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

Interim Report for the Period 03/27/1993 to 07/30/1993

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By
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The Pennsylvania State University
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MASTER

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EXECUTIVE SUMMARY

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

To achieve the objectives of the program, a team of researchers has been assembled from Penn State (Energy and Fuels Research Center (EFRC), Mineral Processing Section, Fuel Science Program, Department of Mineral Economics, and Polymer Science Program), ABB Combustion Engineering Systems (CE), AMAX Research and Development Center (AMAX), and Energy and Environmental Research Corporation (EER). These four organizations are the current members of the Consortium.

Phase I activities are focused on developing clean, coal-based combustion technologies for the utilization of both micronized coal-water slurry fuels (MCWSFs) and dry, micronized coal (DMC) in fuel oil-designed industrial boilers. Phase II research and development activities will continue to focus on industrial boiler retrofit technologies by addressing emissions control and pre-combustion (*i.e.*, slagging combustion and/or gasification) strategies for the utilization of high ash, high sulfur coals. Phase III activities will examine coal-based fuel combustion systems that cofire wastes. Each phase includes an engineering cost analysis and technology assessment. The activities and status of Phase I are described below.

The objective in Phase I is to deliver fully engineered retrofit options for a fuel oil-designed watertube boiler located on a DOD installation to fire either MCWSF or DMC. This will be 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.

TASK 1: COAL BENEFICIATION/PREPARATION

The initial objectives of Task 1 were to select appropriate coals which could meet the specific requirements of the project (low ash and low sulfur) and to prescribe the necessary cleaning steps. Longer-term objectives are to develop improved cleaning procedures which can be used to increase the yield of usable coal and to expand the reserve base of candidate fuels for retrofitted boilers.

Activities in Task 1 this reporting period included identifying and procuring coals, conducting washability studies, evaluating cleaning strategies, investigating optimum MCWSF characteristics with respect to particle size distribution and stabilization, developing a dry coal cleaning technique, and constructing a demonstration-scale fuel preparation facility.

Identification and Procurement of Candidate Coals and Determination of Their Liberation Potential

A set of five candidate coals has been selected, four have been procured, and coal analysis, determination of liberation potential, and liberation modeling have started. Conventional washability studies are in progress for all four coals. Fine washability studies have been initiated on the two high ash and high sulfur coals. The results of these tests will be used to establish the appropriate cleaning strategy for each coal.

Evaluation of Cleaning Strategies

Depending on the relative ease of cleaning of the medium and high ash coals, a general strategy involving appropriate combinations of fine-gravity and surface-based separations has been adopted. Fine gravity separations include cyclone, centrifuge, and magnetic fluid separations. Surface-based cleaning processes include advanced froth flotation, column flotation, and selective agglomeration.

Cyclone Separations

Simulations were performed to investigate the separation of 28x100 mesh coal in a conventional (36 cm) diameter cyclone using a suspension of magnetite and water with an apparent density of 1.28 g/cm³. As would be expected, sharper separations (i.e., lower $ep(x)$ values) were obtained for the coarser particles. If this treatment is extended to finer sizes, i.e., 100x400 mesh size fraction, the fractional recovery curves are much flatter. Consequently, longer separation times and/or higher g's are needed to improve the separation.

Work is continuing in this area investigating the effects of variable interactions on separation efficiency. Likewise, the effects of medium characteristics on cyclone performance are also being investigated, including the size distribution of the dense-medium solids. Simulation results will be compared to those obtained from actual dense-medium cyclone tests.

Centrifuge Separations

Testing is continuing with a "batch" centrifuge to investigate the effect of operating conditions on magnetite classification. The magnetite was obtained from the Pea Ridge Iron Ore Company of Sullivan, Missouri. This material was much finer than that used in commercial coal preparation facilities being nearly 100% < 15 μ m, with approximately 75% < 5 μ m. Even with such fine magnetite, it is likely that a density gradient will form, leading to a relative density differential in the overflow and underflow streams, which in turn can impact separation efficiency. Preliminary tests on the Upper Freeport (Type III; high ash and high sulfur) coal indicated that some of the higher-ash fraction of the coal was being retained in the separator. To minimize this effect, the overall length of the separator was reduced from 152 to 76 mm.

Magnetic Separation

A commercially available separator that uses a rotating magnetic fluid has been obtained recently on loan from DOE and is currently being installed. It will be used to evaluate the application of this technology to fine coal separations.

Advanced Froth Flotation

Flotation testing was initiated for the Pittsburgh and Upper Freeport seam coals. The specific objective was to enhance the separation efficiency of fine particles using a surfactant. Standard procedures were used to conduct tests and suitable models were used to determine the rate and ultimate recovery.

Column Flotation

A laboratory column is under fabrication. Orders for the column instrumentation have been placed and delivery is pending. Cominco and Mott Metallurgical bubble generators have been procured. The former employs high external shear to generate fine bubbles while the latter forces air through a porous media with an average pore opening of 2 μm . The effectiveness of each type of gas sparger in fine coal cleaning will be evaluated.

Selective Agglomeration

Studies of combined agglomeration flotation are being carried out. Pre-agglomerated coal has been separated by flotation. A substantial increase in separation efficiency was observed. Additional studies are in progress to determine the effect of key variables on the separation efficiency.

Establishment of the Required Size Consist for MCWSF Formulation

The size consist requirements in terms of the role of packing and particle interaction forces in determining MCWSF characteristics are being reevaluated. Calculations demonstrate the value of using a true bimodal size distribution for MCWSF formulation. The presence of intermediate sizes in a broad but continuous distribution will lead to reduced packing efficiency for a given solids loading.

Stabilization of Coal/Water Suspensions

Work that has been completed to date on this aspect of the project includes: (1) the construction of a modified form of the Dougherty-Krieger equation describing the dependence of CWSF viscosity on coal particle concentration and size distribution and (2) obtaining some initial models for the sedimentation or settling of the particles in a CWSF using an "effective medium approximation" (*i.e.* the viscosity expression obtained using the modified form of the Dougherty-Krieger equation).

In addition, the dynamics of settling and the equilibrium density profiles that are to be expected in various types of systems were examined. The approach used was systematic in the sense that what would be expected in a system of non-interacting particles (*i.e.* neglecting van der

Waals and Coulombic interactions, but not the "hydrodynamic interactions" (i.e. steric repulsions) that are characteristic of a concentrated slurry) were first considered. The next step is to add various types of interactions to the model and calculate the effect of these forces. The recent work has focused on Coulombic interactions.

Development of a Dry Coal Cleaning Technique

The equipment for assembling a dry grinding circuit was received. This circuit will be capable of providing a range of particle size distributions for TriboElectrostatic separation and will be used primarily to produce a micronized coal.

Work is continuing on the development of a dry beneficiation process based on TriboElectrostatic Separation. The electrostatic separator was modified and a series of shakedown tests was performed with the unit. The preliminary testing was performed using the Upper Freeport coal.

Construction of a Fuel Preparation Facility

The fuel preparation facility (MCWSF and DMC) associated with the demonstration boiler is approximately 75% complete. The DMC circuit is complete and work is underway setting up the MCWSF circuit.

TASK 2: COAL COMBUSTION PERFORMANCE

Activities in Task 2 include evaluating fuels, studying erosion/deposition characteristics of the coal inorganic constituents, determining erosion characteristics of materials subjected to atomized CWSF, and studying the theoretical and experimental particle behavior in the demonstration boiler.

Evaluating Fuels in the Research (1,000 lb steam/h) Boiler

During this reporting period, combustion tests were conducted to evaluate a coal-based fuel called mulled coal. The mulled coal that was produced into a CWSF was stored, pumped, atomized, and burned in a similar manner to other CWSFs tested at Penn State. The combustion performance of the slurried mulled coal was similar to that of the other CWSFs. The mulled coal that was fired as received was more difficult to handle (feed from the hopper to the burner via the screw feeder and eductor) than other pulverized coals tested at Penn State.

The tests that were conducted were short in duration. It is recommended that longer tests be conducted in order to make a detailed evaluation. To be able to conduct pulverized mulled coal tests in the research boiler at Penn State, the coal feed system would have to be modified and the flame scanner relocated within the boiler. In addition, for some commercial applications it is likely that mulled coal will be fired as a blend with pulverized coal, in which case the blend may have very different properties than the mulled coal alone. Tests should also be performed on the blend.

Evaluate Erosion/Deposition Characteristics

Recent work has focused on two areas: Improvement of the metal oxidation component of the erosion-corrosion model, and interpretation of the ash deposition measurements from the demonstration boiler.

Erosion Characteristics of Materials Subjected to Atomized CWSF

In order to obtain more information on atomizer operation and materials of construction, a study has been started to evaluate the erosive behavior of different materials when subjected to an atomized CWSF spray. The test facility, atomizer, CWSF transport and containment systems, mist elimination, material sample mounting, and sample orientation have been designed.

Theoretical and Experimental Studies of Particle Behavior in the Demonstration Boiler

In order to increase understanding of pulverized coal and CWSF turbulent jet flames in an industrial boiler, theoretical and experimental work have been initiated. Initial work includes computational modeling of natural gas firing in the demonstration boiler. The next stage of the modeling work entails the injection of pulverized coal particles and CWSF droplets into the furnace and following their combustion histories. An in-situ particle counter, sizer, and velocimeter will be used to obtain data to verify the model.

TASK 3: ENGINEERING DESIGN

Preliminary design work was initiated. EER visited Penn State to inspect Penn State's demonstration boiler site and fuel preparation facility, discuss various aspects of the designs to be completed, and receive guidance of the upcoming design efforts.

TASK 4: ENGINEERING AND COST ANALYSIS

Activities in Task 4 include selecting the boiler site for the conversion designs, developing a cost minimizing model for retrofitting an existing oil-fired boiler, and analyzing regional market considerations and impacts.

Boiler Selection

Penn State visited several military installations and has had discussions with both civilian and military personnel regarding the use of coal in the military. As a consequence of this activity, Penn State recommended to DOE the Naval Surface Warfare Center at Crane, Indiana as the site for the retrofit designs in Phase I of the program. Upon approval from DOE and DOD, Task 3 will begin.

Process Analysis of MCWSF and DMC

Two types of economic models were used to evaluate retrofitting an existing oil-fired boiler to fire CWSF. These are spreadsheet models and algebraic programming models using the general algebraic modeling system (GAMS). In addition, a stochastic analysis was performed using Crystal Ball, a forecasting and risk management program.

In summary, the GAMS models currently give net present values of retrofitting. They can be modified to yield payback periods as well. The GAMS models analyses are more general and should be used for centralized decision making, while the spreadsheet models are more suitable for specific site decision-making. A combination of net present value and payback period is often used to make commercial investment decisions. For retrofitting scenarios, when the output of the GAMS models is payback periods, as well as their current output, they will become invaluable as decision aids on retrofitting.

Regional Market Considerations and Impacts

An input-output model for an 8-county region surrounding the Crane Naval Weapons Center has been constructed using the IMPLAN Modeling System. A regional I-O table for 1990 and a set of multipliers were generated and the data is being verified by checking with local sources of information.

The regional I-O tables will be used to determine the economic impacts of using MCWSF and DMC at Crane and two or three other sites. The impacts of adoption of these combustion technologies on all DOD boilers within the state of Pennsylvania will also be analyzed. Simulations will be performed with both an I-O model and a computable general equilibrium model. The results will be compared to assess the relative strengths of these two modeling approaches.

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 and the first phase of the program is underway.

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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 (MCWSFs)
- Subtask 1.4 Develop Dry Coal Cleaning Technique
- Subtask 1.5 Produce MCWSFs and Dry, Micronized Coal (DMC) From Dry Clean Coal
- Subtask 1.6 Produce MCWSF 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 MCWSF 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 MCWSF/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 MCWSF and DMC
- Subtask 4.5 Analyze/Identify Transportation Cost of Commercial Sources of MCWSF 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 activities planned for Phase I are summarized below:

Task 1: The coal beneficiation and preparation effort is being conducted by Penn State's Mineral Processing Section with assistance from AMAX and Penn State's Polymer Science Program. This task involves identifying and procuring six coals that can 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 MCWSFs. The coals will be subjected to detailed characterization and used to produce laboratory-scale quantities of MCWSF. A fundamental study of MCWSF stabilization will be conducted. Additional activities include developing a dry coal cleaning technique and producing MCWSFs and DMC from the resulting cleaned coal.

Task 2: The EFRC is conducting the combustion performance evaluation with assistance from CE and Penn State's Fuel Science Program. The technical aspects of converting a fuel oil-designed boiler at a DOD facility will be identified in this task. All appropriate components will be 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 will be determined. As part of this task, MCWSF and DMC will be evaluated in EFRC's 15,000 lb

steam/h watertube boiler. CE will provide a proven coal-designed burner for retrofitting Penn State's boiler. In addition, CE will design the burner for the DOD boiler identified for retrofitting.

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

Task 4: An engineering cost analysis and technology assessment of MCWSF and DMC combustion will be performed by Penn State's Department of Mineral Economics and the EFRC with assistance from the industrial participants. The effort will involve 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 MCWSF and cleaned coal, determining community spillovers, and determining regional market considerations and impacts.

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

The accomplishments and status of Tasks 1, 2, 3, 4, and 5 are presented in Sections 2.0, 3.0, 4.0, 5.0, and 6.0, respectively. Section 7.0 discusses miscellaneous activities that were conducted. References and acknowledgments are contained in Sections 8.0 and 9.0, respectively. The project schedule is given in Figure 1-1, with a description of the milestones contained in Table 1-1.

2.0 TASK 1: COAL BENEFICIATION/PREPARATION

The initial objectives of this activity were to select appropriate coals which could meet the specific requirements of the project and to prescribe the necessary cleaning steps. Longer-term objectives are to develop improved cleaning procedures which can be used to increase the yield of usable coal and to expand the reserve base of candidate fuels for retrofitted boilers.

2.1 Subtask 1.1 Identify/Procure Coals

The Mineral Processing Section, with assistance from AMAX, selected a preliminary set of six candidate coals. The criteria used for the selection have been described previously (Miller et al. 1993b). Based on progress in boiler selection (Subtask 4.1), the list has been narrowed to five and is essentially finalized, subject to approval of the candidate boiler. The modified list and procurement status are presented in Table 2-1.

