	Coal Seam	Fuel Form	Coal Rate (Btu/h)	Air Rate (% O ₂)
DFC	Mid. Kittanning	PC	425,000	5.5
DFC	Mid. Kittanning	PC	425,000	3.0
DFC	Mid. Kittanning	PC	325,000	5.5
DFC	Mid. Kittanning	PC	315,000	3.0
DFC	Freeport (A.R.)	PC	315,000	5.5
DFC	Freeport (A.R.)	PC	315,000	5.5
DFC	Freeport Clean	PC	315,000	5.5
DFC	Freeport Clean	PC	315,000	5.5
DFC	Mid. Kittanning	PC	315,000	5.5
DFC	Mid. Kittanning	CWM	315,000	5.5
DFC	Mid. Kittanning	CWM	315,000	5.5
Research Boiler	Mid. Kittanning	PC	1,600,000	5.0
Research Boiler	Mid. Kittanning	PC	1,600,000	5.0
Research Boiler	Mid. Kittanning	CWM	1,600,000	5.0
Research Boiler	Mid. Kittanning	CWM	1,600,000	5.0

Approximately 250 gallons of a highly loaded CWM was prepared from a Middle Kittanning feedstock for the PAH testing and trace element testing (which is discussed in Section 3.6). The CWM was produced by wet ball milling a nominal -1/4 inch feed in a 2 x 4 ft ball mill using a 0.8 wt.% A-23M (active solids basis) as the dispersant and grinding at a 65 wt.% solids target. The ball mill discharge was diluted to 61 wt.% and then pumped to an Union Process 15-S Attritor Mill where the CWM was ground to minus 100 mesh. The CWM was discharged and then thoroughly mixed with 0.04 wt.% Flocon 4800C stabilizer in a ribbon mixer. The ribbon mixer discharge was then pumped to a 250 gallon baffled storage tank where it was agitated until its use.

Presampling Considerations

Prior to any sampling, both the research boiler and the DFC underwent retrofitting in order to meet the specifications for sampling and pitot tube ports as described in EPA Method 1. A modular sampling train meeting all of the requirements of EPA Methods 5 and 0010 was purchased from Clean Air Engineering. EPA Methods 1 through 4 were utilized to determine various parameters needed for isokinetic sampling of both units. EPA Method 8270-C was selected as the analytical method that would be used in determining the concentrations of PAHs in the collected samples. Extraction of PAHs from the collected particulate matter and the XAD-2 polymeric resin fractions would be done by EPA Method 3540-C, Soxhlet Extraction. Extraction of PAHs from the collected liquid fraction would be done by EPA Method 3510-C, Separatory Funnel Liquid-Liquid Extraction. Sample cleanup would be accomplished by EPA Method 3630-C, Silica Gel Cleanup. All ancillary materials pertinent to these methods were purchased prior to sampling.

The EPA Method 5 Sampling Train

The EPA Method 5 sampling train is designed to isokinetically sample a flue gas stream. A portion of the gas stream is withdrawn from the duct through a heated probe where the particulate matter is filtered out of the stream. The remaining portion of the gas stream is passed through a condenser, a module containing the polymeric resin, and a series of glass impingers immersed in ice water where the remaining condensable species are collected.

Specifically, the sampling train contains the following components. They are listed from the most upstream component to the most downstream component.

A buttonhook borosilicate glass nozzle is located at the end of a sampling probe. The nozzle opening is placed into the flue gas stream facing upstream with pitch and yaw angles of 0°. The inside diameter of the nozzle is precisely known, as its size affects the sampling rate.

The nozzle is connected to a borosilicate probe. The probe is long enough to completely traverse the duct or stack of interest. The probe is encased in a stainless steel heated jacket. While sampling, the probe is maintained at 250°F by a temperature controller. The nozzle is connected to the probe by a Teflon union.

The probe is connected to a glass filter assembly located within a heated oven. The filter assembly is also maintained at 250°F. A filtering media was selected to retain particles larger than 0.2 µm.

Gases exiting the filter assembly are passed through a water-cooled glass condenser to condense PAHs that may be in the vapor phase to the liquid phase. This condensate and

remaining gas phase components are passed over the water-cooled porous polymeric resin contained in a glass module. Many PAHs are adsorbed onto this resin.

Gases and condensed liquids exit the glass resin module into a chilled condensate knockout trap. This trap is similar in design to an empty impinger. The PAHs not retained on the resin are collected in this knockout impinger.

The next 3 downstream chilled impingers are used to collect additional water condensate. The final impinger contains indicating-type silica gel to protect the pump from unwanted moisture. The temperature of the gas stream exiting this final impinger is maintained at or below 68°F. All glass ball-and-socket connections are clamped and made airtight with Teflon O-rings.

The gases are passed through an air tight pump, dry gas meter, across a manometer, (gas samples may be collected at this point if desired), and vented. These devices, along with thermocouple readouts, temperature controllers, manometers, valves, timer and other equipment are contained in a metering console.

Operation of the MM5 Sampling Train

Prior to sampling, data sheets must be prepared, stack access ports must be cleaned, and leak checks must be performed on the sampling system and the pitot system. Using the data generated by EPA Methods 1 through 4, the train is isokinetically operated at the designated traverse points for predetermined durations to ensure EPA sample collection requirements. Proper temperatures and flow rates must be maintained. Leak checks are also performed at the conclusion of the sampling run.

Sample Recovery and Preparation for Analysis

The collected sample is separated into six parts. The subsamples contain materials collected from these particular sections of the sampling train. The first subsample contains the filter paper, filtered solids, and other solids removed from the filter-holder gasket. The second subsample contains recovered materials from the nozzle to the front half of the filter holder. The third subsample contains recovered materials from the resin module. The fourth subsample contains recovered materials from the condensate knockout trap. The fifth subsample contains recovered materials from the back half of the filter paper assembly and the first wet impinger. The sixth and final subsample contains recovered materials from silica gel-filled impinger. These six samples are processed and combined into three sample extracts for analysis. The three final sample extracts include materials extracted from the particulate matter filter and front half rinse; the condensate and condensate rinse; and the sorbent resin, condenser and back half rinse.

The first of the three sample extracts is generated using the following procedure. The recovered particulate matter from the front half rinse, recovered particulate matter from

the filter and the filter itself are spiked with a known amount of a surrogate spiking solution transferred into a glass Soxhlet extraction thimble. (The surrogate compounds are compounds chemically similar to the analytes of interest, but not expected to be contained in the extract. The surrogate compounds are utilized to monitor unusual matrix effects or sample processing errors during the extraction and recovery process.) The glass thimble is placed into a Soxhlet extractor and connected to a round bottom flask containing approximately 10 clean Teflon boiling chips and enough methylene chloride to maintain extraction cycling. A bulb type condenser is connected atop the extractor. A heating mantle is placed under the flask and adjusted to cycle the extractor about once every thirty minutes or less for a total of approximately 18 hours.

The front half rinse is quantitatively transferred to a separatory funnel, and serially extracted three times with methylene chloride. The pH of the rinse is then adjusted to at least 11 with sodium hydroxide and serially extracted three more times. The pH is then adjusted to below 2 using sulfuric acid and serially extracted three additional times. This extract is combined with the Soxhlet extracted material. A Kuderna-Danish (K-D) concentrator is assembled by attaching a 10 ml concentrator tube with Teflon[®] boiling chips to a 500 ml evaporatory flask. The extracts are passed through a sodium sulfate filter to remove any residual water and transferred into the concentrator. A prewet three-ball macro Snyder column is placed atop the concentrator. The concentrator assembly is placed into a hot water bath and concentrated to 6-8 ml within 30 minutes. The apparatus is allowed to cool. The three-ball macro column and evaporatory flask are removed and replaced with a two-ball micro Snyder column and the extraction is further concentrated to approximately 4 ml. The extract is then quantitatively transferred to a vial, diluted to a final volume of 5 ml, and stored at or below 4°C until analyzed.

The second of the three sample extracts is generated using the following procedure. The condensate and condensate rinse samples are combined and transferred to a separatory funnel, spiked, and serially extracted with methylene chloride exactly as is done with the front half rinse.

The third of the three sample extracts is generated using the following procedure. The porous polymeric resin is transferred to a glass extraction thimble, spiked and processed identically as the particulate matter sample.

The condensate and resin extracts are combined, residual water is removed, and then concentrated as described above. Blank samples are extracted concurrently with the collected samples. All extract samples are spiked with internal standards just prior to analysis.

Gas Chromatography/Mass Spectrometry System Evaluation

A Gas Chromatograph/Mass Spectrometer (GC/MS) system is used for extract analysis. The system must be temperature programmable suitable for splitless injection. A fused-silica capillary column capable of PAHs separation is required. Other specifications for the GC/MS system including GC/MS interface, data acquisition system and other ancillary equipment is described in EPA Method 8270.

The GC/MS system must be properly hardware-tuned. Background subtraction should be designed only to eliminate column bleed or instrument background ions. GC column performance must be evaluated and injection port inertness must be confirmed. Calibration standards are analyzed and their response factors are calculated and evaluated. A system performance check using approved System Performance Check Compounds is performed and the results are evaluated. The percent relative standard deviation of the compounds are calculated as is the linearity of the calibration curve. If system tuning, calibration check, performance check, internal standard response and retention time data meet minimum method requirements, analysis of the extracts can begin.

GC Analysis

Prior to GC/MS analysis, 1 μ l aliquot of the samples are analyzed on a Perkin Elmer 8500 GC system. The system is equipped with a J&W Scientific DB-5 capillary column. This screening procedure will check the concentration of the analytes and determine if dilution or further concentration of the samples is necessary. GC screening is underway.

GC/MS Analysis

Finally, a spiked 1 μ l aliquot of concentrated extract is injected into the GC/MS system. The species are separated by the gas chromatograph and analyzed by the mass spectrometer. Analysis is being conducted currently.

Data Interpretation

Data interpretation will be performed during the next reporting period

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. Activities that were conducted during this reporting period included finalizing the sampling protocol and analytical methods, setting up a 'clean' laboratory for assembling sample trains and recovering the samples, training personnel in sampling and recovery techniques, and performing pilot-scale tests.

Pilot-scale tests were conducted firing pulverized coal and coal-water mixtures (CWMs) in Penn State's down-fired combustor (300,000 Btu/h) and research boiler (1.5 million Btu/h) while sampling the flue gas for trace element emissions. The objectives of

the testing were to become familiar with the sampling methods and obtain preliminary information on the partitioning (solid vs. gas) of the trace elements in the flue gas, the effect of fuel form (pulverized coal or CWM) on trace element emissions, overall and baghouse penetration, and scale up (down-fired combustor vs. research boiler).

A listing of the tests conducted is given in Table 3-4. The tests were conducted to investigate the following parameters on trace element emissions:

- The effect of coal type -- Tests 1 and 2;
- The effect of coal cleaning -- Tests 2 and 3;
- The effect of fuel form -- Tests 1, 6, 7A and 7B and Tests 4 and 5; and
- The effect of scale up -- Tests 1 and 4 and Tests 5, 6, 7A, and 7B.
- Reproducibility -- Tests 6, 7A, and 7B.

In addition, Tests 7A and 7B were conducted to determine reproducibility of sampling at one location on the same day as well as to determine reproducibility between sampling on different days (i.e., Tests 6 (inlet), 7A, and 7B).

All samples have been analyzed and the results tabulated. It was found after the first three tests that insufficient sample was being analyzed by the laboratory and many of the results were below the detection limits. Consequently, the sample preparation technique was modified such that more of the sample was used by the laboratory. This technique was used for analyzing the samples from Tests 4 through 7A. Because the first three tests are used in nearly all the comparisons listed above, the tests will be repeated during the next reporting period. The interpretation of the results will be presented in the next semiannual report after the testing is completed.

3.7 Subtask 1.7 Nitrogen Containing Groups in Coal Study

During this reporting period, a project to study the nitrogen containing groups in coal was added. The work to be accomplished and the progress to date are discussed in Section 8.4.

3.7.1 Work to be Accomplished

The analysis of nitrogen containing functional groups in coal is a difficult analytical problem, but an important one in terms of understanding the extent and origin of pollutants such as the various oxides that are formed in combustion.

It is well established that nitrogen is predominantly present in the form of heterocyclic aromatic structures, presumably as both basic nitrogen and N-H, but the relative proportions of each and their propensity to form oxides are not easily measured. In this part of the program, an approach is used that is based on the use of FTIR to quantitatively determine the amount of various types of nitrogen containing groups in coal.

Table 3-4. Matrix Summary for the Trace Element Testing

Test Number ^a	1	2	3	4	5	6	7A	7B
Date	04/23/97	04/28/97	04/30/97	06/09/97	06/11/97	06/16/97	06/18/97	06/18/97
Coal Seam	Middle Kittanning	Freeport (Raw) ^b	Freeport (Cleaned) ^c	Middle Kittanning	Middle Kittanning	Middle Kittanning	Middle Kittanning	Middle Kittanning
Fuel Form	Pulverized Coal	Pulverized Coal	Pulverized Coal	Pulverized Coal	Coal-Water Mixture	Coal-Water Mixture	Coal-Water Mixture	Coal-Water Mixture
Furnace Type	Down-Fired Combustor	Down-Fired Combustor	Down-Fired Combustor	Research Boiler	Research Boiler	Down-Fired Combustor	Down-Fired Combustor	Down-Fired Combustor
Firing Rate (Btu/h)	362,000	345,000	360,000	1,652,000	1,680,000	372,000	362,000	362,000

^a All tests, except for Tests 7A and 7B, consisted of baghouse inlet and outlet sampling. Baghouse inlet sampling only was conducted during Tests 7A and 7B to determine reproducibility between tests.

^b Parent coal before cleaning

^c Cleaned by CQ, Inc.

These measurements can then be used to correlate structure to the propensity of different coals to form oxides.

Two different approaches are being used to measure nitrogen containing groups in coal. The first depends upon derivatization. Pyrrole type structures can be acetylated to give amide groups that are readily measured in the infrared. This methodology is already established. Basic nitrogen groups are more difficult to analyze. The approach being investigated involves the formation of complexes with alkyl halogens and because infrared spectroscopy is particularly sensitive to species with strong dipoles, the resulting bands should be extremely intense, allowing the measurement of low concentrations of basic nitrogen. This is in the process of being investigated.

The second approach being utilizing depends upon fixing organic nitrogen as inorganic nitrates in the low temperature ashing process.

3.7.2 Progress to Date

The establishment of the low temperature ashing methodology has been delayed by the need for repair of the instrument. In the meantime, samples have been sent to an outside vendor for ashing. These are to be returned in October so that the analysis can begin.

In terms of the derivatization work, a large number of coal samples have been acetylated and the spectra are presently being curve-resolved. NH content as a function of rank will be determined during the next reporting period.

The methylation procedure has proved more difficult, as the reaction conditions are crucial. In preliminary work, a styrene/vinyl pyridine copolymer is being characterized to establish methodology. The spectra of the methylated sample and the original copolymer are compared in Figure 3-12. Practically all the bands are changed upon methylation, which suggests that we are reacting aromatic ring CH groups in addition to the basic nitrogen functionality. Milder conditions of methylation are being studied in current work.