Task 1 - Coal Beneficiation/Preparation

1992 1993 1994

Figure 1-1. Milestone Schedule

Task 1 - Coal Beneficiation/Preparation 1992
(cont.)

1993

1994

Sept Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec Jan Feb Mar Apr

Subtask 1.4 Develop Dry Coal Cleaning Technique

Subtask 1.4.1 Dry Grinding Studies

Subtask 1.4.2 Deagglomeration Studies

Subtask 1.4.3 Dry Separations

Subtask 1.5 Produce MCWSFs and Micronized Coal from Dry, Clean Coal

Subtask 1.5.1 Produce Micronized Coal from Dry, Clean Coal

Subtask 1.5.2 Produce MCWM from Dry, Clean Coal

Subtask 1.6 Produce MCWSF and Dry, Micronized Coal for the Demonstration

Subtask 1.6.1 Shakedown Dry, Micronized Coal Circuit

Subtask 1.6.2 Install MCWSF Equipment

Subtask 1.6.3 Shakedown MCWSF Equipment

Subtask 1.6.4 Coal Cleaning

Subtask 1.6.5 Coal Micronizing

Subtask 1.6.6 MCWSF Preparation

Subtask 1.7 Project Management and Support

Subtask 1.7.1 Project Management and Technical Advisement

Subtask 1.7.2 Drafting / Technical Secretarial Support

Subtask 1.7.3 Budget Management / Project Administration

Task 2 - Combustion Performance Evaluation

1992

1993

1994

Sept Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec Jan Feb Mar Apr

Subtask 2.1 Boiler Retrofit

- Subtask 2.1.1 Finalize Burner/Atomizer Design
- Subtask 2.1.2 Procure and Install Burner
- Subtask 2.1.3 Optimize Burner Firing Dry, Micronized Coal
- Subtask 2.1.4 Optimize Burner Firing CWSF

Subtask 2.2 Fuel Evaluation in Research Boiler

- Subtask 2.2.1 Test Sample of Type I CWSF
- Subtask 2.2.2 Test Sample of Type II CWSF
- Subtask 2.2.3 Test Sample of Type III CWSF

Subtask 2.3 Performance Evaluation of MCWSF and Dry, Micronized Coal in Demonstration Boiler

Dry, Micronized Coal Testing

- Subtask 2.3.1 100-Hour Milestone
- Subtask 2.3.2 200-Hour Milestone
- Subtask 2.3.3 300-Hour Milestone
- Subtask 2.3.4 400-Hour Milestone
- Subtask 2.3.5 500-Hour Milestone
- Subtask 2.3.6 600-Hour Milestone
- Subtask 2.3.7 700-Hour Milestone
- Subtask 2.3.8 800-Hour Milestone
- Subtask 2.3.9 900-Hour Milestone
- Subtask 2.3.10 1,000-Hour Milestone
- Subtask 2.3.11 Technical Advisement by CE

Task 2 - Combustion Performance Evaluation(cont.)

MCWSF Testing

- Subtask 2.3.12 100-Hour Milestone
- Subtask 2.3.13 200-Hour Milestone
- Subtask 2.3.14 300-Hour Milestone
- Subtask 2.3.15 400-Hour Milestone
- Subtask 2.3.16 500-Hour Milestone
- Subtask 2.3.17 600-Hour Milestone
- Subtask 2.3.18 700-Hour Milestone
- Subtask 2.3.19 800-Hour Milestone
- Subtask 2.3.20 900-Hour Milestone
- Subtask 2.3.21 1,000-Hour Milestone
- Subtask 2.3.22 Technical Advice by CE

Evaluate Erosion / Deposition Characteristics

- Subtask 2.3.23 Identify Erosion and Deposition Regimes
- Subtask 2.3.24 Match Simultaneous Erosion and Deposition
- Subtask 2.3.25 Compare Heat Transfer Surface Performance
- Subtask 2.3.26 Procedure for Determining Optimum Convective Section Gas Velocity
- Subtask 2.3.27 Comparison of Performance of Three Tube Materials

[illegible]

Table 1-1. Milestone Description

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Task 1. Coal Beneficiation/Preparation			
Subtask 1.1. Identify/Procure Coals			
Subtask 1.1, No. 1	Establish selection criteria	10/15/92	10/15/92
Subtask 1.1, No. 2	Preliminary list of candidate coals	02/01/93	02/01/93
Subtask 1.1, No. 3	Short list	03/01/93	03/01/93
Subtask 1.1, No. 4	Final list based on boiler selection	08/01/93	
Subtask 1.1, No. 5	Procure samples	08/15/93	
Subtask 1.2. Determine Liberation Potential			
Subtask 1.2.1. Conventional Washability Analysis on Type I and Type II Samples			
Subtask 1.2.1, No. 1	Review of published data	06/01/93	
Subtask 1.2.1, No. 2	Analysis of Type I complete	06/15/93	06/01/93
Subtask 1.2.1, No. 3	Analysis of Type II complete	08/31/93	07/31/93
Subtask 1.2.2. Fine Washability Analysis on Type II and Type III Samples			
Subtask 1.2.2, No. 1	Review of published data	06/01/93	06/01/93
Subtask 1.2.2, No. 2	Analysis of Type II complete	08/31/93	
Subtask 1.2.2, No. 3	Analysis of Type III complete	08/15/93	
Subtask 1.3. Produce Laboratory-Scale Quantities of MCWM			
Subtask 1.3.1, No. 1	Identify Cleaning Strategies	09/15/93	
Subtask 1.3.2. Evaluate Conventional Gravity Separations			
Subtask 1.3.2, No. 1	Test work on Type I complete	09/01/93	
Subtask 1.3.2, No. 2	Test work on Type II complete	10/15/93	
Subtask 1.3.2, No. 3	Test work on Type III complete	11/01/93	
Subtask 1.3.3. Evaluate Fine Gravity Separations			
Subtask 1.3.3, No. 1	Cyclone test rig set-up	11/30/92	11/30/92
Subtask 1.3.3, No. 2	Initiate magnetite classification studies	12/01/92	12/01/92
Subtask 1.3.3, No. 3	Initiate batch centrifuge testing	02/01/93	
Subtask 1.3.3, No. 4	Preliminary centrifuge data evaluation	08/31/93	
Subtask 1.3.3, No. 5	Procure continuous centrifuge	08/01/93	
Subtask 1.3.3, No. 6	Initiate selectivity studies on Type III coals	06/01/93	06/01/93
Subtask 1.3.3, No. 7	Magnetite classification studies complete	06/15/93	06/15/93
Subtask 1.3.3, No. 8	Procure saturation magnetization analyzer	08/01/93	
Subtask 1.3.3, No. 9	Procure variable speed pump	08/15/93	
Subtask 1.3.3, No. 10	Preliminary test work complete	12/31/93	
Subtask 1.3.4. Evaluate Advanced Froth Flotation			
Subtask 1.3.4, No. 1	Reagent selection	06/01/93	
Subtask 1.3.4, No. 2	Initiate test work on Type II samples	06/15/93	
Subtask 1.3.4, No. 3	Initiate test work on Type III samples	07/01/93	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 1.3.4, No. 4	Type II test work complete	08/31/93	
Subtask 1.3.4, No. 5	Type III test work complete	08/31/93	07/31/93
Subtask 1.3.4, No. 6	Data evaluation completed	10/31/93	
Subtask 1.3.5. Evaluate Column Flotation			
Subtask 1.3.5, No. 1	Complete column design	05/01/93	05/15/93
Subtask 1.3.5, No. 2	Procure bubble generators	06/01/93	06/01/93
Subtask 1.3.5, No. 3	Complete column fabrication	07/15/93	
Subtask 1.3.5, No. 4	Complete test work	12/31/93	
Subtask 1.3.6. Evaluate Selective Agglomeration			
Subtask 1.3.6, No. 1	Initiate wetting studies	01/15/93	01/15/93
Subtask 1.3.6, No. 2	Initiate 3-phase aggregation studies	01/31/93	01/31/93
Subtask 1.3.6, No. 3	Fabricate test cell	02/15/93	02/15/93
Subtask 1.3.6, No. 4	Complete preliminary test work on Type II samples	09/31/93	
Subtask 1.3.6, No. 5	Complete preliminary test work on Type III samples	09/15/93	
Subtask 1.3.6, No. 6	Complete detailed studies on Type II samples	12/31/93	
Subtask 1.3.7. Investigate Solid-Liquid Separations			
Subtask 1.3.7, No. 1	Preliminary evaluation complete	08/01/93	
Subtask 1.3.7, No. 2	Initiate studies on test coals	08/31/93	
Subtask 1.3.7, No. 3	Complete studies on test coals	10/31/93	
Subtask 1.3.8. Select Cleaning Flowsheet(s)			
Subtask 1.3.8, No. 1	Establish flowsheet for Type I sample	12/01/93	
Subtask 1.3.9. Establish Required Size Consist for Slurry Formulation			
Subtask 1.3.9, No. 1	Complete for Type I samples	08/30/93	
Subtask 1.3.9, No. 2	Complete for Type II samples	08/15/93	
Subtask 1.3.9, No. 3	Complete for Type III samples	09/30/93	
Subtask 1.3.10. Investigate Conventional Ball Milling			
Subtask 1.3.10, No. 1	Complete test work for Type I samples	07/31/93	
Subtask 1.3.10, No. 2	Complete test work for Type II samples	09/01/93	
Subtask 1.3.10, No. 3	Complete test work for Type III samples	10/31/93	
Subtask 1.3.11. Stirred Media Milling			
Subtask 1.3.11, No. 1	Procure stirred media mill	07/15/93	07/15/93
Subtask 1.3.11, No. 2	Complete test work on Type I samples	08/15/93	
Subtask 1.3.11, No. 3	Complete test work on Type II samples	10/01/93	
Subtask 1.3.11, No. 4	Complete test work on Type III samples	12/01/93	
Subtask 1.3.12. Investigate Attrition Milling			
Subtask 1.3.12, No. 1	Establish test procedure	09/15/93	
Subtask 1.3.12, No. 2	Evaluate preliminary data	10/15/93	
Subtask 1.3.12, No. 3	Complete evaluation	12/31/93	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 1.3.13. Lab-Scale Slurry Production			
Subtask 1.3.13, No. 1	Type I produced	09/15/93	
Subtask 1.3.13, No. 2	Type II produced	10/30/93	
Subtask 1.3.13, No. 3	Type III produced	12/31/93	
Subtask 1.3.14, No. 1	Modify viscosity and sedimentation rate models to account for PSD; compare model predictions to experimental observations	06/30/93	
Subtask 1.3.15, No. 1	Modify viscosity and sedimentation rate models to account for inter-particle attractive forces; compare model predictions to experimental observations	06/30/93	
Subtask 1.3.16, No. 1	Modify models to include effect of polymer additives, oxidation, and aggregate phenomena	03/01/94	
Subtask 1.4. Develop Dry Coal Cleaning Technique			
Subtask 1.4.1. Dry Grinding Studies			
Subtask 1.4.1, No. 1	Procure compressor system	03/15/93	03/15/93
Subtask 1.4.1, No. 2	Set up closed-circuit grinding system	05/15/93	
Subtask 1.4.1, No. 3	Procure pilot-scale jet mill	05/30/93	
Subtask 1.4.1, No. 4	Procedure established for Type III samples	08/31/93	
Subtask 1.4.1, No. 5	Produce micronized product for dry beneficiation studies	09/15/93	
Subtask 1.4.2. Deagglomeration Studies			
Subtask 1.4.2, No. 1	Establish standardized test procedure	09/01/93	
Subtask 1.4.2, No. 2	Initiate humidity and reagent testing	10/01/93	
Subtask 1.4.2, No. 3	Procure laser diagnostic system	09/01/93	
Subtask 1.4.2, No. 4	Complete humidity testing	12/01/93	
Subtask 1.4.3. Dry Separations			
Subtask 1.4.3, No. 1	Procure power supplies	03/01/93	03/01/93
Subtask 1.4.3, No. 2	Fabricate prototype test unit	05/01/93	05/01/93
Subtask 1.4.3, No. 3	Complete preliminary testing	08/31/93	
Subtask 1.4.3, No. 4	Complete testing	12/31/93	
Subtask 1.5. Produce MCWMs and Micronized Coal from Dry, Clean Coal			
Subtask 1.5.1, No. 1	Produce Micronized Coal from Dry, Clean Coal	02/01/94	
Subtask 1.5.2, No. 1	Product MCWM from Dry, Clean Coal	03/01/94	
Subtask 1.6. Produce MCWM and Dry, Micronized Coal for the Demonstration			
Subtask 1.6.1, No. 1	Shakedown dry, micronized coal circuit	07/31/93	
Subtask 1.6.2, No. 1	Complete CWM Preparation Facility	07/01/93	
Subtask 1.6.2, No. 2	Procure automated valves	08/31/93	
Subtask 1.6.2, No. 3	Install CWM equipment	09/30/93	
Subtask 1.6.3, No. 1	Shakedown CWM circuit	10/31/93	
Subtask 1.6.4, No. 1	Coal Cleaning	11/30/93	
Subtask 1.6.5, No. 1	Coal Micronizing	12/31/93	
Subtask 1.6.6, No. 1	MCWM Preparation	04/01/94	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 1.7. Project Management and Support			
Subtask 1.7.1, No. 1	Project Management and Technical Advisement	04/01/94	
Subtask 1.7.2, No. 1	Drafting/Technical Secretary Support	04/01/94	
Subtask 1.7.3, No. 1	Budget Management/Project Administration	04/01/94	
Task 2. Combustion Performance Evaluation			
Subtask 2.1. Boiler Retrofit			
Subtask 2.1.1, No. 1	Finalize burner/atomizer design	05/31/93	
Subtask 2.1.2, No. 1	Procure and install burner	08/31/93	
Subtask 2.1.3, No. 1	Optimize burner firing dry, micronized coal	09/30/93	
Subtask 2.1.4, No. 1	Optimize burner firing CWM	12/31/93	
Subtask 2.2. Fuel Evaluation in Research Boiler			
Subtask 2.2.1, No. 1	Test sample of Type I CWM	10/15/93	
Subtask 2.2.2, No. 1	Test sample of Type II CWM	11/30/93	
Subtask 2.2.3, No. 1	Test sample of Type III CWM	01/31/94	
Subtask 2.3. Performance Evaluation of MCWM and Dry, Micronized Coal in Demonstration Boiler			
<u>Dry, Micronized Coal Testing</u>			
Subtask 2.3.1, No. 1	Procure fire suppression system for the baghouse	06/01/93	
Subtask 2.3.1, No. 2	Modify conditioning screw	07/01/93	
Subtask 2.3.1, No. 3	100-hour milestone firing dry, micronized coal	10/22/93	
Subtask 2.3.2, No. 1	200-hour milestone firing dry, micronized coal	10/29/93	
Subtask 2.3.3, No. 1	300-hour milestone firing dry, micronized coal	11/05/93	
Subtask 2.3.4, No. 1	400-hour milestone firing dry, micronized coal	11/12/93	
Subtask 2.3.5, No. 1	500-hour milestone firing dry, micronized coal	11/19/93	
Subtask 2.3.6, No. 1	600-hour milestone firing dry, micronized coal	11/26/93	
Subtask 2.3.7, No. 1	700-hour milestone firing dry, micronized coal	12/03/93	
Subtask 2.3.8, No. 1	800-hour milestone firing dry, micronized coal	12/10/93	
Subtask 2.3.9, No. 1	900-hour milestone firing dry, micronized coal	12/17/93	
Subtask 2.3.10, No. 1	1,000-hour milestone firing dry, micronized coal	12/31/93	
Subtask 2.3.11, No. 1	Technical Advisement by CE	12/31/93	
<u>MCWM Testing</u>			
Subtask 2.3.12, No. 1	100-hour milestone firing micronized CWM	01/28/94	
Subtask 2.3.13, No. 1	200-hour milestone firing micronized CWM	02/04/94	
Subtask 2.3.14, No. 1	300-hour milestone firing micronized CWM	02/11/94	
Subtask 2.3.15, No. 1	400-hour milestone firing micronized CWM	02/18/94	
Subtask 2.3.16, No. 1	500-hour milestone firing micronized CWM	02/25/94	
Subtask 2.3.17, No. 1	600-hour milestone firing micronized CWM	03/04/94	
Subtask 2.3.18, No. 1	700-hour milestone firing micronized CWM	03/11/94	
Subtask 2.3.19, No. 1	800-hour milestone firing micronized CWM	03/18/94	
Subtask 2.3.20, No. 1	900-hour milestone firing micronized CWM	03/25/94	
Subtask 2.3.21, No. 1	1,000-hour milestone firing micronized CWM	04/01/94	
Subtask 2.3.22, No. 1	Technical advisement by CE	04/01/94	
<u>Evaluate Erosion/Deposition Characteristics</u>			
Subtask 2.3.23, No. 1	Identify erosion and deposition regimes	11/30/92	11/30/92
Subtask 2.3.24, No. 1	Model simultaneous erosion and deposition	09/30/93	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 2.3.25, No. 1	Procure Zirconia/Platinum sensor/recorder	10/15/93	
Subtask 2.3.25, No. 2	Compare heat transfer surface performance firing micronized dry coal and CWM	02/28/94	
Subtask 2.3.26, No. 1	Develop procedure for determining optimum convective section gas velocity	02/28/94	
Subtask 2.3.27, No. 1	Comparison of performance of three tube materials	03/31/94	
Subtask 2.4. Evaluate Emissions Reduction Strategies			
Subtask 2.4.1, No. 1	Determine emissions from micronized coal testing	12/31/93	
Subtask 2.4.2, No. 1	Determine emissions from CWM testing	04/01/94	
Subtask 2.5. Project Management and Support			
Subtask 2.5.1, No. 1	Project management and advisement	04/01/94	
Subtask 2.5.2, No. 1	Staff supervision, test planning, and quality control	04/01/94	
Subtask 2.5.3, No. 1	Data reduction and interpretation	04/01/94	
Subtask 2.5.4, No. 1	Drafting/technical secretarial support	04/01/94	
Subtask 2.5.5, No. 1	Budget management/project administration	04/01/94	
Task 3. Engineering Design			
Subtask 3.1. Micronized CWM/Dry, Micronized Coal Preparation Facilities			
Subtask 3.1.1, No. 1	Design of micronized CWM preparation facility by Amax	11/15/93	
Subtask 3.1.2, No. 1	Design of dry micronized coal preparation system by EER	10/15/93	
Subtask 3.2. Fuel Handling			
Subtask 3.2.1, No. 1	Design of fuel system by EER	10/15/93	
Subtask 3.2.2, No. 1	Technical support and design of fuel system by PSU	10/15/93	
Subtask 3.3. Burner System			
Subtask 3.3.1, No. 1	Design of burner by CE for selected boiler	09/15/93	
Subtask 3.3.2, No. 1	Design of auxiliary components by EER	11/15/93	
Subtask 3.4. Ash Removal, Handling, and Disposal			
Subtask 3.4.1, No. 1	Design of ash system by EER	09/30/93	
Subtask 3.5. Air Pollution Control			
Subtask 3.5.1, No. 1	Design of emission control by EER	11/15/93	
Subtask 3.6. Integrate Engineering Design			
Subtask 3.6.1, No. 1	Integrate system components	01/15/94	