3.8 Subtask 1.8 Conduct NO_x Reduction Study

The main objective of this study is to understand the detailed mechanism by which NO_x emissions are lowered when cofiring coal and MCWM compared to coal firing. The study will be conducted in Penn State's down-fired combustor (DFC).

3.8.1 Conduct Cofiring Tests in the DFC

Coal will be fired through the central pipe of the burner, and slurry fuel will be injected in Port 2 or 3 (as appropriate) downstream to simulate the reburn conditions. CWSF will be fired with coal at 0, 10, 20, and 30% of the thermal input. A total of thirteen tests in the DFC will be performed.

Figure 3-12. FTIR SPECTRA OF A STYRENE / VINYL PYRIDINE COPOLYMER BEFORE AND AFTER METHYLATION

Baseline flue gas concentration and temperature profiles along the combustor will be generated with coal firing. This will provide the controlled conditions to study and demonstrate the influence of cofiring coal and coal water slurry fuel on the NO_x emissions. CEM system will be used to measure O_2 , NO_x and CO at various port levels to clearly identify the location at which NO_x is produced and destroyed. Axial oxygen concentration will also provide the information on the stoichiometric ratio at the CWSF injection level. Char samples will be extracted from the combustor to measure the char composition (C,H and N). Data on nitrogen distribution between char and volatiles will be obtained. All testing will be completed by December 31, 1997.

3.8.2 Analysis of the Results

The analysis of the results will be completed by March 31, 1998.

3.9 Subtask 1.9 Evaluate BioLime as a SO_2/NO_x Reduction Strategy

3.9.1 Establish Baseline Reburn Limits with BioLime™

The objective of this work is to establish the limits under which BioLime™ injection can reduce the NO_x levels by 50% and SO_2 levels by 90%. The data generated so far was using high inlet NO_x and SO_2 levels. Therefore, this work will establish the lower limits for its use. This task will be performed using the DFC with an inlet NO_x concentration of 100, 200 and 300 ppm. These tests will be conducted using natural gas flame and doping the flue gases with SO_2 and NO_x gases and injecting the Biolime™ down stream.

3.9.2 Establish Operating Limits for BioLime™

The objective of this work is to establish the lower SO_2 limits for 90% sulfur capture.

3.9.3 Pilot-Scale Testing of Wood Feedstock with High NO_x Retention Formula

This work involves at least six tests with the High NO_x Retention Formula in the DFC to optimize the conditions and understand the emission control behavior of BioLime™. The burner on the DFC will be modified to accommodate air staging or to use another reburn fuel upstream to reduce NO_x levels by about 50% from the baseline values in the previous subtasks (ie., to about 0.4 lb/MM Btu). High NO_x Retention Formula injected down stream will be optimized such that NO_x level can be reduced by an additional 75% to about 0.1 lb/MM Btu.

3.9.4 Fundamental Study of the Predominant Mechanism

Primary objective of this work is to study the fundamentals to improve the understanding of the mechanisms that are involved in the process of NO_x reduction by specifically studying:

- 1) homogeneous gas phase reaction of HC radicals and NO by simulated species in a laboratory-scale reactor
- 2) the influence of water in the production of CO that may react with NO_x .

3.9.5 Scale up of BioLime™ Injection Technology

The optimum parameters that are identified in the DFC tests will be used to inject the High NO_x Retention Formula into the 1,000 lb steam/h watertube research boiler to study the scale-up factors. Handling behavior of the BioLime™ will be studied and a circuit will be developed to avoid the pluggage of nozzles by incorporating online strainers etc. Tests will be performed to study the effect of boiler load variation to establish the performance of BioLime™.

This task also involves demonstration of the technology under the conditions determined in the previous activities in the 15,000 lb steam /h demonstration boiler for at least a two week period. This demonstration involves looking at preparation and handling, and emission control aspects to facilitate further scale-up to a commercial unit. The demonstration will be based on 16 hour tests each day (operated for two shifts 8 hours each including heat up time). A low to medium sulfur coal will be used for the study. No major modifications to the Boiler are anticipated at this stage.

4.0 PHASE II, TASK 2: COAL PREPARATION/UTILIZATION

Activities in Phase II, Task 2 primarily focused on preparing the final report and initiating a study with Carnegie Mellon University to study the fundamental behavior of atomization. Results of the study are presented in Section 4.1.

4.1 Subtask 2.10 Conduct Atomization Study

No work was conducted on this subtask during this reporting period.

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

Phase II, Task 3 has been completed except for Subtask 3.10, integration of analysis.

5.1 Subtask 3.10 Integration of Analyses

Activities during this reporting period focused on investigating the regional economic benefits of decreased dependence on imported oil and using new coal combustion technologies.

5.1.1 Introduction

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 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 (e.g., Miller et al., 1997). 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 (see, e.g., Bohi and Toman, 1993). 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 that are at least politically stable. Even if the security issue wanes, however, the economic stimulus from increased domestic energy production remains an attractive benefit of increased coal utilization. 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 GNP and nearly 150,000 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 developed by Li (1994) to examine the widespread adoption of coal-fired industrial boilers in Pennsylvania as determined by Schaal (1995; 1997) was employed. 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.

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

5.1.2 Market Penetration Model

This section summarizes the market penetration of a technology that allows retrofitting of oil- or gas-fired industrial boilers to utilize coal potential in forms such as a micronized coal-water mixture (MCWM). The decision to retrofit a boiler to fire MCWM must include consideration of the practical difficulties to be overcome. Recent pilot operations, however, have successfully demonstrated the capability of advanced burner design and operations to utilize coal-based slurries with no cofiring of other fossil fuels and limited derating of the boiler's total capacity (Miller et al., 1997).

Significant advantages are realized through the use of coal-based slurry fuels. The first is the elimination of fine coal particles during transport of solid by coal trucks, trains, conveyors, etc. This shipment of the coal fines constitutes a potential explosion hazard, and the dispersal of fines in the atmosphere constitutes a health hazard. Also, coal fines are much harder to dry, and the increased moisture can interfere with equipment operations. Little effort is expended in retrieving fine coal particles from coal mining and washing activities, and they are predominantly discarded as refuse. Slurrying the coal fines, however, mitigates these problems since the slurry can be pumped like oil and stored in similar tanks to reduce fugitive dust emissions. A second advantage is that it is easier to clean coal fines since the ash- and sulfur dioxide-producing mineral matter distributed throughout the coarse coal are more easily separated from the cleaner-burning coal. Third, with a long tradition of coal use, Pennsylvania has large quantities of such refuse available as a potential resource of coal-based slurry fuels.

A model that considers the costs to produce the boiler retrofit fuel, the costs to transport MCWM to the retrofitted boilers, and the capital and operation/maintenance costs of retrofitting was used to estimate the market penetration of the technology. The model minimizes the cost to boiler owners given the location of each boiler, its individual characteristics, and the location of each possible source of MCWM. The decision to retrofit is assumed to be made if the total costs of retrofitting are less than the costs to continue firing oil or gas. The model is 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 MCWM (general equilibrium impacts are taken into account below). Another assumption is that there would be no increase or decrease of boiler utilization due to displacing other types of boilers at a given site. A firm may own several different types of boilers at a single site and choose to operate the ones that provide the greatest competitive advantage at a particular point in time.

Cost curves for transportation, capital costs of retrofitting, and operation were developed. One of the key features of this model is its recognition that the production of

fuels at each supply point is subject to economies of scale. That is, the per unit cost of MCWM production fell as production at a single supply point increased.

Ideally, the model would be run with detailed data on several thousand boilers in Pennsylvania. The approach taken by Schaal (1995) was to simplify the data gathering effort by concentrating the detailed analysis to a subregion and then generalizing the results to the State as a whole.