Milestone	Description	<u>Planned</u> <u>Completion</u> <u>Date</u>	<u>Actual</u> <u>Completion</u> <u>Date</u>
Subtask 3.7. Project Management and Support			
Subtask 3.7.1, No. 1	Project management and technical advisement	01/15/94	
Subtask 3.7.2, No. 1	Penn State technical review	01/15/94	
Subtask 3.7.3, No. 1	Drafting/technical secretarial support	01/15/94	
Subtask 3.7.4, No. 1	Budget management/project administration	01/15/94	
Task 4. Engineering and Economic Analysis			
Subtask 4.1, No. 1	Survey Boiler Population/Identify Boilers for Conversion	08/31/93	
Subtask 4.2, No. 1	Identify Appropriate Cost-Estimating Technologies	05/31/93	
Subtask 4.3, No. 1	Estimate Basic Costs of New Technologies	08/31/93	
Subtask 4.4. Process Analysis of MCWM and Dry, Micronized Coal			
Subtask 4.4.1, No. 1	Penn State Analysis	08/31/93	
Subtask 4.4.2, No. 1	Industrial Participants Assistance/Advisement	08/31/93	
Subtask 4.5, No. 1	Analyze/Identify Transportation Cost of Commercial Sources of MCWM and Cleaned Coal for Dry, Micronized Coal Production	09/30/93	
Subtask 4.6, No. 1	Determine Community Spillovers	07/31/93	
Subtask 4.7, No. 1	Regional Market Considerations and Impacts	08/31/93	
Subtask 4.8. Integrate the Analysis			
Subtask 4.8.1, No. 1	Penn State Review of Industrial Participants Contribution	01/31/94	
Subtask 4.8.2, No. 1	Penn State Integration of the Analysis	01/31/94	
Subtask 4.8.3, No. 1	Industrial Participants Assistance in Preparing, and Review of, the Integrated Analysis	01/31/94	
Subtask 4.9. Project Management and Support			
Subtask 4.9.1, No. 1	Project Management and Advisement	02/01/94	
Subtask 4.9.2, No. 1	Drafting/Technical Secretarial Support	02/01/94	
Subtask 4.9.3, No. 1	Budget Management/Project Administration	02/01/94	
Task 5. Final Report/Submission of Design Package			
Subtask 5.1, No. 1	Industrial Participants Submission to Penn State/Review Final Package	04/30/94	
Subtask 5.2, No. 1	Penn State Technical Preparation	04/30/94	
Subtask 5.3, No. 1	Report Preparation Support Services	04/30/94	

Table 2-1. Revised list of test coals and procurement status.

Sample Designation	I-1	II-1	II-2	III-1	III-2
Seam	Taggart	Lower Kittanning	Indiana VII	Upper Freeport	Pittsburgh
State	Virginia	Pennsylvania	Indiana	Pennsylvania	Pennsylvania
County	Wise	Jefferson	Sullivan	Jefferson	Greene
Mine	Westmoreland	Doverspike Bros. (Dora #6)	AMAX (Minnehaha)	Troutville	CONSOL, (Bailey)
Estimated Seam Reserves (Million Tons)	50	480	400	8000	6000
Classification	Type I	Type II	Type II	Type II	Type III
Procurement Status	Sample Received 6/10/93	Sample Received 6/18/93	Source Identified and availability confirmed	Sample Received 6/2/93	Sample Received 6/14/95

2.2 Subtask 1.2 Determine Liberation Potential

Published data on the test coals have been reviewed. Proximate analyses and Hardgrove Grindability Index determinations have been conducted on samples of four of the five coals. The results are given in Table 2-2.

Table 2-2. Proximate Analysis and Hardgrove Grindability of Test Coals.

Coal: Seam:		I-1 Taggart	II-1 Lower Kittanning	II-2 Indiana VII	III-1 Upper Freeport	III-2 Pittsburgh
Proximate Analysis	Moisture%	1.7	2.0	n/a*	31.3	2.5
	Volatile %	34.2	33.1	n/a	28.0	34.7
	Fixed Carbon%	62.1	55.5	n/a	59.1	56.1
	Ash%	2.0	9.4	n/a	11.5	6.9
	Total Sulfur%	0.59	0.78	n/a	.07	1.76
Hardgrove Grindability Index		47	68	n/a	76	56

* not applicable

Conventional and fine coal washability analyses are in progress on the four already-procured coals. The conventional washability studies involve splitting the as-received samples into four size fractions: +1/4", 1/4"x28 mesh, 28x100 mesh and -100 mesh, followed by sink/float separations at six relative densities: 1.3, 1.4, 1.5, 1.6, 1.8 and 2.0. These separations have been completed for all four coals. Sulfur and ash determinations on the individual size/relative density fractions are in progress.

Fine-coal washability studies have been initiated on the Type III coals (See Miller, et al. 1993b for a description of coal types.) crushed to -28 mesh using a hammer mill. Sink/float separations have been carried out at relative densities of 1.3, 1.4, 1.5, 1.6 and 2.0 on the 28x100 and -100 mesh fractions. Further liberation studies will be conducted on samples ground to finer sizes. The results of these tests will be used to establish the appropriate cleaning strategy for each coal.

Liberation Modeling

While the function of comminution in this case is to produce an advantageous size distribution that subsequently produces a highly concentrated MCWSF that combusts efficiently, a secondary aspect is the associated liberation of undesirable materials in the coal - *i.e.*, mineral matter that produces particulates and SO₂ upon combustion. If additional liberation is achieved, then the undesirable materials should be separated from the coal prior to combustion. However, taking advantage of the liberation/separation aspect requires proper integration of the fuel preparation system. In order to do this optimally, it is necessary to be able to predict the liberation achieved for the particular devices utilized.

Liberation modeling, unfortunately, is not easily accomplished. From a comminution viewpoint, the liberation model needs to state what fraction of material of composition c_l and size x_k that breaks to size x_i will be of composition c_j . Then the liberation model combined with the appropriate comminution model will predict the washability analysis of the comminuted product -

	SIZE INTERVAL:			
	1	2	---	n
COMPOSITION				
INTERVAL				
1	$p_{11}A_{11}$	$p_{21}a_{21}$		$p_{n1}A_{n1}$
2	$p_{12}a_{12}$	$p_{22}a_{22}$		$p_{n2}a_{n2}$
-				
-				
-				
m	$p_{1m}a_{1m}$	$p_{2m}a_{2m}$		
$p_{nm}a_{nm}$				

The p_{ij} values are calculated by

$$p_{ij} = \sum_k \sum_l d_{i;k/l} \phi_{j;ik/l} f_{kl} \quad 2-1$$

where $d_{i;k/l}$ is the comminution model that predicts what fraction of material of size x_k and composition c_l , f_{kl} will break to size x_i , and $\phi_{j;ik/l}$ is the liberation model and is calculated as

$$\phi_{j;ik/l} = M(c_{j;ik/l}) - M(c_{j-1;ik/l}) \quad 2-2$$

where $M(c;ikl)$ is the cumulative mass of material of size x_i , created by comminution material of size x_k and composition c_l , that is of composition c or less. A typical plot of M vs. c , for various degrees of liberation, is shown in Figure 2-1.

If a washability analysis is performed on the size x_i material, then the M vs. c plot is known as the elementary ash curve. Consequently, if we can predict the elementary ash curve for materials of size x_i , created by comminuting material of size x_k and composition c_l , then we have a liberation model.

The a_{ij} values, for example the expected ash content of material in size class i and composition class j , are calculated by

$$a_{ij} = \sum_k \sum_l d_{i;k,l} \alpha_{j;k,l} f_{kl} \quad 2-3$$

where $\alpha_{j;ikl}$ is the ash unit value and is calculated as

$$\alpha_{j;ikl} = A(c_{j;ikl}) - A(c_{j-1;ikl}) \quad 2-4$$

where $A(c;ikl)$ is the cumulative ash units of material of size x_i , created by comminuting material of size x_k and composition c_l , that is of composition c or less. A typical plot of A vs. M for various degrees of liberation is shown in Figure 2-2.

This plot is known as the Mayer Curve. Since

$$dA(c;ikl)/dM(c;ikl) = c \quad 2-5$$

it follows that

$$A(c;ikl) = \int_0^c c \, dM(c;ikl) \quad 2-6$$

Thus, in order to predict the product washability analysis, it is necessary to predict the M vs. c curves.

Determining the functional forms for the M vs. c curves is a very time consuming process. Starting with a minus 1 1/2" air table product, for example, size and composition samples must be prepared; *e.g.*, 4 x 6 mesh, 30-40% ash (1.60 x 1.80). From a 1 ton sample, only 500-1,000 g of this material are obtained! The sample is then comminuted, the product is fractionated on the basis of size and relative density, and the ash contents determined, *i.e.*, a washability analysis is performed. The elementary ash curves are plotted, analyzed and fitted. This protocol is being performed on several of the samples.

Figure 2-1. Typical M-C plot for various degrees of liberation

Figure 2-2. Mayer Curves for various degrees of liberation

2.3 Subtask 1.3 Produce Laboratory-Scale Quantities of Micronized Coal-Water Slurry Fuels

Depending on the relative ease of cleaning (Type II or Type III), a general strategy involving appropriate combinations of fine-gravity and surface-based separations has been adopted.

Evaluate Fine Gravity Separations

The prediction of the performance of dense-medium separation devices is difficult due in part to the interaction or compounding of operating variables such as the flow rate, the magnitude of the g-force, turbulence, and the characteristics of the dense medium. The effects of various operating conditions on dense-medium separation using a batch free-settling model have been examined previously (Klima and Luckie 1989, 1990). In this case, the model was based on the assumption that particles separated under free-settling conditions in a medium of constant density within a uniform field. Thus, a pseudo dense-medium liquid, such as a suspension, which is not stable, cannot be accurately simulated because of the density gradients which will exist within the liquid. Furthermore, this model was not able to simulate the effect of a change in solids concentration on separation efficiency.

Recently, a hindered-settling model was developed and used to evaluate the classification behavior of a polydisperse particulate system (Austin et al, 1992). This model was used to investigate the variation of the particle size distribution with time under different settling conditions. Dense-medium separation can be viewed in a similar fashion whereby the dense-medium solids, coal, and refuse, settle in water. Since the principle of separation also depends on the differential settling rate of these particles in the suspension, it should be possible to analyze dense-medium separation using the batch hindered-settling model.

Consider the cylindrical batch device shown in Figure 2-3. If particles are in motion in such a device due to the settling (convection) and mixing (diffusion), it is possible to account for their movement into and out of an element within this device. In a hindered-settling regime, the movement of particles of a particular size and density, due to both convection and diffusion, would be a function of the concentration of these particles in the element. Since the separation occurs primarily in the vertical (z) direction, the separating force (gravity) and the level of mixing are important only in this direction. Thus, if the mixing is characterized by a single eddy-diffusion coefficient, then the rate of accumulation for particles of size x to $x+dx$ and density ρ to $\rho+d\rho$ in an element z to $z+dz$ is given by

$$\frac{\partial \phi(x, \rho, z, t)}{\partial t} = D \frac{\partial^2 \phi(x, \rho, z, t)}{\partial z^2} - \frac{\partial (V(x, \rho, z, t) \phi(x, \rho, z, t))}{\partial z} \quad 2-7$$

Figure 2-3. Batch settling column

The rate of accumulation for the liquid in the same element is given by

$$\frac{\partial(1-\phi(z,t))}{\partial t} = - \frac{\partial(U_f(z,t)(1-\phi(z,t)))}{\partial z} \quad 2-8$$

where

$\phi(x,\rho,z,t)$ = volume fraction of particles of size x to $x+dx$ and density $\rho+d\rho$, in the element at position z to $z+dz$ and time t .

D = diffusion coefficient.

$V(x,\rho,z,t)$ = velocity of particles of size x to $x+dx$ and density $\rho+d\rho$ at location z to $z+dz$ and time t , with respect to the wall of the container.

$\phi(z,t)$ = total volume fraction occupied by the solids in the element at position z to $z+dz$ and time t .

$1-\phi(z,t)$ = volume fraction occupied by the liquid in the element at position z to $z+dz$ and time t .

$U_f(z,t)$ = velocity of the liquid with respect to the wall in the element at position z to $z+dz$ and time t .

Now consider the cylinder in Figure 2-3 with particles uniformly dispersed in water. If these particles are allowed to settle for some time t and then the cylinder is cut at some fractional height L/H , the particles below this cut height can be defined as the refuse and the particles above the cut height as the product. Since the particle size/density distribution at any location can be estimated from the solution to Equations 2-7 and 2-8 (Lee, 1989; Austin et al, 1992), the fraction of feed particles of size x and density ρ which reports to the product after time t is given by

$$K(\rho;x,t) = \frac{\int_0^{L/H} \phi(x,\rho,z,t) dz'}{\phi_o(x,\rho)} \quad 2-9$$

where

$\phi_o(\rho,x)$ = initial volume fraction of particles of size x and density ρ .

$\phi(x,\rho,z,t)$ = volume fraction of particles of size x and density ρ at location z of the settling column after time t .

$z' = z/H$

A plot of a set of values from Equation 2-9 versus ρ for a given particle size is called a fractional recovery (partition) curve. As is common in gravity concentration, this curve can be characterized by a location modulus and a distribution modulus. The location modulus is defined as the density of those particles which have an equal probability of reporting to either the clean coal or to the refuse, *i.e.*, the density corresponding to a fractional recovery value of 0.5. This location modulus for a given size is denoted by $dp(x)$ and can be adopted as the separation density for that size (Figure 2-4). A distribution modulus is used to characterize the efficiency of separation. In this case, the mean probable error for a given size is defined as

$$ep(x) = (\rho_{25}(x) - \rho_{75}(x))/2 \quad 2-10$$

where

$\rho_{25}(x)$ = density corresponding to 0.25 on the fractional recovery curve

$\rho_{75}(x)$ = density corresponding to 0.75 on the fractional recovery curve

Thus, as $ep(x)$ approaches one, the separation approaches ideal, while as $ep(x)$ approaches zero, no separation occurs, but rather the particles are split in the ratio L/H . The fractional recovery values can be fit to a mathematical function (model) from which the characteristic parameters can be obtained. One such model that has been shown to fit dense medium data is the logistic function given by

$$K(\rho;x) = \frac{1}{1 + \exp[(1.099/ep(x))(\rho - dp(x))]} \quad 2-11$$

The parameters $dp(x)$ and $ep(x)$ can be found by using a nonlinear optimization routine.

Cyclone Separations

In order to produce an acceptable yield for the Type II or Type III coals, the range of particle sizes to be processed must be extended to fine sizes. Currently, most coal cleaning facilities treat coal down to about 28 mesh, and in some cases, down to 100 mesh, utilizing dense-medium cyclones. It is likely that cleaning of the 28x100 mesh size fraction would be required for a Type II coal to produce an acceptable yield of low ash, low sulfur material and even finer sizes would be required for a Type III coal. Because of the ability to make low density separations, with the capability of processing coals containing large amounts of near-gravity material, dense-medium separation would be the likely choice in these cases. Using the batch-settling model, an analysis of the change in the separation efficiency for a wide variety of conditions can be made. Appropriate parameters can be used to describe the cyclone operation in

Figure 2-4. Fractional recovery curve showing the relative density of separation

terms of retention time, number of g's, etc. (as discussed in Miller, et al., 1993b), the feed washability (*i.e.*, the size and density distribution), and the dense medium characteristics.

Simulations were performed to investigate the separation of 28x100 mesh coal in a conventional (36 cm) diameter cyclone using a suspension of magnetite and water with an apparent density of 1.28 g/cm³. The corresponding set of simulation conditions are given in Table 2-3. The fraction of each coal species which reported to the product (Equation 2-9), was calculated by the batch hindered-settling model. Figure 2-5 shows the variation of the fractional recovery curves with particle size. As would be expected, sharper separations (*i.e.*, lower $ep(x)$ values) were obtained for the coarser particles. If this treatment is extended to finer sizes, *i.e.*, 100x400 mesh size fraction, the curves in Figure 2-6 are obtained. In this case, the fractional recovery curves are much flatter. Consequently, longer separation times and/or higher g's are needed to improve the separation (as discussed in Miller, et al., 1993b).

Work is continuing in this area investigating the effects of variable interactions on separation efficiency. Likewise, the effects of medium characteristics on cyclone performance are also being investigated, including the size distribution of the dense-medium solids. Simulation results will be compared to those obtained from actual dense-medium cyclone tests.

Centrifuge Separations

Although dense-medium cyclones will likely be used to clean coal down to 100 mesh and perhaps even 400 mesh when utilizing an ultrafine (micronized) magnetite-based process, certain coals will require grinding to top sizes of 100 mesh or finer to achieve liberation. Such grinding would invariably create a large fraction of -400 mesh material. Under these conditions, it may not be practical to utilize dense-medium cycloning since smaller diameter (*i.e.*, lower capacity) units may be required to generate a sufficient number of g's. Also, because of the trade-off between the number of g's and the retention time, it may not be possible to separate the -400 mesh coal efficiently even using a smaller diameter cyclone. Alternatively, it should be possible to use a continuous solid-bowl centrifuge for dense-medium separation, also employing an ultrafine-magnetite/water suspension. Because of the ability to control independently the mean retention time and the number of g's, it should be possible to separate much finer particles compared to a cyclone. In addition, the amount of turbulence that occurs in a centrifuge should be lower since high inlet pressures are not required as is the case in a cyclone. Also, by changing the scroll speed, it may be possible to vary the pulp split independently, and in turn, change the relative density of separation at a constant medium relative density. The batch hindered-settling model will be used to investigate these variables.

Table 2-3. Simulation conditions for a dense-medium cyclone operation.

Total Height	18.0 cm
Relative Cut Height	0.6
Number of g's	120.0
Retention Time	1.75 s.
Diffusion Coefficient	16.0 cm ² /s

Size/Density Distribution of Coal Particles

	495μm	351μm	246μm	175μm	Composite
1.25 g/cm ³	0.145	0.204	0.185	0.142	0.676
1.35 g/cm ³	0.026	0.031	0.022	0.012	0.091
1.45 g/cm ³	0.014	0.014	0.010	0.007	0.045
1.55 g/cm ³	0.015	0.015	0.010	0.006	0.046
1.70 g/cm ³	0.010	0.010	0.007	0.004	0.031
2.30 g/cm ³	0.037	0.039	0.023	0.013	0.112
Composite	0.247	0.313	0.256	0.184	1.0

Characteristics of the dense medium.

Medium Density	1.28 g/cm ³
Media Type	Magnetite
Density, g/cm ³	4.8
Vol. Fraction	
Solids	0.074
Water	0.926
Media Size	
Conventional	95% < 53 μm
Med.-to-Coal Ratio	5:1

Figure 2-5. Variation of the fractional recovery curves with particle size for the 28 x 100 mesh size fraction

Figure 2-6. Variation of the fractional recovery curves with particle size for the 100 x 325 mesh size fraction

Another potential advantage of the solid-bowl centrifuge is that it can be used to classify particles at very fine sizes. In fact, these devices have been used in the minerals industry to separate particles less than 10 μm (Scheffler and Zahr, 1980). The capability to classify in this range would be very valuable in producing "custom" size distributions for the MCWSFs.

Testing is continuing with a "batch" centrifuge to investigate the effect of operating conditions on magnetite classification. The magnetite was obtained from the Pea Ridge Iron Ore Company of Sullivan, Missouri. This material was much finer than that used in commercial coal preparation facilities being nearly 100% < 15 μm , with approximately 75% < 5 μm . Even with such fine magnetite, it is likely that a density gradient will form, leading to a relative density differential in the overflow and underflow streams, which in turn can impact separation efficiency. Preliminary tests utilizing the Upper Freeport (Type III) coal indicated that some of the higher-ash fraction of the coal was being retained in the separator. To minimize this effect, the overall length of the separator was reduced from 152 to 76 mm.

The high-g, solid-bowl centrifuge will be ordered shortly. This unit will allow continuous testing of dense-medium centrifugation and of ultrafine classification. The results from this study can be scaled to a larger diameter unit that can be used in a production facility.

Magnetic Fluid Separation

As an alternative to using a suspension of solids and water as a dense medium, it is possible to utilize a ferro (magnetic) fluid as the separating medium. These fluids consist of a colloidal suspension of sub-micron magnetite particles dispersed in water. The fineness of the magnetite particles prevents the solids from settling in the fluid. When a magnetic field is applied to the fluid, the particles align themselves in the direction of the field. The result of this alignment is that a "buoyant" or "levitation" force is produced, allowing the particles to be separated according to the density difference between the particles and the fluid, similar to that in float-sink separations. When the magnetic field is removed, the particles return to a random orientation. Consequently, no magnetic flocculation occurs. The strength of the buoyant force can be regulated by changing the strength of the magnetic field and/or concentration of the fluid.

A commercially available separator that uses a rotating magnetic fluid is the Magstream separator (Walker et al., 1990). One of these units has been obtained recently on loan from the U.S. Department of Energy and is currently being installed. It will be used to evaluate the application of this technology to fine coal separations.

Evaluate Surface-Based Cleaning Processes

Advanced Froth Flotation

To increase the efficiency of separation, surfactants were used. Block co-polymers consisting of hydrophobic polypropylene oxide (PPO) and hydrophilic polyethylene oxide (PEO) groups were selected based on previous experience with such reagents. These reagents, which are

commercially available, have been found to be effective in enhancing the separation efficiency of some coals. A list of the surfactants used in this investigation and their characteristics is given in Table 2-4. Other reagents to selectively disperse ash-forming minerals and depress sulfur-bearing minerals will be used if needed.

Table 2-4. Selected properties of the surfactants used in this study.

Surfactant Code*	Number of Hydrophobic PPO Groups	Number of Hydrophilic PEO Group	M.W	HLB	Surface Tension @ cmc, dyne/cm
BC1			2700	2.1	36.0
BC2	30	26	2650	11	43.0
BC3	56	39	4950	9	34.0
BC4	56	60	5900	13	33.0

* Ethylene oxide-propylene oxide block copolymers

PPO: Polypropylene oxide

PEO: Polyethylene oxide

Flotation testing was initiated for two Type III coals from the Pittsburgh and Upper Freeport seams. The specific objective was to enhance separation efficiency of fine particles using a surfactant. Several methods are available to enhance separation efficiency. These include:

- Aid capture of fine particles by small bubbles
- Increase hydrophobicity to increase rate of flotation - use of surfactant.
- Increase hydrophobicity of particles which might increase the extent of hydrophobic aggregation.
- Aid capture of fine particles by oil droplets followed by flotation of aggregates.
- Selective Agglomeration to produce larger 'particles' which can be floated readily.

A comprehensive approach is being used in this project to exploit some or all of the above methods.

Standard procedures were used to conduct tests and suitable models were used to determine the rate and ultimate recovery.

Flotation Kinetics Models

Flotation rate data are essential for design of flotation systems. Flotation tests are being conducted to obtain the relevant information. The first step in the evaluation of flotation results was to select a model to evaluate the flotation kinetics. Approximately 25 models in the literature were reviewed, and they are grouped as:

First-order models

Second-order models

Miscellaneous models: Froth flow, gas adsorption, two phase, law of proportionality, etc.