Candidate industrial boiler retrofits were drawn from a census of boilers obtained from the Pennsylvania Department of Labor and Industry (1994). This census included all types of boilers that were insured for use during 1992-1993. The data provided were classified as to the particular boiler type in use at each location as summarized in Table 5-1. This allowed for a 'first-pass' sifting of the database to isolate a subset of boilers for further analysis. Since the retrofit technology only applied to water-tube boilers, the total number of existing retrofit candidates was reduced to 6,936. Limiting the analysis to the Indiana-Cambria two-county region further reduced the number of boilers to 462. Reducing the population space to a few hundred boilers enabled detailed data to be gathered on nearly 60 percent of these boilers.

This analysis provides a range of boiler adoption estimates based on a combination of pessimistic and optimistic assumptions. On the low side, the two-county market penetration model identified only 6 boilers out of 462, or 1.3 percent, as economically viable for retrofit, which translate into only 90 boilers in the entire State. A further pessimistic assumption made to establish a floor on market penetration was to consider the distribution of boilers throughout Pennsylvania. As shown in Figure 5-1, it can be seen that the boilers located in the eastern part of the State are not readily served from the coal producing regions of the west central to southwestern parts of the State. With this consideration in mind, it was estimated that only 40% of water-tube boilers are located in areas that could consider retrofitting as a viable option. This result left an estimated 36 boilers in the State as economic to retrofit, with a total consumption of only 660 thousand tons of coal per year (Schaal, 1995).

In further work, Schaal (1997) considered several factors that may alter the outlook for market penetration of the technology. The first was that the distribution of boilers by size in the two-county region may not be representative of the Statewide boiler distribution. The capital costs of retrofitting also follow economies of scale with increasing boiler size, and a different size distribution of boilers may reveal a greater concentration of ideal boiler retrofits. The second factor was the sensitivity of the number of retrofits to the differential in cost between the incumbent fossil fuel (oil or gas) and the coal-based slurry fuel. Other sensitivities included interest rates and boiler utilization factors. In addition, the

Table 5-1. Summary of Pennsylvania Boilers by Type

Boiler	Number	Percent
Cast Iron	30,760	46.4
Fire Tube	12,093	18.3
Water Tube	6,936	10.5
Electric	4,228	6.4
Other	<u>12,245</u>	<u>18.5</u>
Total	66,262	100.0

Figure 5-1. Pennsylvania Water-Tube Boilers by 3-Digit Zip Code Region

assumption regarding eastern Pennsylvania boilers not having access to coal-based fuel sources was relaxed.

The retrofit technology is appropriate for boilers with allowable working pressures of at least 200 psig and under a maximum output of 200 MM Btu per hour. Data gathered from the two-county sample allowed estimation of boiler output from working pressure. The estimate of output allowed winnowing the population space for boiler retrofit candidates to 950 for the entire State and provided an improved estimate of their capital and operating costs of retrofitting.

The market penetration of the technology was found to be highly sensitive to the differential in fuel costs. Coal-based slurry fuel was projected to have a delivered price of \$1 per MM Btu. The weighted average price paid by the industrial sector for the fuels to be displaced was \$3.79 per MM Btu in 1993 (U.S. DOE/EIA, 1995). Combining a sensitivity analysis of differential fuel costs with the improved state-wide model of boiler size resulted in a more optimistic outlook for the market penetration of the technology as shown in Table 5-2. A minimum of \$2 per MM Btu is required before any retrofits are undertaken, while at \$3.80 per MM Btu all candidates are economic to retrofit. Table 5-3 summarizes the Pessimistic, Base, and Optimistic levels of market penetration of the retrofit technology used in modeling the impacts of technology adoption on the Pennsylvania economy.

5.1.3 The Pennsylvania CGE Model

This section summarizes the model used to perform the general equilibrium impacts of new coal-water slurry boilers. The reader is referred to Li (1994) for a detailed presentation of the model equations, data upon which it is based, and the manner of model construction.

The selection of a model framework was based on the following criteria:

1. It must reflect the economic characteristics of Pennsylvania—an industrialized and highly interdependent economy.
2. It must include the manufacturing sector's ability to adopt new technology—industries' ability to substitute among fuel inputs in the production process.
3. It must be able to model the economy's energy trade balance—the relative competitiveness of indigenous fuels with respect to those imported from other states and other countries.
4. It must be able to address both microeconomic and macroeconomic aspects of energy and environmental policy—both sectoral and economy-wide impacts.

The modeling framework chosen was the computable general equilibrium (CGE) analysis. This approach depicts an economy-wide equilibrium, in which all agents

Table 5-2. Pennsylvania Market Penetration Results at Varying Differential Fuel Cost

Differential Fuel Cost (\$/MM Btu)	Number of Retrofits	Viable Population (percent)	Retrofit TCR (10 ⁶ \$)	Retrofit Savings (10 ⁶ \$/yr)	MCWM Consumption (10 ¹² Btu)	Increased Coal Consumption (10 ³ tons)
2.04	63	7	459	4.5	28.8	1,210
2.29	122	13	806	14.1	47.4	1,988
2.54	140	15	897	26.6	51.7	2,171
2.79	237	25	1,304	41.1	68.6	2,887
3.04	360	38	1,748	59.2	85.4	3,584
3.29	611	64	2,607	86.6	116.3	4,879
3.54	635	67	2,678	116.0	118.6	4,976
3.79	950	100	3,545	150.9	145.1	6,088

^aAnalysis assumes the following:

Boiler utilization rate—40%
Transportation radius—25 miles
Interest rate—8%
Useful life—20 yrs.

Table 5-3. Market Penetration Estimates for Three Scenarios

	Pessimistic	Base	Optimistic
Number of Retrofitted Boilers	36	276	551
Estimated Additional Coal Consumption, thousand tons per year	662	2,534	5,068
Percentage Change in Pennsylvania Industrial Sector Coal Demand	5%	18%	35%
Percentage Change in Pennsylvania Total Coal Demand	1%	5%	9%

independently maximize their own objective functions in response to price signals and subject to resource, technology, and income constraints. CGE modeling is a widely used approach in taxation, trade, and regulatory impact modeling (see e.g., surveys by Shoven and Whaley, 1984; and Bandara, 1991). CGE overcomes the drawbacks of other models by including aggregate macro information, sectoral distinctions, economic interdependencies, price-response mechanisms, competitiveness features, resource constraints, and substitution possibilities. Its strong features best satisfy our model selection criteria.

Overview of the Model

The Pennsylvania CGE model is a long-run, static, single-region model based on the following assumptions:

1. The product and factor markets are competitive, i.e., no economic agents are able to exercise monopoly power in the markets.
2. The State of Pennsylvania is a small, open economy, i.e., it has little or no influence on the supply and demand of goods in the national economy or their prices.
3. Monetary variables do not play an explicit role, i.e., transactions are in *real* terms.
4. Technological change (both embodied and disembodied), other than that associated with new boiler adoption, is not explicitly taken into account in the period of study.
5. Prices are flexible enough to assure the existence of a general equilibrium; producers and consumers can fully adjust without any time lag after external shocks.

The major features of the model are its emphasis on production technology and its focus on trade theory. The structure of input demand in this model resembles that of several well-known national and regional CGE models (e.g., the model developed by Robinson et al., 1990, 1993, and the regional model by Kraybill, 1990). Important modifications are made in the specification of the production technology for energy and materials. The model adopts a two-part production function, in which the intermediate inputs are assumed to follow a fixed-coefficient Leontief technology, and the two primary inputs, capital and labor, are modeled using a two-tiered, or nested, Generalized Leontief cost function. The first tier allows substitutions among capital (K), labor (L), energy (E), and materials (M). The second tier specifies interfuel and intermaterial substitutions inside the energy and material aggregates.