The Classical First-order (CFO) model together with rectangular (FRD) and sinusoidal (FSD) distributions of floatabilities were reviewed in Miller, et al., 1993b. Various first-order flotation models and a few others were evaluated and a new model was developed because the exiting models were deemed to be unsatisfactory. It was determined that some of the models give a good fit in certain conditions whereas others are better under different conditions. The reasons are not clear, however. Based on this experience a new model was developed and it is described in the following paragraphs.

A First-order Flotation Kinetics Model with Normal Distribution of Floatabilities. In this model the rate of flotation is assumed to be a normal distribution about a mean value. This model is capable of fitting the rate data under a wide variety of flotation conditions and the fitting errors were found to be small in the cases tested thus far.

The general form of the first-order rate equation with a floatability distribution $f(k)$ is:

$$R(t) = R_i \left\{ 1 - \int_0^{\infty} f(k) e^{-kt} dk \right\} \quad 2-12$$

Where $R(t)$ is the recovery at time t , and R_i is the ultimate recovery.

If a normal distribution of floatabilities is assumed, then

$$f(k) = \frac{\exp\{-(k-\mu)^2/2\sigma^2\}}{\sigma\sqrt{2\pi}} \quad \text{where } 0 < k < \infty \quad 2-13$$

and

$$R = R_i \{ 1 - 0.5 e^{-A} (\text{erf } B - \text{erf } C) \} \quad 2-14$$

where μ is the mean and σ is the standard deviation of the normal distribution curve. The quantities A , B and C are defined by the following equations:

$$A = -\mu t + 0.5 \sigma^2 t^2 \quad (2-14a)$$

$$B = (t\sigma + \mu/\sigma)/\sqrt{2} \quad (2-14b)$$

$$C = (t\sigma - \mu/\sigma)/\sqrt{2} \quad (2-14c)$$

Model Evaluation. The results of the flotation kinetics tests were presented previously (Miller, et al., 1993b). The frequency distributions fitted to the kinetics data are given in Figure 2-7 for the Upper Freeport seam coal and in Figure 2-8 for the Pittsburgh seam coal. The experimental conditions are given in the figure captions. The results of fitting four different models are given. It can be seen that the predicted value of the floatabilities are strongly model dependent, making it necessary to select the model which most accurately represents the actual distribution of floatabilities. The floatability distributions vary with coal type and conditions of flotation, as expected. The model fitting errors are given as mean residual square (MRS) errors in the insets in the respective figures. For the Upper Freeport coal the MRS increased in the order:

$$FND < FRD < FSD < CFO \quad (2-15)$$

and, for the Pittsburgh seam coal, it increased in the order:

$$FND \sim CFO < FRD < FSD \quad (2-16)$$

The errors were least for the Model FND. This model is being evaluated further using the flotation results for other test conditions. In addition, results of individual size fractions are being evaluated to determine the flotation response as a function of particle size. The effect of particle size on flotation is well recognized but the specific data for a given coal are generally not available. Such information is necessary to optimize flotation. The effect of particle size will be evaluated using the flotation models.

Role of Surfactants. Flotation tests were carried out to determine the effect of

- Surfactant concentration, and
- Surfactant type.

The results were analyzed using the total combustible matter recovery (CMR) and % ash in the clean product and the results are presented in Figure 2-9. The corresponding ash recovery curves are given in Figure 2-10. The data for flotation in the absence of surfactant are given for comparison. In this figure the results of pre-agglomerating the coal are also included but they will be discussed in the section on Selective Agglomeration. Based on these results the following observations were made:

- For the BC2 surfactant, 1×10^{-4} kg/T (the lowest concentration tested) gave the best results with 80% CMR and 3.1% ash.

Figure 2-7. Frequency distributions of flotation rates of the overall sample predicted by various first-order flotation kinetics models for the Upper Freeport coal. Inset: The mean residual square error of the fits for various models. Frother: 0.33 kg/T MIBC; Collector: 1.3 kg/T Dodecane. Model: CFO (—); FRD (- - -); FSD (- · -); FND (···)

Figure 2-8. Frequency distributions of flotation rates of the overall sample predicted by various first-order flotation kinetics models for the Pittsburgh coal. Inset: The mean residual square error of the fits for various models. Frother: 0.33 kg/T MIBC; Collector: 1.3 kg/T Dodecane. Model: CFO (—); FRD (- - -); FSD (- · -); FND (···)

Figure 2-9. Effect of surfactant concentration on the combustible matter recovery (CMR) and Ash % for the Pittsburgh coal. Frother: 0.5 kg/T MIBC; Collector: 0.07 kg/T Dodecane. (∇ - BC2; $\bullet$ - BC4)

Figure 2-10. Performance of flotation under various conditions for Pittsburgh Seam coal. Frother: 0.5 kg/T MIBC; Collector: 0.07 kg/T Dodecane.
 (◆ - no surfactant; ▼ - 0.1 g/T BC2; ● - 20 g/T BC4;
 ■ - Preagglomeration with 20 g/T BC4)

- For the BC4 surfactant, a higher concentration was required to obtain low ash (3%) but the CMR decreased to 67%.
- At low surfactant concentrations, the surfactant with fewer ethylene oxide groups gave lower ash at a CMR of about 80%.
- Except at very low concentrations, the increase in number of ethylene oxide groups decreased the ash by about 0.5% and the CMR by about 10%.

These studies are being continued.

Column Flotation

In the previous semiannual progress report (Miller, et al., 1993b), a new mass transfer approach to flotation column design was presented. The validity of this approach was tested using literature data from a variety of applications. In the present approach to column design, the bubble surface area emerges as a key design and scale-up variable. However, the parameters controlling the availability of bubble surface are the gas rate and bubble generator design. Thus knowledge of the maximum gas velocity for column flotation, and how this changes with the scale of the column is required for design and scale-up.

The maximum gas flow rate for column flotation has been shown to be in the bubbly flow regime (Ityokumbul, 1992a). Using dimensional analysis, the maximum gas velocity for column flotation was recently determined to be (Ityokumbul, 1993b):

$$U_{g,max} = 0.11 D_c^{0.5} \quad (2-17)$$

In Miller, et al., 1993b, it was shown that the height of a transfer unit, HTU, for pyrolusite flotation was higher than the corresponding value for fluorite. For the 0.064 m flotation column used by Ynchausti et al. (1988), the pyrolusite and fluorite flotations were carried at gas velocities above and below the maximum value predicted by Equation 2-17. Analysis of published data revealed that in most large diameter flotation columns ($D_c > 0.5$ m), the operational gas velocities were less than 40% of the maximum value predicted by Equation 2-17 (see Figure 2-11). This may partially explain the low carrying capacities observed in large diameter columns. In addition, the optimum recovery zone heights determined were considerably shorter than conventional column designs and agreed rather well with those of the first column installations at Inspiration Copper Company, Ltd.

The laboratory column is under fabrication. Orders for the column instrumentation have been placed a delivery is pending. A Cominco and Mott Metallurgical bubble generators have been procured. The former employs high external shear to generate fine bubbles while the latter forces air through a porous media with an average pore opening of 2 μ m. A schematic diagram of the experimental set-up and the two bubble generators are shown in Figures 2-12 and 2-13. The effectiveness of both of the gas spargers in fine coal cleaning will be evaluated.

Figure 2-11. Comparison of operational to the theoretical maximum gas velocities in column flotation

Figure 2-12. Schematic diagram of the flotation column set-up

Cominco Sparger

Static Sparger

Figure 2-13. Schematic diagram of the procured bubble generators

Selective Agglomeration

The addition of small quantities of oil to a coal-water slurry promotes the selective agglomeration of hydrophobic coal particles leaving liberated (hydrophilic) ash minerals dispersed in the aqueous phase. The oil-agglomeration process has been the subject of numerous laboratory and pilot-scale studies (Mehrotra et al., 1983; Capes et al., 1990; Pawlak et al., 1989; Simmons and Keller, 1986) but has not found wide commercial application. The process does, however, have considerable potential for deep cleaning of coal at fine sizes, especially for applications in coal-water slurry fuel technology which avoids the problems of dewatering the fine, clean-coal product. The process is particularly attractive for use in combination with froth flotation to enhance recovery of the agglomerated material.

The use of oil agglomeration, at very low oil-addition levels, for sulfur and ash rejection in fine (-200 mesh) coal is being investigated. Under a separate DOE-sponsored project, the wetting phenomena which provide the driving force for agglomerate formation and the growth of agglomerates in three-phase (oil-water-coal) systems is being studied.

Wetting behavior is being evaluated in terms of the various contact angles (solid-liquid-liquid and solid-liquid-gas) which define the attachment of oil droplets to solid surfaces in our aqueous medium. A technique known as interface partitioning, which has recently been developed (Wei et al., 1992), is being used for determining contact angles on small particles at liquid-gas and liquid-liquid interfaces. Agglomerate growth is being studied by in-situ measurement of particle/agglomerate size in agitated coal-water slurries with small quantities of added oil. Following preliminary, baseline studies on "pure" (coal-water-oil) systems, the role of surfactants in wetting and agglomerate formation will be investigated in some detail.

Studies of combined agglomeration flotation are also being carried out. Pre-agglomerated coal has been separated by flotation and the results are given in Figure 2-10. A substantial increase in separation efficiency was observed. Additional studies are in progress to determine the effect of key variables on the separation efficiency.

Establish Required Size Consist for Slurry Formulation

The size distribution of the solid particles is a critical factor in the production of high-density MCWSF with acceptable viscosity. It is generally accepted that broad size distributions are desirable since they afford the most opportunity for efficient packing of the particles. However, there seems to be little agreement over the "optimum" size distribution, and trial-and-error methods involving changes in the fine-grinding procedure are usually adopted. The size-consist requirements in terms of the role of packing and particle interaction forces in determining slurry characteristics are being reevaluated.

Particle Interactions

Solid particles dispersed in water are subject to forces of interaction which become increasingly important as particle size is reduced.

van der Waals Forces act between any pair of molecules and, by extension, between any particle and its neighbors. The term van der Waals force is generally applied to the interaction between either permanent or induced dipoles in a pair of molecules. Typically, the energies of interaction are associated with an inverse sixth power variation with molecular separation. The forces are always attractive. The interaction between particles can be estimated by summing the pair-wise molecular interactions (Hamaker, 1936). Analytical expressions have been derived for a variety of particle geometries (plate-plate, sphere-sphere, sphere-plate, etc.). A useful approximation for the attractive force between dissimilar spheres of composition i and j and diameter x_i and x_j immersed in a fluid medium k is:

$$F_{ijk} = \frac{A_{ijk}x_i x_j}{12(x_i + x_j) H^2} \quad 2-18$$

where H is the surface-to-surface separation of the particles and A_{ijk} is known as the Hamaker constant for interaction between materials i and j in medium k . More exact expressions, including corrections for electromagnetic retardation effects at large separations are available in the literature (Schenkel and Kitchener, 1960; Clayfield and Lumb, 1971; Gregory, 1981).

The overall, effective Hamaker constant for a given interaction can be estimated from

$$A_{ijk} = (\sqrt{A_i} - \sqrt{A_k})(\sqrt{A_j} - \sqrt{A_k}) \quad 2-19$$

where A_i , A_j and A_k refer to interactions of the separate components in vacuum. For identical particles ($i = j$), A_{ijk} is always positive and the net force is always attractive. On the other hand, for dissimilar particles ($i \neq j$), A_{ijk} can be positive or negative depending on the values of the individual constants and it is possible for the net force to be a repulsion. Typical values of Hamaker constants A_{ij} for common solids and liquids are available in publications by Visser (1972) and Fowkes (1964).

Electrical Forces result from electrochemical equilibrium between particles and ionic species in liquid (especially aqueous) solutions. The charged particles attract oppositely charged ions from solution leading to the establishment of an electrical double layer at the solid-liquid interface. Interaction forces arise as the electrical double layers surrounding two particles overlap. The magnitude and range of the interaction force depend on the electrical potential difference between

the solid and liquid phases and on the ionic strength of the solution - which controls the extent of the double layer away from the particle surface.

Electrical double layer interaction forces have been studied at length by colloid scientists, and numerous theoretical expressions, appropriate for a variety of conditions, are available to describe their magnitude (Overbeek, 1952). A useful, general relationship for estimating the double layer interaction was given by Hogg, Healy and Fuerstenau (1966). Based on this work, the force can be expressed as:

$$F_{ij} = \frac{\epsilon \kappa x_i x_j}{4(x_i + x_j)} \frac{e^{-\kappa H}}{1 - e^{-2\kappa H}} \left[(\zeta_i^2 + \zeta_j^2) e^{-\kappa H} - 2\zeta_i \zeta_j \right] \quad 2-20$$

where x_i and x_j are equivalent sphere particle diameters, ϵ is the dielectric constant for the medium and κ is the Debye-Huckel reciprocal thickness parameter defined by

$$\kappa^2 = \frac{8\pi e^2 I}{\epsilon kT} \quad 2-21$$

in which e is the electronic charge, I is the ionic strength of the medium, k is Boltzmann's constant and T is the absolute temperature.

The quantity ζ in Equation (2-20) is the so-called Zeta Potential of the particles which provides an estimate of the electrical potential drop across the mobile part of the double layer. In general, the zeta potential depends on the composition of the solid and solution phases; for aqueous systems it varies in particular with the pH and ionic strength of the solution. A detailed discussion of the zeta potential and its significance in colloidal systems has been published by Hunter (1981).

The force due to the double layer interaction can represent either attraction or repulsion depending on the relative sign and magnitude of the zeta potentials. For identical particles with finite zeta potential ($\zeta_1 = \zeta_2$), the force is invariably repulsive, for particles with zeta potentials of opposite sign it is always attractive, while for particles whose zeta potentials have the same sign but different magnitude, the force can change from repulsion at large separation to attraction as the particles come into contact (Hogg, Healy and Fuerstenau, 1966; Overbeek, 1988).

Chemical Forces due to the formation of chemical bonds between particles in contact can contribute to the strength of agglomerates. However, such forces are of extremely short range and play little or no role in the production and properties of coal-water slurry fuels.

Solvation Forces are a result of interaction between particle surfaces and a liquid medium. The formation of structured layers of either solvent molecules or adsorbed solute species can contribute to these effects. Soluble polymers can have very significant effects on particle interactions. Complete coating of particle surfaces by adsorbed polymer typically leads to strong

repulsion between particles (Napper, 1983) while partial coatings can promote aggregation by polymer bridging from one particle to another (Smellie and La Mer, 1958).