The overall structure of this model is illustrated by a schematic diagram in Figure 5-2. Basically, there are four interrelated components: production, trade, demand, and income. Each component is further decomposed into several parts. The arrows in the diagram show the interlinkages of different parts in the model. When all economic agents interact together and jointly optimize their objective functions, a set of endogenous equilibrium prices is determined to clear all markets in the economy.

The Choice of Functional Form

The specification of production technology in an empirical analysis requires the selection of a suitable functional form. Cobb-Douglas, CES, and Leontief functions were rejected because of their undesirable properties, such as predetermined restrictions on the elasticities of substitution. Instead, flexible function forms were chosen, which are second-order approximations of a technology and place no a priori restriction on substitution possibilities.

The use of flexible functional forms is not without limitations. The separability assumption widely adopted in economic research imposes restrictions on their flexibility. Another problem lies in the ability of flexible functions to approximate arbitrary technologies globally, because these functions are only second-order numerical or differential approximations at a point. Still another is the possibility of violating concavity conditions.

The two-tiered Generalized Leontief (GL) cost functions approach chosen for the models was used for the following reasons:

1. The elasticities of substitution between inputs may be a mix of low and high levels.
2. GL functions involve fewer parameters to be calibrated or estimated than other flexible functional forms.
3. For intermediate inputs other than K, L, E, and M, fixed input proportions were assumed. Since the GL form collapses to a Leontief function under certain conditions, intuitively, it seems desirable to choose the GL form for consistency. The GL form generally performs better in cases with low elasticities or a mixture of high and low elasticities, while the TL form is apparently preferable for high elasticities (see e.g., Caves and Christensen, 1980; Despotakis, 1986). In addition, different functional forms may yield quite different results for the same data set and the same economic assumptions (Baffes and Vasavada, 1989).

Figure 5-2. Schematic Diagram of the Pennsylvania CGE Model

Trade

For an open, regional economy like that of Pennsylvania, trade is very important and must be carefully handled conceptually and empirically. In CGE analysis, there are two approaches to modeling the terms of trade in a small, open economy. One method assumes product homogeneity among countries or regions. The other approach specifies product differentiation by country (or region) of origin into the demand structure.

The first approach can be regarded as an application of traditional trade theory. It is theoretically attractive but may turn out to be too restrictive for a large scale CGE model. The widely accepted Armington (1969) assumption can free CGE models from the limitation of traditional trade theory, by stipulating that similar goods originating from different countries (or regions) are imperfect substitutes. Thus, domestic consumers of commodities within one aggregated sector actually consume a mixture of domestically produced and imported goods.

There are various reasons to justify this approach. Bergman (1982) found that in a relatively aggregated CGE model, the aggregated indices for import prices, import quantities, domestic production costs, and domestic production are correlated. Another reason is the commonly observed cross-hauling problem associated with imperfect trade statistics or highly aggregated data. This phenomenon can be easily explained and handled by the Armington assumption. In addition, the Armington assumption can avoid the occurrence of unrealistically strong specialization effects when a change in trade policy is modeled with traditional trade theory.

The treatment of trade in the Pennsylvania CGE model follows the traditional small, open economy assumption, with the application of the Armington assumption on the import demand side. Trade with other regions and foreign countries is modeled as a two-stage decision process. The world prices of imports, the prices of imports from other regions, the world prices of exports, and the prices of exports to other regions are all exogeneously given. On the import side, the consumer, at the first stage, maximizes the utility of consuming composite goods subject to a budget constraint by substituting between foreign goods and domestic goods. At the second stage, a choice is again made between locally produced goods and goods from other regions. At each stage, the Armington assumption is employed and a constant elasticity of substitution (CES) function is used to aggregate imperfect substitutes. On the export side, the producer, at the first stage, minimizes the cost of producing joint products to furnish domestic consumption and foreign demand. Then, at the second stage, the producer again makes supply decisions between local sale and export supply to other regions. At each stage, a constant elasticity of transformation (CET) function is used for aggregation. This two-stage decision structure and the

specification of imperfect substitution and transformation imply assumptions of separability and the lack of income effects.

Model Closure and Macro Balances

The model closure problem in general equilibrium models is synonymous with the overidentification problem in a mathematical simultaneous equation system. To solve this problem, either one constraint has to be dropped from the model, or one previously exogenous variable or model parameter must be determined endogenously. This process is called the imposition of a closure rule in general equilibrium models. Following Sen's taxonomy (Sen, 1963), four types of closure rules are usually adopted by modelers in CGE analysis:

1. Classical: Full employment is achieved, and the economy-wide wage rate is forced to adjust endogenously. Aggregate investment is endogenous and financed by total savings.
2. Keynesian: Unemployment is allowed to happen in the economy. The economy-wide average wage rate is fixed, and labor supply is determined endogenously.
3. Kaldorian: Full employment is attained, and aggregate investment is set exogenously. Aggregate investment is equated to total savings through the endogenous adjustment of the price level and the functional distribution of income.
4. Johansen: Full employment is achieved and aggregate investment is set exogenously. Government expenditures and tax revenues adjust endogenously to restore the savings-investment balance.

The closure rule adopted here is classical, which is consistent with the long-run nature of the Pennsylvania CGE model. In addition to the closure rule, a set of macro balancing identities is necessary to make the CGE model consistent. These are producer's equilibrium, goods market clearing, the government budget deficit, the balance of trade, and an investment-savings identity.

Factor Mobility

Factor mobility is an important empirical issue, especially in regional economic modeling. Two types of mobility must be considered: factor mobility across sectors and factor movements across regions. In most CGE models, labor is assumed to be perfectly mobile across sectors, while capital is modeled as sector specific in the short run and fully mobile across sectors in the long run. In the Pennsylvania CGE model, both labor and capital are assumed to be fully mobile across industries. Given the long-term nature of the model and the fact that the Pennsylvania economy is well developed and highly

industrialized, this modeling decision should have less impact on the accuracy of the estimates than other simplifications that were adopted.

Interregional capital movement can be easily modeled by setting net regional savings as endogenous. Interregional labor movement, on the other hand, poses more difficulty. Interregional labor movement may be the result of natural migration, a change of workers' preference, and a change in spatial employment patterns due to external shocks. For example, a more stringent environmental regulation may exert relatively heavier pressure on Pennsylvania coal industries compared to the other states. Therefore, the unemployed Pennsylvania coal miners may consider moving to adjacent coal producing states or exiting the industry.

The ideal approach to modeling interregional labor mobility is the expression of migration as a function of explanatory variables based on observed data. Such attempts in CGE analysis have been limited, however, as in the treatment of partial labor mobility by Whalley and Trela (1986) and the impressive work by Norrie and Percy (1983).

Alternatively, in a manner consistent with the Classical closure rule, a fixed labor supply is assumed for the initial simulations. This assumption is then relaxed in a sensitivity test that calls for any unemployed workers migrating to other states, or any excess demand for labor being completely satisfied by workers immigrating to Pennsylvania from other states. This approach essentially models labor mobility as a residual; however, it is an endogenous determination of this important variable. Note that, although the labor supply is varied, a pure Keynesian closure rule is not used, which would allow for an underemployment equilibrium. Such an outcome is reasonable for a (closed) national economy in the long run, but it is more typical (and reasonable) in regional modeling to assume that labor migration moves the non-structural unemployment rate toward zero in the long run for any given region (see also Kelkenny and Robinson, 1990).

5.1.4 Application

MCWM conversion was simulated in the five major sectors that contain the majority of industrial boilers in Pennsylvania: Plastics, Glass, Stone and Clay, Nonferrous Metals, and Other Manufacturing. For lack of more detailed information, it was assumed that the same target conversion for each sector in terms of increased coal consumption (see the second row of each partition of Table 5-4). This, however, results in differing percentages of petroleum replacement among sectors (see the last row of each partition in Table 5-4), with the Stone and Clay product sector being the locus of the greatest percentage displacement of oil.

The results of the simulations are presented in Tables 5-5 and 5-6 under varying conditions relating to CGE model closure and import conditions. The former refers to

Table 5-4. Calculation of Coal Substitution for Petroleum in Boiler Retrofit Sectors

<u>Pessimistic Scenario (4.6%)</u>	Nonferrous Metals	Plastic	Glass	Stone	Other Manufac
Base Coal consumption (\$)	2137	1190	334	20045	76564
Increased coal consumption (%Δ)	4.60	4.60	4.60	4.60	4.60
Increased coal consumption (\$)	98	55	15	922	3522
Increased coal consumption (ton)	3	2	1	31	117
Increased coal consumption (mmBtu)	86	48	13	804	3071
Replaced petroleum consumption (mmBtu)	86	48	13	804	3071
Replaced petroleum consumption (bbl)	14	8	2	134	512
Replaced petroleum consumption (\$)	312	174	49	2927	11179
Base petroleum consumption (\$)	24870	20846	10730	11201	417309
Replaced petroleum consumption (%Δ)	1.25	0.83	0.45	26.13	2.68
<u>Mid-Range Scenario (17.5%)</u>	Nonferrous Metals	Plastic	Glass	Stone	Other Manufac
Base coal consumption (\$)	2137	1190	334	20045	76564
Increased coal consumption (%Δ)	17.50	17.50	17.50	17.50	17.50
Increased coal consumption (\$)	374	208	58	3508	13399
Increased coal consumption (ton)	12	7	2	117	447
Increased coal consumption (mmBtu)	326	182	51	3059	11684
Replaced petroleum consumption (mmBtu)	326	182	51	3059	11684
Replaced petroleum consumption (bbl)	54	30	8	510	1947
Replaced petroleum consumption (\$)	1187	661	186	11134	42529
Base petroleum consumption (\$)	24870	20846	10730	11201	417309
Replaced petroleum consumption (%Δ)	4.77	3.17	1.73	99.40	10.19
<u>Optimistic Scenario (35.0%)</u>	Nonferrous Metals	Plastic	Glass	Stone ^a	Other Manufac
Base coal consumption (\$)	2137	1190	334	20045	76564
Increased coal consumption (%Δ)	35.00	35.00	35.00	17.50	35.00
Increased coal consumption (\$)	748	417	117	3508	26797
Increased coal consumption (ton)	25	14	4	117	893
Increased coal consumption (mmBtu)	652	363	102	3059	23367
Replaced petroleum consumption (mmBtu)	652	363	102	3059	23367
Replaced petroleum consumption (bbl)	109	61	17	510	3895
Replaced petroleum consumption (\$)	2374	1322	371	11134	85057
Base petroleum consumption (\$)	24870	20846	10730	11201	417309
Replaced petroleum consumption (%Δ)	9.55	6.34	3.46	99.40	20.38

Price of coal is \$30/ton; price of refined petroleum is \$21.84/bbl.

Heat content of coal is 26.16 million Btu/ton; heat content of refined petroleum is 6 million Btu/bbl.

^aFigures are the same as Mid-Range Scenario so as not to exceed 100% substitution.

Table 5-5. Macroeconomic Impacts of Industrial Boiler Retrofit using MCWM Technology --All Scenarios (percentage change)

Variable	Case I	Case II	Case III	Case IV
<u>Pessimistic Scenario (4.6%)</u>				
Real GRP	0.010	0.043	0.003	0.021
Price Index	0.002	0.004	0.003	0.004
Total industry output	0.001	0.036	-0.014	0.000
Total employment	—	0.044	—	0.029
Total regional exports	-0.022	-0.004	-0.046	-0.048
Total regional imports	0.044	0.093	0.031	0.057
Total foreign exports	-0.060	-0.020	-0.083	-0.070
Total foreign imports	-0.048	-0.014	-0.068	-0.057
<u>Mid-Range Scenario (17.5%)</u>				
Real GRP	0.026	0.107	0.009	0.051
Price Index	0.011	0.014	0.012	0.014
Total industry output	0.001	0.087	-0.038	-0.005
Total employment	—	0.108	—	0.068
Total regional exports	-0.049	-0.006	-0.113	-0.118
Total regional imports	0.119	0.239	0.081	0.141
Total foreign exports	-0.145	-0.046	-0.206	-0.175
Total foreign imports	-0.117	-0.033	-0.169	-0.143
<u>Optimistic Scenario (35.0%)</u>				
Real GRP	0.041	0.169	0.014	0.079
Price Index	0.018	0.023	0.020	0.024
Total industry output	0.001	0.136	-0.063	-0.011
Total employment	—	0.170	—	0.105
Total regional exports	-0.075	-0.008	-0.180	-0.187
Total regional imports	0.194	0.384	0.129	0.222
Total foreign export s	-0.240	-0.083	-0.338	-0.291
Total foreign imports	-0.193	-0.061	-0.277	-0.238

- Case I: No restrictions on regional coal imports, classical closure rule.
Case II: No restrictions on regional coal imports, Keynesian closure rule.
Case III: Fixed regional coal imports, classical closure rule.
Case IV: Fixed regional coal imports, Keynesian closure rule.

Table 5-6. Microeconomic Impacts of Industrial Boiler Retrofit Using MCWM Technology --
Mid-range Scenario for Key Sectors (percentage change)

Sector/ Variable	Case I	Case II	Case III	Case IV
<u>Coal</u>				
Price	0.027	0.023	0.053	0.047
Industry output	0.700	0.794	1.544	1.612
Employment	0.686	0.806	1.538	1.625
Regional exports	0.669	0.766	1.508	1.579
Regional imports	0.894	0.958	—	—
Foreign exports	0.536	0.673	1.383	1.482
Foreign imports	—	—	—	—
<u>Oil & natural gas</u>				
Price	-0.086	-0.060	-0.080	-0.062
Industry outputs	0.020	-0.044	0.010	-0.039
Employment	0.023	-0.012	0.022	-0.007
Regional exports	0.024	-0.042	0.029	-0.024
Regional imports	-0.488	-0.380	-0.481	-0.421
Foreign exports	-0.122	-0.145	-0.135	-0.151
Foreign imports	-0.344	-0.279	-0.351	-0.321
<u>Nonferrous metals</u>				
Price	0.029	0.032	0.030	0.033
Industry output	-0.205	-0.068	-0.428	-0.444
Employment	-0.214	-0.056	-0.430	-0.432
Regional exports	-0.237	-0.112	-0.463	-0.490
Regional imports	0.107	0.255	-0.106	-0.115
Foreign exports	-0.412	-0.236	-0.627	-0.616
Foreign imports	0.459	0.503	0.224	0.139

- Case I: No restrictions on regional coal imports, classical closure rule.
Case II: No restrictions on regional coal imports, Keynesian closure rule.
Case III: Fixed regional coal imports, classical closure rule.
Case IV: Fixed regional coal imports, Keynesian closure rule.

whether we assume a full employment economy (classical closure rule) or allow for underemployment equilibrium (Keynesian). The latter refers to whether we allow for some of the increased coal use to be imported from other states versus insisting it all be Pennsylvania coal.