Hydrophobic Forces have recently been postulated as a distinct class (Israelachvili, 1985), but should perhaps be more properly regarded as a special case of salvation forces.

Attractive, van der Waals' forces and repulsive, electrical double layer and steric interaction forces due to adsorbed, dispersant layers probably assume a dominant role in coal-water slurry fuels. In the absence of repulsion, the attractive forces lead to particle aggregation and network formation with a corresponding increase in apparent viscosity. The presence of repulsive forces gives rise to the development of repulsive energy or force barriers between particles which prevent their coming into actual contact. Typically, these barriers lead to minimum particle separations in the range of 0.01 to 0.1 μm .

By preventing aggregation or network formation, the development of repulsive barriers generally contributes to the reduction of CWSF viscosity. On the other hand, the barrier itself represents an additional excluded volume which increases the effective solids volume in suspension. Such effects can become significant for very fine particles. For particles of size x with minimum separation H_m , the effective solids volume fraction ϕ is increased to

$$\phi_{\text{eff}} = \phi \left(1 + \frac{H_m}{2x} \right)^3 \quad 2-22$$

For 0.1 μm particles with a minimum separation of 0.05 μm , this would correspond to almost a doubling of the effective solids concentration.

Particle interactions also play a role in another important characteristic of coal-water slurry fuels: sediment consolidation. Practical coal-water slurry fuels are inevitably subject to some settling during long-term storage. This becomes a problem if the resulting sediments are highly consolidated ("hard-packed") and not easily redispersed by agitation. Network formation due to net attraction between particles generally promotes settling but opposes consolidation by forming rigid but relatively open structures which can easily be broken down by agitation. Very strong repulsive interactions can also inhibit consolidation by preventing close approach of particles. Both of these conditions can, however, contribute to increased slurry viscosity.

Particle Packing

It has long been recognized that particles of uniform size, arranged at random, pack to a solids volume fraction of about 0.6. These packing densities can be increased substantially by the addition of smaller particles which can fit into the interstices between the original particles. For CWSF applications, it is convenient to consider the reverse (but entirely equivalent) situation of adding coarser material to a suspension of fine particles.

Consider a suspension of particles of size x_1 with solids concentration ϕ_1 . If coarser particles (size x_2) are added, each particle (initially) adds its own solid volume to the suspension. Thus

$$V = V_1/\phi_1 + V_2 \quad 2-23$$

where V is the total slurry volume, V_1 and V_2 are the respective solid volumes.

By definition, the slurry concentration (volume fraction) is

$$\phi = \frac{V_1 + V_2}{V} \quad 2-24$$

and the fraction of coarse particles is

$$Q = \frac{V_2}{V_1 + V_2} \quad 2-25$$

It follows that

$$\phi = \frac{\phi_1}{1 - Q(1 - \phi_1)} \quad 2-26$$

which describes the increase in solids loading due to the addition of coarse material.

Obviously, such an increase in loading cannot continue indefinitely. Eventually, the coarse particles cease to act independently; they begin to disturb the packing of the finer material and finally reach a packing limit of their own.

The maximum possible loading occurs when there is just enough fine-particle slurry to fill the voids in a bed of close-packed coarse particles. In this case,

$$V = V_2/\phi_2^* \quad 2-27$$

where ϕ_2^* is the maximum packing fraction for the coarse material (typically about 0.6). The void volume V_v (available to fine-particle slurry) is

$$V_v = (1 - \phi_2^*)V \quad 2-28$$

It follows that the maximum loading occurs when the fraction of coarse particles in the mixture is Q_m such that

$$Q_m = \frac{\phi_2^*}{\phi_1 (1 - \phi_2^*) + \phi_2^*} \quad 2-29$$

The corresponding maximum solids loading is

$$\phi_m = \phi_2^* (1 - \phi_1) + \phi_1 \quad 2-30$$

Some examples of calculated solids loadings for coarse-particle/fine-slurry mixtures are shown in Figure 2-14. The substantial increases in loading which can, potentially, be achieved can be seen clearly. It is also apparent that a range of options is available for producing a CWSF with a given loading. Thus, a loading of 50% solids overall can be accomplished by adding about 30% coarse particles to a 40% slurry or 70% coarse particles to a 20% slurry. Obviously, the rheological and settling characteristics of these different (but same-density) CWSFs would not be expected to be the same.

In principle, further increases in solids loading could be obtained by the addition of a third, still finer or coarser component in the appropriate amount. However, experience with powders suggests that such improvements are not generally achieved in practice (Cross, 1985).

In order to obtain the optimum packing from binary mixtures, it is necessary that the size ratio x_2/x_1 be as large as possible. In real CWSFs, however, there are practical limits on this ratio. Combustion and burner requirements generally limit the upper size, x_2 to less than about 100 μm . Grinding costs and, to some extent, rheology constraints place limits on the finer size x_1 .

The ability to achieve high packing density is largely determined by the ratio of the average separation H_2 of the large particles to the size of the fine material. For a "dilute" (non close-packed) coarse fraction, assuming an average cubic arrangement, the mean particle separation can be estimated as follows:

The volume of slurry associated with an average (size x) particle is

$$v_s = k_v x^3 / \phi \quad 2-31$$

where k_v is the column shape factor ($=\pi/6$ for spheres). For a cubic arrangement, the average center-to-center separation is

$$v_s^{1/3} = (k_v / \phi)^{1/3} x \quad 2-32$$

and the average surface-to-surface separation for the coarse component is:

$$H_2 = \left[(k_v / \phi)^{1/3} - 1 \right] x_2 \quad 2-33$$

Figure 2-14. Slurry preparation from binary mixtures

The excluded-volume effect noted above restricts the size (x_1) of the fine-particle fraction. For stabilized particles, the minimum separation H_m (see Equation 2-22) is essentially constant and independent of particle size. Thus, as size x is reduced, the excluded volume effect described by Equation 2-22 becomes increasingly important and places an upper limit on the concentration ϕ_1 .

The particle size limitations can be illustrated by considering a hypothetical CWSF prepared at 50% solids by weight from various combinations of coarse and fine particles. The packing effect is described by the ratio of the coarse-particle separation H_2 to the fine-particle size x_1 . A large value indicates that the fine-particle slurry can readily fill the space between coarse particles. The excluded volume effect is reflected by the effective fine-particle concentration $(\phi_1)_{\text{eff}}$ as defined by Equation 2-22. High values would be expected to correspond to high CWSF viscosity.

The results of such calculations, based on a coarse-particle size x_2 of 75 μm and a minimum separation of the fine particles of 0.05 μm , show that the packing effect becomes critical when the fine-particle component is dilute and relatively coarse. As expected, the excluded volume effect becomes significant when the fine-particle component is concentrated and extra fine.

These calculations also demonstrate the value of using a true bimodal size distribution for CWSF formulation. The presence of intermediate sizes in a broad but continuous distribution will invariably lead to reduced values of H_2/x_1 and correspondingly reduced packing efficiency for a given solids loading.

Stabilization of Coal/Water Suspensions

Work that has been completed to date on this aspect of the project includes: (1) the construction of a modified form of the Dougherty-Krieger equation describing the dependence of CWSF viscosity on coal particle concentration and size distribution and (2) obtaining some initial models for the sedimentation or settling of the particles in a CWSF using an "effective medium approximation" (*i.e.* the viscosity expression obtained using the modified form of the Dougherty-Krieger equation).

In addition, the dynamics of settling and the equilibrium density profiles that are to be expected in various types of systems were examined. The approach used was systematic in the sense that what would be expected in a system of non-interacting particles (*i.e.* neglecting van der Waals and Coulombic interactions, but not the "hydrodynamic interactions" (*i.e.* steric repulsions) that are characteristic of a concentrated slurry) were first considered. The next step is to add various types of interactions to the model and calculate the effect of these forces. The recent work has focused on Coulombic interactions and this is described in the following section.

The Settling of Charged Coal Particles - Description of Results

During the last reporting period (Miller, et al., 1993b), the general equations describing the equilibrium profile $\phi(h)$ of the settled CWSF, where $\phi(h)$ is the volume fraction of coal particles at

a depth h , were formulated. Knowing the interparticle forces the dependence of the coal volume fraction ϕ on the depth h after the CWSF has settled can be calculated. It was calculated that for the simplest situation, where the only interaction force is the steric repulsion between coal particles, the density profile has a sharp transition from clear water to the close packing limit, ϕ_m as illustrated in Figure 2-15. In other words, the CWSF is completely "settled". Evidently, Brownian motion and steric repulsion alone cannot ensure a good stabilization of a CWSF. This is, of course, to some degree intuitively obvious, but it is the essential starting point for any model of coal sedimentation.

It was decided that the next logical step is a consideration of the effect of Coulombic interactions because:

- 1) These are expected to be repulsive and hence aid in CWSF stabilization (there are some complications here, however)
- 2) Charged groups can be readily introduced onto the surface of coal particles
- 3) Such groups are also "naturally" introduced as a consequence of oxidation.

Because the chemical group that is most commonly formed during oxidation is carboxylic acids, attention was focused on species of the form

so that the surface of the particles can become negatively charged and an electrical double layer forms around each particle, as two double layers repel one other, there will be repulsion between particles. This is illustrated schematically in Figure 2-16.

The thickness of the double electric layer is, roughly speaking, the Debye length r_D . If the water contains various ions of valences z_i ($i = 1, 2, \dots$), and of concentrations n_i , then

$$r_D = \left(\epsilon \epsilon_0 kT / \sum e^2 z_i n_i \right)^{1/2} \quad (2-35)$$

In water solutions the usual range of the Debye length is between 1 and 100 nm and can be altered within this range by varying the concentration of surface charged species, the pH and ionic strength of the suspending medium (water), etc. Equations that describe the dependence of coal concentration ($\phi(h)$) on the Debye length were obtained and for simplicity of presentation the mathematical development of the model is not described here, rather it is contained in the following section. Here, the key features of the results will be summarized.

The equilibrium concentration (volume fraction) profile for coal particles with a Debye length of 1, 10 and 100 nm were calculated. For each of these cases, particles where 1%, 10% and 20% of their surface areas consisted of charged species such as COO^- , which are formed as a

Figure 2-15. Equilibrium profile - nonstabilized coal particles

**Figure 2-16. Repulsion between charged surface groups
(electrical double layer)**

result of oxidation, were considered. For a small Debye length of 1 nm, the profile shown in Figure 2-17 is calculated. A maximum (close packing) volume fraction of $\phi = 0.67$ was assumed and it can be seen that for all coverages the equilibrium profile is essentially close packed, with a sharp transition or interface between the settled slurry and the clear water supernatant. In other words, the electrical repulsive forces between the coal particles are, in this case, too short-range to prevent settling. There is a crucial point here that is worth noting, however. The concentration transition is not quite as sharp as in slurries without charged species (see Figure 2-15) and even a small concentration deviation from maximum packing can lead to a dramatic drop in viscosity (typical viscosity profiles were described in Miller, et al., 1993b). Accordingly, a plot of viscosity ratio $K (= \eta^*/\eta_s)$, Miller, et al 1993b) shows that at 20% coverage there is a "manageable" viscosity that extends a few centimeters into the settled slurry (Figure 2-18). This suggests that it should be possible to "move" a settled slurry of this type by continually "sweeping away" the surface layer using a flow of water. The slurry will attempt to establish a new surface layer equilibrium that in turn will also be swept away.

If, by adjusting the pH of the slurry or adding electrolytes, the Debye length is extended to about 10 nm, then the interface between the "settled" portion of the slurry and the clear water overlayer becomes more diffuse and a region of manageable (*i.e.* non infinite) viscosity extends further into the slurry, as illustrated in Figures 2-19 and 2-20. Unfortunately, as the Debye length is increased beyond 10 nm this stabilization is lost as the electrical double layer becomes too diffuse and the repulsive forces too weak to stabilize the slurry. Figures 2-21 and 2-22 show the return of the sharp settled slurry/clear water interface for slurries with a Debye length of 100 nm.

These results clearly show that arranging slurry conditions so that the Debye length is about 10 nm produces optimum results (at any coverage of charged species), but this alone is insufficient to prevent settling. As a result, additives must be used such as polymer stabilizers and in Phase II of the program the affect of stabilizers on viscosity and sedimentation will be investigated.

The Settling of Charged Coal Particles - Derivation of Equations

To calculate the density profile, the equations described in Miller, et al., 1993b are used as the starting point. The profile $\phi(h)$ is determined by the set of equations:

$$h/L_o = - \int_{\phi(0)}^{\phi(h)} d(\Gamma(\phi)\phi)/d\phi \quad d\phi/\phi \quad (2-36)$$

$$\phi(0) \Gamma(\phi(0)) - \phi(H) \Gamma(\phi(H)) = (H/L_o) \phi_{init} \quad (2-37)$$

Figure 2-17. Coal volume fraction profile
Debye radius = 1 nm

Figure 2-18. Viscosity profile
Debye radius = 1 nm

Figure 2-19. Coal volume fraction profile
Debye radius = 10 nm

Figure 2-20. Viscosity profile
Debye radius = 10 nm

Figure 2-21. Coal volume fraction profile
Debye radius = 100 nm

Figure 2-22. Viscosity profile
Debye radius = 100 nm

Note that Equation 2-37 is slightly different to that given in the previous report (Miller, et al 1993b), because the surface of the slurry is now defined as the zero point. In Equations 2-36 and 2-37

$$L_o = kT/V_o g(\rho_c - \rho_w) \approx 10^{-11} \text{ m} \quad (2-38)$$

where ρ_c and ρ_w are densities of coal and water, respectively, V_o is the volume of a coal particle, g is the gravitation constant, H is the height of the vessel, ϕ_{init} is its initial coal volume fraction (assumed to be uniform), and the function Γ is determined by

$$\Gamma(\phi) = (V_o/\phi kT) \pi(\phi) \quad (2-39)$$

where $\pi(\phi)$ is the osmotic pressure of the coal particles.

For the electrically stabilized slurry it can be written

$$\pi(\phi) = \pi_o + p_{el} \quad (2-40)$$

where π_o describes steric repulsion only, as discussed previously (Miller, et al., 1993b). The π_o term gives;

$$\Gamma_o = 1.85/(\phi_{close} - \phi) \quad (2-41)$$

The electric contribution is

$$p_{el} = - \partial F_{el}/\partial V \quad (2-42)$$

where F_{el} is the free energy of the interaction between the electrical double layers.