The results of the various cases (in effect, sensitivity analyses) are relatively similar in qualitative terms. For example, in the Pessimistic Scenario, coal boiler conversion has a positive impact on the Pennsylvania economy, but only in the range of a 0.003% to 0.043% increase in Gross Regional Product (GRP). It also results in upward pressure on prices, though only to a minuscule extent. The Optimistic Scenario calls for GRP increases ranging from 0.014% to 0.169%. The fact that the GRP effects increase by a factor of 4 when the conversion target increases by a factor of 8 reflects the nonlinearities inherent in the model.

Just how significant are these numbers? The Pennsylvania GRP is about \$200 billion annually, so a 0.1% increase is \$200 million. A 0.1% increase in employment is 6,000 jobs, which is a significant impact in human terms.

The impacts on selected sectors are presented in Table 5- 6 for the Mid-Range Scenario (17.5% substitution). For example, coal industry output is projected to increase by 0.7% to 1.6%. There is also a slight increase in coal prices, but the results in Table 5-5 indicate that this has no overall injurious effect on the State's economy.

The impact on the State's Oil and Gas sector is much smaller in percentage terms than the increase in coal output, for the main part, because the majority of the feedstock for oil-fired boilers is imported from other states. Moreover, the decrease in the price of oil and gas as a result of lower demand following conversion is a positive stimulus to the State's economy.

The results for the Nonferrous Metals industry indicate a very slight price increase and a small decrease in output. The model is still being examined to provide more insight into why these take place.

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 Evaluation of Dry Grinding/Classifier Circuit

Experimental data obtained from laboratory studies of jet milling and air classification of Upper Freeport seam coal are being used to evaluate the use of closed-

circuit dry grinding for fine coal production. The classification results were obtained using a Donaldson, Acucut classifier and have been used to establish performance data (size-selectivity curves) for that device. The grinding studies were carried out in a Majac Mini-Grinder (jet mill) operated in closed-circuit with the Acucut classifier. Because of the very limited amount of grinding which occurs in each pass through the mill, it is not feasible to obtain direct measures of the breakage characteristics (breakage rate, primary breakage distribution). Consequently, this information has to be obtained indirectly by circuit simulation using the experimental classifier size-selectivity data and an iterative search procedure to estimate the breakage parameters. In the absence of a general body of information on the breakage characteristics associated with jet milling, it is necessary to evaluate a variety of potential models for the breakage process and, in particular, for the size dependence of the breakage parameters.

7.2 Subtask 1.2 Physical Separations

7.2.1 Fine Coal Classification

The fine-coal classification tests using the continuous, solid-bowl centrifuge were completed. The last series of tests was conducted using weir setting 3, which gave the second deepest pool setting (i.e., setting 1 = shallowest pool, setting 4 = deepest pool). These tests were also run at a slurry feed rate of 11.4 L/m (3 gpm) and a solids concentration of 10% coal (by weight) using -100 mesh Upper Freeport seam coal. The centrifuge bowl and scroll speeds were both varied as before. Table 7-1 summarizes the operating conditions for this series of tests.

As was done previously, the coarse (scroll discharge) and fine (weir overflow) streams were sampled and dried. A sample of each product was then analyzed using a Microtrac X-100 particle size analyzer. Figure 7-1 shows the reconstituted (calculated) feed size distribution and product size distribution curves for centrifuge tests 1 and 2. As can be seen, the product size distribution of the weir discharge stream for test 2 was finer than that of test 1, while the scroll discharge was coarser. This demonstrates the ability to change the size distributions of the product streams by varying the scroll speed.

The circulation ratio (defined as the mass flow rate of the coarse fraction divided by the mass flow rate of the fine fraction) was calculated using the size distribution data and the least absolute sum technique (as described in a previous report). Using the circulation ratio, along with the size distribution data, the size selectivity values were determined. These values were then fitted to the logistic function using a non-linear optimization routine to determine the cut size (d_{50}), sharpness index (SI), and apparent bypass (a). The fitted parameters are given in Table 7-1, and the curves are shown in Figure 7-2. Overall, the cut size of the centrifuge ranged from about 7 to 10 μm . The sharpness indexes were very

Table 7-1. Summary of the Operating Conditions and Test Results for the Solid-Bowl Centrifuge (feed rate = 11.4 L/min, weir setting three (second deepest pool), solids concentration = 10% by weight).

Test	Main Speed (rpm)	Back Drive (rpm)	Circulation Ratio	d ₅₀ (μm)	κ	a
1	4,600	4,125	7.93	7.4	0.52	0.41
2	4,600	3,650	5.83	7.0	0.59	0.22
3	4,600	2,700	4.10	10.5	0.54	0.29
4	4,600	800	14.42	7.2	0.50	0.65
5	3,750	1,850	9.01	8.6	0.53	0.48

Figure 7-1. FEED AND PRODUCT SIZE DISTRIBUTIONS FOR CENTRIFUGE TESTS 1 AND 2 WHEN SEPARATING -100 MESH UPPER FREEPORT SEAM COAL
(test 1: filled symbols, test 2: open symbols)

Figure 7-2. EFFECT OF BACK DRIVE SPEED ON THE SIZE SELECTIVITY CURVES IN THE SOLID-BOWL CENTRIFUGE

similar and ranged from 0.50 to 0.59. As was seen at other weir settings, the bowl and scroll speeds impacted the apparent bypass values significantly, which ranged from 0.22 to 0.65 (Table 7-1). Such high bypass values indicate that a substantial fraction of the feed coal is reporting to the coarse stream, resulting in a finer size distribution of the coarse material. On the other hand, the bypass does not affect the size distribution of the fine stream.

In cases when the sharpness indexes are similar (as for these tests), it is possible to reduce the size selectivity curves to a single reduced classification curve. First, the classification values for a given test are calculated by

$$c_i = (s_i - a)/(1 - a)$$

where s_i is the size selectivity value for a given size interval and a is the apparent bypass. A plot of the classification values versus size gives a curve ranging from 0 to 1. As noted in a previous report, the cut size and sharpness index are derived directly from the classification curve. The reduced classification curve is then generated by plotting the classification values versus the reduced size (defined as the size divided by the cut size). The reduced curve for centrifuge tests 1-4 is shown in Figure 7-3.

Except for test 1, the values fall on a single curve. In such cases, this curve can be used to predict separator performance. For example, by selecting an appropriate cut size and apparent bypass, it is possible to generate the corresponding size selectivity values, which in turn can be used to calculate the product size distribution for a given feed size distribution.

7.3 Subtask 1.3 Surface-Based Separation Processes

7.3.1 Evaluation of Flotation System Performance

The rate constants for the batch, batch with no paddling (batch*), and pilot plant tests are given in Table 7-2 for different frother concentrations. In these tests the batch data refers to a typical kinetics test in which froth is removed continuously by manual paddling. A comparison of the rate constants for the three cases is given in Figure 7-4 in which the data are plotted as a function of frother concentration. The plant data refers to the flotation kinetics tests obtained in the pilot plant circuit consisting of four cells. The data marked as batch* refers to the tests in which no paddling was employed and the froth was allowed to flow on its own accord. The results confirm that froth mobility plays a very significant role in determining the overall kinetics in a continuous operation. This effect is commonly ignored in laboratory testing. At the beginning of this project motorized paddles were placed on top of the laboratory cell but were found to be unsatisfactory. A large number of particles were sticking to the paddles. The froth factor, defined as the ratio of the rate constant for the laboratory test to the pilot plant test or the batch flotation rate without

Figure 7-3. REDUCED CLASSIFICATION CURVE FOR CENTRIFUGE TESTS 1-4

Table 7-2. Flotation Rate Constants and Froth Factors

Frother conc. (kg/T)	Rate constants (min^{-1})			Froth Factor ($k_{\text{lab}}/k_{\text{plant}}$)	
	Batch	Batch*	Plant	Batch*	Plant
0.2	1.7517	0.5995	0.1149	2.92	15.25
0.3	1.9205	0.7198	0.1356	2.67	14.61
0.4	2.1737	0.9704	0.2505	2.24	8.68
0.45	2.0228	0.9068	0.2601	2.23	7.78
0.5	2.0528	0.8636	0.1912	2.38	10.74

Table 7-3. Change in Flotation Rate Constants and Froth Factors Due to the Addition of Collector for the Batch, Batch with no Paddling (Batch*), and Pilot-Plant Tests.