To calculate F_{el} the fact that the electric double layers are thin is used. Therefore, it can be assumed that the particles packing structure is close to the close packing limit. In other words, imagine that each particle is surrounded by a thin 'coat' of thickness s , so that in effect the slurry can be modeled as a system of close-packed particles of radius $a + s$, where a is the true radius. In this case

$$\partial F_{el}/\partial V = (\partial F_{el}/\partial s) (\partial s/\partial V) \quad (2-43)$$

and for close-packing

$$((a+s)/a)^3 = \phi_{\text{close}}/\phi \quad (2-44)$$

and, since

$$\phi = 4/3 \pi a^3 N/V \quad (2-45)$$

where N is the number of particles, gives

$$\partial s / \partial V = (a + s) / 3V \quad (2-46)$$

To calculate F_{el} the fact that $s \ll a$ is used, so that only nearest neighbors have overlapping layers. If each particle has an average of l neighbors (for random close packing $l \approx 10$), and the repulsive force between two neighboring particles is $P(s)$, then

$$\partial F_{el} / \partial s = - (Nl/2) P(s) \quad (2-47)$$

In the Derjaguin approximation the force $P(s)$ is then

$$P(s) = 2\pi \epsilon \epsilon_0 (kT/e)^2 (a/r_D) (\Psi_s)^2 \exp(-2s/r_D) / (1 + \exp(-2s/r_D)) \quad (2-48)$$

where Ψ_s is the dimensionless parameter, determined by the electric potential ψ_s of the particles surface. For a monovalent group (e.g. COO^-)

$$\Psi_s = e\psi_s/kT \quad (2-49)$$

The potential of the coal surface is determined by three factors:

- 1) the constant K_i of the ionization reaction (Equation (2-15))
- 2) the concentration of the ions $[\text{H}^+]_0$ in the solution.
- 3) the concentration $n = [\text{A}^-]$ of the anchored groups on the coal particles surface.

The Guoy-Chapman model is used to calculate Ψ_s . The equilibrium condition on the surface of the particles can be written as

$$[\text{A}^-] [\text{H}^+]_s = K_i (n - [\text{A}^-]) \quad (2-50)$$

Therefore the surface charge is

$$Q = e[A^-] = (eK_i n)/(K_i + [H^+]_s) \quad (2-51)$$

If the bulk concentration of H^+ ions is $[H^+]_o$, then the surface concentration is

$$[H^+]_s = [H^+]_o \cdot \exp(-\Psi_s) \quad (2-52)$$

Accordingly, this gives three variables: $[H^+]_s$, Q and Ψ_s and two Equations 2-51 and 2-52. To obtain solutions, an independent relationship between the surface charge and the surface potential is required. This relationship can be obtained using the Loeg, Overbeek and Wiersema approximation for $a/r_D \gg 1$. This approximation gives

$$Q = 2 (\epsilon \epsilon_0 kT \sum z_i n_i)^{1/2} \cdot \sinh(-1/2 \Psi_s) \quad (2-53)$$

From equations 2-51 to 2-53 it then follows that

$$(K_i n / (K_i + [H^+]_o \exp(-\Psi_s))) = (2 \epsilon \epsilon_0 kT / e^2 r_D) \sinh[-1/2 \Psi_s] \quad (2-54)$$

For $K_i \gg [H^+]_o \exp(-\Psi_s)$ (i.e. the surface groups are almost completely ionized) this equation gives

$$\Psi_s = -2 \operatorname{arcsinh} \frac{e^2 r_D n}{2 \epsilon \epsilon_0 k T} \quad (2-55)$$

The density profile then becomes;

$$h = -L_o \int_{\phi(o)}^{\phi(h)} (d(\Gamma_o(\phi)\phi)/d\phi) (d\phi/\phi) - L_1 \int_{\phi(o)}^{\phi(h)} (d(\gamma_{el}(\phi)\phi)/d\phi) (d\phi/\phi) \quad (2-56)$$

where L_o and Γ_o are given by Equations 2-38 and 2-41 and

$$L_1 = (\epsilon \epsilon_0 \Psi_s^2 / 4ag (\rho_c - \rho_w) r_D) (kT/e)^2 \quad (2-57)$$

$$\gamma_{el}(\phi) = \exp(-2s(\phi)/r_D) / (1 + \exp(-2s(\phi)/r_D)) \quad (2-58)$$

and $s(\phi)$ is determined by Equation 2-43. Inside the transition layer ϕ is near ϕ_{close} . Therefore

$$d(\Gamma\phi)/d\phi \approx \phi (d\Gamma/d\phi) \text{ and } (d(\gamma\phi)/d\phi) \approx \phi (d\gamma/d\phi) \quad (2-59)$$

Then using Equation 2-36 and supposing $\Gamma_o(0) \approx 0$, $\gamma_{el}(0) \approx 0$ gives

$$h = H(\phi_{init}/\phi_{close}) - \Gamma_o(\phi) L_o - \gamma_{el}(\phi) L_l \quad (2-60)$$

The most interesting parameter for the CWSF is the viscosity coefficient $K = \mu/\mu_o$. As ϕ goes to ϕ_{close} , K goes to infinity. In the Dougherty-Krieger approximation

$$K = (1 - (\phi/\phi_{close})^\rho)^{-\rho/\phi_{close}} \quad (2-61)$$

where $\rho \approx 2.67$.

The profiles $\phi(h)$ and $K(h)$ for various values of r_D are described in the preceding section. In performing the calculations it was assumed that the factor n describing the concentration of groups on the coal surface can be calculated in terms of the fraction of surface area occupied by the charged species and that COO^- groups cover approximately $100\text{\AA}^2$ each.

2.4 Subtask 1.4 Develop a Dry Coal Cleaning Technique:

The equipment for assembling the dry grinding circuit was received. The circuit consists of an opposing jet, fluid-energy mill in closed circuit with a Donaldson Acucut classifier (Figure 2-23). The compressed air (~ 760 kPa) for the jet mill is supplied by a rotary screw compressor, while the flow of air through each jet is monitored with a differential pressure gauge. This circuit will be capable of providing a range of particle size distributions for TriboElectrostatic separation and will be used primarily to produce micronized coal. In order to produce the coarser ("PC") material, stage crushing using a hammermill and a high-speed pulverizer will be used. A typical size distribution of the coal generated by this procedure is shown in Figure 2-24.

Dry Beneficiation

Work is continuing on the development of a dry beneficiation process based on TriboElectrostatic Separation (Link et al., 1990). The electrostatic separator was modified by adding a series of flow straighteners (~ 5 mm diameter by ~ 100 mm long plastic tubes) at the feed end to the separator whereby sweep air could be drawn through the tubes (Figure 2-25). A series of shakedown tests was performed with the unit.

The preliminary testing was performed using the Upper Freeport coal. Initially, a 50 g sample of the coal was fed to the separator. At this time, no attempt was made to control the feed rate. Dried, compressed air was used as the aerosolizing stream, although nitrogen will be used in subsequent tests. The gap between the separator plates were set at 115 mm, with a voltage drop

Figure 2-23. Schematic diagram of the dry grinding circuit

Figure 2-24. Size Distribution of the coarse ground coal

Figure 2-25. Schematic diagram of the TriboElectrostatic Separator

across the plates of 52 kV (± 26 kV). After the separation was completed, the plates were removed and the coal and refuse fractions were separated at spaced increments along the length of each plate. The samples were weighed to determine the yield at each point and then analyzed for ash content. Total sulfur analysis was also done on two of the samples. The results are given in Table 2-6 and Figures 2-26 through 2-28.

2.5 Subtask 1.5 Produce MCWMs and Micronized Coal from Dry, Clean Coal

No work was scheduled or performed in Subtask 1.5 this reporting period.

2.6 Subtask 1.6 Produce MCWM and Dry, Micronized Coal for the Demonstration Boiler

Fuel Preparation Facility

Work on this subtask focused on completing the fuel preparation facility (MCWSF and DMC) associated with the demonstration boiler (15,000 lb steam/h boiler). The facility is approximately 75% complete. The remaining construction item to be completed is an inspection from the Pennsylvania Department of Labor & Industry. The facility will be turned over to Penn State after the inspection. Figure 2-29 is a plan view of the demonstration boiler site. The boiler is located adjacent to Penn State's East Campus Steam Plant (ECSP) in the boilerhouse labeled 'new addition'. Details of the ECSP, demonstration boiler and ancillary components, and a chronology of Penn State's previous efforts in coal-water slurry fuel research can be found elsewhere (Miller et al., 1993a; Miller and Scaroni, 1990 a,b). In addition, the baghouse, the 15,000 gallon CWSF storage tank, the CWSF transfer station, the diagnostics laboratory trailer, and the future emissions control systems site are shown in Figure 2-29.

A schematic diagram of the equipment train in the fuel preparation facility is shown in Figure 2-30. There are two circuits in the facility, one for producing dry, micronized coal and one for producing MCWSF.

Dry, Micronized Coal Preparation Circuit

The dry, micronized coal preparation circuit is complete. The 50-ton coal hopper, coal crusher, metal detector, reddler elevator, 5-ton surge bin, screw feeder, booster fan and TCS mill (pulverizer) have been installed. A dual-control system has been installed to allow operation of the circuit from either the coal preparation facility or the demonstration boiler.

MCWM Preparation Circuit

Work is currently underway setting up the MCWSF preparation circuit. The 50-ton coal hopper, reddler elevator 5-ton surge bin, and screw feeder are common to the dry, micronized coal and MCWSF circuits. The ball mill has been delivered, cleaned (a used mill was donated by Allis Minerals Systems), leveled, and anchored. It is being modified in that the motor is being relocated underneath the mill due to space constraints. In addition, the hydraulic system and feed screw (screw located in the ball mill inlet hopper) are being rebuilt. The ball mill will be deflaked and painted and associated piping and pumps installed.

Figure 2-26. Direct ash values as a function of separator length

Figure 2-27. Cumulative ash as a function of separator length

Figure 2-28. Total yield as a function of separator length

Figure 2-29 Overall site view showing the location of the fuel preparation facility and future emissions control site

Figure 2-30. Schematic diagram of the equipment train in the fuel preparation facility

The MCWSF preparation circuit includes several moyno progressive cavity displacement pumps, a 30-inch screen, several tanks (process, blend, waste water), a sand mill, and a plate filter press. The pumps and sand mill were donated by CE, as part of the cost-sharing component of the program, and were part of their pilot-scale coal-water mixture preparation facility. Penn State personnel inspected each piece of equipment, disassembled it, and determined its operability. Equipment that was in, or near working condition was cleaned, reassembled, in some cases rebuilt, and painted. A list of the equipment that have been reconditioned was previously reported (Miller, et al., 1993b). Installation of this equipment will begin after the facility is turned over to Penn State.

The goal is for the overall site (boiler and MCWSF preparation facility) to be a zero-discharge facility. Consequently, a filter press is being procured to process waste water. This includes water that is generated from flushing lines, off-specification MCWSF, and water used to clean the facility (equipment and floors). The solid material will be removed from the water the water will be reused in the production of MCWSF.

3.0 TASK 2: COAL COMBUSTION PERFORMANCE

3.1 Subtask 2.1 Boiler Retrofit

No work was conducted this reporting period.

3.2 Subtask 2.2 Fuel Evaluation in the Research Boiler

In this subtask, candidate fuels will be evaluated in Penn State's 1,000 lb steam/h research boiler. Details of the boiler and auxiliary components were previously presented (Miller, et al., 1993b).

Mulled Coal Testing

During this reporting period, three combustion tests were conducted to evaluate a coal-based fuel produced by Energy International, Inc. (EI). The fuel, called mulled coal, was tested on an as-received basis and as a coal-water slurry fuel.

Results

Mulled coal is produced from filter cake obtained from coal cleaning processes. Two mulled coal combustion tests were originally planned, one using the as-received material (fired in suspension) and one with the mulled coal produced into a CWSF. However, because the high moisture content of the first shipment (~41-42 wt.%) caused operability problems when fired in suspension (as discussed below), EI air dried a sample of the mulled coal (labeled Sample #3 by Penn State) until the moisture content was ~18 wt.% and then shipped it to Penn State. This sample was then fired in suspension.

Analyses of the mulled coal samples that were shipped to Penn State are given in Table 3-1, which contains the proximate and ultimate analyses, calorific value, and particle size distributions.

Table 3-1. Mulled Coal (MC) Analysis

	Mulled Coal (As Received)		MC Produced into CWSF		MC Tested on April 7, 1993	
	As Det.	Dry Basis	As Det.	Dry Basis	As Det.	Dry Basis
PROXIMATE ANALYSIS (wt.%)						
Moisture	40.7	--	42.5	--	17.7	--
Volatile Matter	21.9	37.0	21.7	37.8	30.2	36.7
Fixed Carbon	36.3	61.2	34.9	60.7	50.8	61.7
Ash	1.1	1.9	0.9	1.5	1.3	1.6
ULTIMATE ANALYSIS (wt.%)						
Carbon	--	--	49.4	85.9	70.6	85.8
Hydrogen	--	--	3.2	5.6	4.8	5.8
Nitrogen	--	--	0.9	1.5	1.2	1.5
Sulfur	--	--	0.3	0.6	0.5	0.6
Oxygen	--	--	2.8	4.9	3.9	4.7
Ash	--	--	0.9	1.5	1.3	1.6
Calorific Value (Btu/lb)	8,889	14,990	8,748	15,215	12,617	15,330
Particle Size ^a (μ m)	--		33.3		42.4	
D(v, 0.9)	--		12.0		13.7	
D(v, 0.5)	--		4.1		4.4	
D(v, 0.1)	--					

^aParticle size was measured using a Malvern 2600C Particle and Droplet Sizer. Particle sizes refer to volume fractions that are less than the indicated size

Samples #1 and 2 were obtained from the first shipment while Sample #3 was taken from the second shipment.

A discussion of the test results is contained in the following sections. Table 3-2 contains a summary of the combustion tests.