Collector conc. (kg/T)	Rate constants (min^{-1})			Froth Factor ($k_{\text{lab}}/k_{\text{plant}}$)	
	Batch	Batch*	Plant	Batch*	Plant
0	1.9205	0.7198	0.1356	2.67	14.16
0.1	2.5493	0.9068	0.2964	2.81	8.60

Figure 7-4. COMPARISON OF FLOTATION RATE CONSTANTS FOR THE BATCH, BATCH WITH NO PADDLING (BATCH*), AND PILOT PLANT TESTS AT DIFFERENT FROTHER CONCENTRATIONS

paddling, is a function of the frother concentration. In the presence of an oily collector, such as dodecane, the froth factor was smaller as can be seen from the results in Table 7-3 and Figure 7-5. These results are not surprising since the collector is likely to increase froth stability.

From these studies one may conclude that the lower than expected recovery in the pilot plant flotation circuit were due to low mobility and less stability of the froth. It should be possible to improve the performance with the help of a frother which is likely to give a more mobile froth. The use of an appropriate frother will also improve the recovery of coarse particles in the pilot plant operation.

8.0 PHASE III, TASK 2 EMISSIONS REDUCTION

8.1 Subtask 2.1 SO₂ Reduction

No work was conducted in Subtask 2.1 during this reporting period.

8.2 Subtask 2.2 NO_x Reduction

8.2.1 Research Objectives

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. O₂ concentrations of 3-5 vol.%;
 3. H₂O concentration of 10-20 vol.%;
 4. SO₂ concentrations of 500-1,000 ppm;
 5. NO concentrations of 100-500 ppm;
 6. No regeneration of sorbent/catalyst required; and
 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.

8.2.2 Current Status of the Bench-Scale Catalyst Tests

A new series of Bench-scale tests of the NOxCat® LT 920 catalyst (supplied by Engelhard Corporation for this study) is commencing to supplement the tests that were completed in Fall 1996. This previous bench-scale work was summarized in a previous

Figure 7-5. EFFECT OF COLLECTOR ADDITION ON FLOTATION RATE CONSTANT FOR THE BATCH, BATCH WITH NO PADDLING (BATCH*), AND PILOT PLANT TESTS

semiannual technical progress report (Miller et al., 1996b). These new tests were suggested by Engelhard to determine a critical parameter for demonstration-scale and future commercial application of this process. The objective of the new tests is to examine the influence on catalyst behavior of changes in precious metal loading on the catalyzed monoliths. Since the recommendation from the bench-scale tests is to operate this catalyst at low space velocity, the implementation of the catalyst will require large catalyst volumes. A larger catalyst volume means a larger capital expenditure for the catalyst because of both the cost of the precious metals and the support materials. If the precious metal loading can be decreased without an appreciable change in catalyst performance, a significant cost saving could be achieved.

8.2.3 Current Status of Pilot-Scale Testing

The bench-scale testing was extended to the pilot-scale through use of Penn State's down-fired combustor (DFC). Preliminary pilot-scale tests were completed in early 1997 and examined the operation of a larger sample of the NOxCat® LT 920 catalyst while the DFC was fired on natural gas. These tests confirmed the observations of the bench-scale tests with a simplified (SO₂ free) flue gas. Subsequent pilot-scale tests, planned tentatively for November 1997, will examine the behavior of the catalyst during simultaneous deSO_x-deNO_x operation, wherein a dry sorbent and ammonia will be injected into the flue ductwork of the DFC. Catalyst samples will be mounted in one of the nine filter bags of the DFC baghouse, while blank monoliths will be mounted in the other 8 bags to provide equal pressure drop through each bag. The NO_x conversion and catalyst selectivity will be monitored across the catalyzed filter bag.

8.3 Subtask 2.3 VOC and Trace Elements

No work was conducted on Subtask 8.3 during this reporting period.

9.0 PHASE III, TASK 3 ECONOMIC ANALYSIS

Phase III, Task 3 has been completed except for Subtask 3.8, integration of analysis. No work was conducted on Subtask 3.8 during this reporting period.

10.0 PHASE III, TASK 4 EVALUATION OF DEEPLY-CLEANED COAL AS BOILER FUELS

Activities in Task 4 included receiving three deeply-cleaned coals from Cyprus-Amax. In addition, one parent coal was also received.

10.1 Subtask 4.1 Modify MCWM Preparation Circuit

Subtask 4.1 was previously completed.

10.2 Subtask 4.2 Fuels Characterization

During this reporting period, the remaining deeply-cleaned filter cake samples were received from Cyprus-Amax. A total of 205 nominal one ton supersacks have been

delivered to Penn State where they are currently being stored. An itemized list of these samples is provided in Table 10-1. Only a limited amount of Indiana VII filter cake was shipped due to its reported high moisture content (> 50 wt.%).

A nominal 350 lb composite sample for each of the filter cake samples was produced by sampling the individual supersacks. The composite sample is being used to characterize the chemical composition and the slurryability of the six filter cake shipments. Proximate and ultimate analyses, calorific value, and ash fusion temperatures and major/minor elements are being determined for each composite sample. The slurryability of the filter cake has started. Slurryability is being determined using a two-pronged approach. Initially, the as-received filter cake is formulated without the use of viscosity or stability modifiers and without manipulating the particle size distribution to determine an as-received slurryability. The initial slurryability testing will be followed by a more extensive formulation. The second formulation step will involve the use of viscosity and stability modifiers (e.g., A-23M and Flocon 4800C, respectively) to produce a stable, highly loaded MCWM. If needed, the particle size distribution of the filter cake will be modified to improve slurry rheology and static stability. The filter cakes are currently undergoing the initial formulation step.

11.0 PHASE III, TASK 5 FINAL REPORT/SUBMISSION OF DESIGN PACKAGE

No work was conducted on this task.

12.0 MISCELLANEOUS ACTIVITIES

A project review meeting was held on June 11, 1997 at FETC (Pittsburgh). Representatives from DOE, the Corps of Engineers, and Penn State were in attendance.

13.0 NEXT SEMIANNUAL ACTIVITIES

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

- Complete the characterization of the ceramic filter system (i.e., $PM_{2.5}$ and PM_{10} , and condensable particulate matter measurements) and compare its performance to the fabric filter baghouse;
- Test the sodium bicarbonate duct injection system;
- Conduct pilot-scale NO_x catalyst tests;
- Interpret results from the Phase II 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 the final report for Phase II, Task 3, Economic Analysis;
- Complete NO_x reduction study (Phase II, Task 1);

Table 10-1. Summary of Cyprus-Amax Deeply Cleaned Filter Cakes

Coal	Cleaning Method	# Bags
Taggart	Column Flotation	50
Taggart	Oil Agglomeration	31
Hiawatha	Column Flotation	50
Hiawatha	Oil Agglomeration	66
Indiana VII	Column Flotation	1
Indiana VII	Oil Agglomeration	7

- Complete preliminary evaluation of BioLime as a SO₂/NO_x reduction strategy (Phase II, Task 1);
- Complete Phase III, Task 1, Coal Preparation/Utilization;
- Complete Phase III, Task 5, Economic Analysis;
- Complete initial and expanded MCWM formulation (Phase III, Task 1) and;
- Begin pilot-scale MCWM production (Phase III, Task 1).

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