Test #1

Tests #1 and 2 were conducted on March 23, 1993 with representatives of EI in attendance. The mulled coal was to be first fired as received and then as a CWSF. The procedure that was used when firing the mulled coal in suspension was as follows:

- 1) The boiler was preheated firing natural gas at a rate of ~2 million Btu/h until the quarl reached a predetermined temperature.
- 2) The natural gas-fired preheater was started and the secondary air was preheated to 190-230°F.
- 3) The pulverized coal entrainment air was started and the coal feeder turned on, introducing the mulled coal.
- 4) The mulled coal feed rate was increased while the natural gas was decreased.

Test #1 was conducted firing the mulled coal in pulverized form for only 15 minutes. Handling of the mulled coal was a problem as the screw feeder did not feed it consistently. This resulted in slugging into the boiler and the flame pulsated between yellow-white and black. Consequently, the natural gas flow could not be eliminated and was retained at a high level (50% of the thermal input into the boiler) for safety reasons.

The pulsing also caused other problems. When slugs of coal were fed into the boiler, there was insufficient oxygen available for complete coal combustion. This resulted in the formation of a substantial quantity of CO and a high baghouse temperature. The CO concentration in the baghouse outlet was higher than that at the economizer inlet. This, coupled with the rising baghouse temperature, was a cause for alarm and the test was terminated after 15 minutes of operation. The baghouse temperature was ~400°F and rising and was near the maximum operating temperature of the bags when the test was terminated.

Test #2

The procedure that was used when firing the mulled coal in slurried form was as follows:

- 1) The mulled coal was first mixed in a ribbon mixer with a dispersant (provided by EI) that transformed the mulled coal into a CWSF. This was performed by Penn State personnel under the direction of representatives from EI.
- 2) After the suspension test, the boiler was fired with natural gas at a rate of ~2 million Btu/h to maintain system temperatures until the CWSF test was conducted.

Table 3-2. Summary of Test Results

Date of Test:	March 22, 1993	March 22, 1993	April 7, 1993
Test Number:	1	2	3
Fuel Form Tested:	Pulverized Coal	CWSF	Pulverized Coal
Combustion Air Preheat Temperature (°C)	88.6	110.8	92.2
Economizer Temp. (°C)	318.5	268.5	229.4
Thermal Input (%)			
Coal	50	0	100
Natural Gas	50	0	0
CWSF	0	100	0
Selected Air Flow Rates (scfm)			
Primary	5.0	4.0	5.0
PC entrainment	25.0	0	25.0
Tertiary	58.0	60.0	50.0
Atomizing	0	139	0
Flue Gas Analysis			
O ₂ (%)	7.9	7.7	7.9
CO (ppm)	168	165	186
CO ₂ (%)	9.6	11.8	12.6 ^a
SO ₂ (ppm)	68	164	197
NO _x (ppm)	271	485	477
Char/Ash Analysis:			
- Combustibles in hopper char/ash	Not determined	64.0 wt.% (d.b.) ^b	48.3 wt.% (d.b.)
- Combustibles in baghouse char/ash	Not determined	31.8 wt.% (d.b.)	28.4 wt.% (d.b.)

^aAnalyzer was not stable^bDry basis

- 3) Atomizing air was introduced at a pressure of ~100 psig. The CWSF was then introduced and the flow rate was slowly increased to the desired rate while decreasing the natural gas flow to zero.

The flame appeared stable during the test but large particles were observed burning on the boiler hearth (floor). Char/ash samples were collected from the convective section hoppers and baghouse hopper and analyzed for their ash contents. The combustibles in the char/ash samples are reported in Table 3-1. The quantity of combustibles in the fly ash (~30%) is a typical value observed when firing pc or CWSF in Penn State's research boiler.

When evaluating a pulverized coal or CWSF, Penn State uses the ash content of the char/ash sample to determine the combustion efficiency. The ash content of the char/ash sample is related to the ash content of the feed material by the equation:

$$\Delta W = [1 - A_o(100 - A')/A'(100 - A_o)] \times 100 \quad (3-1)$$

where ΔW = percent weight change (combustion efficiency), daf coal

A_o = proximate ash content of fuel, dry

A' = proximate ash content of char/ash sample, dry

Using this equation, the combustion efficiencies of the mulled coal based on the samples from the convective pass hoppers and the baghouse were 97 and 99%, respectively. However, the overall combustion efficiency was significantly lower than this since there was a significant amount of material deposited on the floor of the boiler. This material was not collected and analyzed but past experience firing pc and CWSF has shown that the material on the floor of the boiler is usually high in combustibles. With other pcs and CWSFs, however, the quantity deposited on the floor is usually not significant.

Figure 3-1, which shows the relationship between the ash content of a coal, the ash content of the char formed during combustion, and the resulting combustion efficiency, is included for reference. It shows that for a coal with a low ash content (*e.g.*, 2.0 wt.%), the coal combustion efficiency is likely to be high for char/ash samples with combustibles ranging from 20 to 80%.

Test #3

A second suspension firing test was conducted on April 7, 1993. The test procedure was identical to that listed above. Test 3 was a repeat of Test 1 except that the moisture content of the mulled coal was reduced from 44 to 17 wt.%. Less handling problems were experienced and the coal was burned without natural gas support. However, after 30 minutes of testing, the flame scanner did not sense the flame and the safety interlocks shut off the boiler. The reason for this is not clear. The results are summarized in Table 3-2.

Figure 3-1. Relationship between the ash content in a coal, the ash content in the char formed during combustion, and the resulting combustion efficiency

Conclusions and Recommendations

The mulled coal that was produced into a CWSF was stored, pumped, atomized, and burned in a similar manner to other CWSFs tested at Penn State. The combustion performance of the slurried mulled coal was similar to that of the other CWSFs.

The mulled coal that was fired as received was more difficult to handle (feed from the hopper to the burner via the screw feeder and eductor) than other pulverized coals tested at Penn State. The mulled coal with the high moisture content could not be fired in the research boiler. The mulled coal with the lower moisture content was easier to handle than the case with the higher moisture content but was still more difficult to handle than other pulverized coals tested at Penn State.

The tests that were conducted were short in duration. It is recommended that longer tests be conducted in order to make a detailed evaluation. To be able to conduct pulverized mulled coal tests in the research boiler at Penn State, the coal feed system would have to be modified and the flame scanner relocated within the boiler. In addition, for some commercial applications it is likely that mulled coal will be fired as a blend with pulverized coal, in which case the blend may have very different properties than the mulled coal alone. Tests should also be performed on the blend.

3.3 Subtask 2.3 Performance Evaluation of MCWM and Dry, Micronized Coal in the Demonstration Boiler

Evaluate Erosion/Deposition Characteristics

Recent work has been focused on two areas: Improvement of the metal oxidation component of the erosion-corrosion model, and interpretation of the ash deposition measurements from the demonstration boiler.

Metal Oxidation

The treatment of the carbon steel oxidation in the erosion-corrosion model has been based on an extrapolation of higher temperature work of Davies et al. (1951) to the region covered by the testing in this program (350 to 710°F). Davies' activation energy is very high, resulting in a rapid transition of the erosion-corrosion mechanism from ductile metal to brittle oxide erosion with increasing temperature. Observations of erosion in the presence of nitrogen, air, and oxygen also provided data for determination of the oxygen concentration dependence of the erosion-corrosion rate (Miller et al. 1993b). The measurements suggest that the order of the oxidation reaction with respect to oxygen is approximately 2. A review of the literature on the subject of iron oxidation showed that the activation energy at temperatures near 600°F is much lower than that obtained from Davies et al.'s measurements and that the order of the reaction with respect to oxygen is between 0 and 1. Resolution of these problems is being addressed.

Ash Deposition

Measurements of ash deposition on a 25 mm diameter tube placed in the convective section of the demonstration boiler when firing a coal-water slurry fuel were reported previously (Miller et al. 1993b). The loading of ash (kg of ash/m² of tube surface) was determined as a function of position around the circumference of the tube. The deposit was less than 1 μm thick on the upstream side and 10 to 30 μm thick on the downstream side after 6 hours of exposure to flue gas. Measurements at a particular location on the tube surface at different the tube temperatures showed that deposition increased with increasing temperature difference between tube and gas, suggesting that the dominant mechanism of deposition is thermophoresis (Motion of particles driven by a temperature gradient in the gas. The direction of motion of the particles is from higher to lower temperature, toward the cool surface of a convective tube, for example.).

A model was constructed in which deposition competes with erosion on the upstream side of the tube, and deposition alone occurs on the downstream side. The temperature gradient at different positions on the circumference was determined from the angle dependence of the Nusselt number for heat transfer. There are two adjustable parameters: the thermal conductivity of the ash particles, which determines the thermophoretic velocity, and the erosivity of ash and unburned char toward the deposited ash. Using the parameters which fit the data, it was estimated that deposition on the upstream sides of convective tubes in the demonstration boiler, when firing coal-water slurry fuel (containing ~60 wt. % coal and 3.5wt.% ash in the coal) at 90% coal combustion efficiency, will be negligible at gas velocities greater than approximately 10 ft/s (3 m/s). Combining this result with the predictions of the erosion-corrosion model, it was found that there is a range of optimum gas velocities, within which neither deposition nor erosion will be excessive, which is from approximately 10 to 39 ft/s (3 to 12 m/s), corresponding very closely to the actual range of gas velocities in the convective section of the demonstration boiler at full load.

Determine Erosion Characteristics of Materials Subjected to Atomized Coal-Water Slurry Fuel

Background/Introduction

The internally-mixed atomizer tips used in demonstration boiler during a recently completed 500-hour test program firing coal-water slurry fuel (CWSF) containing ~60 wt. % solids and 3.5 wt. % ash in the coal (Miller et al 1993a), experienced excessive erosive wear under normal operating conditions. Droplet outlet passages became elliptical resulting in poor atomization and hence, inefficient combustion. Lifetimes of the nozzles ranged from 8 to 125 hours. The short atomizer life results in high operating costs and excessive boiler downtime. In an attempt to obtain more information on atomizer operation and materials of construction, a study has been started to evaluate the erosive behavior of different materials when subjected to an atomized CWSF spray.

When doing erosion studies, the most important parameters to monitor are impact angle and velocity. In order to conduct a study of candidate materials, an experiment was designed in which both angle of impact and droplet velocity are known and can be varied. The goal is to create diverse erosive environments covering a range of atomizer designs.

Experimental Design

The experiments will be conducted in a small test facility (Figure 3-2) that has been designed for investigating the effects of impact angle and atomization air pressure on erosion characteristics. Design considerations included atomizer selection and sizing, CWSF transport and containment, mist elimination, material sample mounting, and sample orientation.

The test facility, 2' x 2' x 2', is sufficiently large to allow the droplets to disperse before exiting the chamber and to provide room for housing additional instrumentation or plumbing. The body of the chamber consists of 1/2" thick aluminum plate and the sample stage is constructed from 1/4" aluminum plate.

Atomized CWSF will be collected in the bottom of the chamber and it will be removed after a test run is completed. CWSF that is not collected at the bottom of the container will be ventilated during operation through an 1/2" eductor mounted on the side of the chamber. Ventilated mist leaves the chamber and moves through flexible polypropylene tubing to the bottom of a water tank. Ventilated air bubbles to the surface and CWSF droplets disperse throughout the liquid.

The atomizer that will be used to produce droplets for the experiment is an internally mixed oil nozzle manufactured by Delevan, model 33769-9 (Figure 3-3). The nozzles have been modified to accommodate CWSF by drilling the outlet port to a larger dimension, (approximately 0.19 cm.) in order to prevent coal particles from blocking the orifice. The CWSF feed rate will be ~3.95 gph.

The materials to be analyzed for erosion will be situated on a stage fixed with a rotating axis. The center of the material sample can be varied to any length.

Spray characterization will be done using an in-situ particle sizing probe. The probe works using laser light scattering principles and is capable of measuring droplet concentrations, size distributions, and velocities, all in real time.

CWSF Selection

Due to differences in the abrasiveness of different coals, the erosion data obtained for one CWSF may not be applicable to materials subjected to wear by another. The CWSF used therefore, will be the one used in the 1,000-hour demonstration. In addition to typical fuel analyses (proximate, ultimate, heating value, solids loading, viscosity, etc.), the mineral matter will be analyzed and the average particle size of the quartz and pyrite particles measured.

Figure 3-2. Atomization / Erosion test facility

Figure 3-3. Schematic diagram of the Delavan Nozzle

Material Selection

Many materials are reported to be wear resistant but often this means resistant to abrasion (sliding contact) not erosion (particle impact). In fact, many times wear resistant materials erode more quickly than soft materials due to the erosion mechanisms involved. The materials to be used will possess different mechanical properties. Five or six materials will be tested. The group will likely consist of metals, ceramics, and composites.

Analysis

The material sample will be removed from the testing chamber every two hours for analysis. Analysis will consist of surface profilometry, weight loss measurements, and scanning electron microscopy. From the data collected, erosion rates will be calculated, erosive mechanisms identified, and the material best suited for atomizer construction identified.

Theoretical and Experimental Studies of Particle Behavior in the Demonstration Boiler

The application of coal or coal based fuels to an industrial boiler presents several technical challenges which include:

- satisfactory combustion efficiency
- handling coal and ash
- controlling emissions

In order to overcome these challenges, the combustion process in the boiler needs to be analyzed, well understood, and characterized. The burning of volatile matter and char in a turbulent diffusion flame is a complex process. Despite a good deal of fundamental data available on this topic from single particle studies, there is a shortage of data available for industrial type combustors. While recognizing the importance of the role of the small-scale experiments, they do not simulate all of the many processes which occur in practical combustors. To increase understanding of pulverized coal and CWSF turbulent jet flames in an industrial boiler, theoretical and experimental work has been initiated.

Theoretical Background

Fragmentation During Devolatilization

Fragmentation of CWSF agglomerates during devolatilization has been observed in a number of bench scale experiments. It has been suggested that as jets of volatiles are issued from the CWSF agglomerate, they impart rotation to the agglomerate. This rotation (or more specifically angular velocity) produces an angular momentum, which in turn generates a centrifugal force. It is conceivable that this centrifugal force can promote the separation of weakly adhering coal particles from the CWSF agglomerate during devolatilization.

2 of 2

Char Fragmentation

Under combustion conditions typical of an industrial boiler, CWSF agglomerates and pulverized coal particles burn in a regime where O₂ penetrates partially into the pores of the particles. As the carbon is consumed in the outer regions of the particle and the porosity increases, the structural strength of this region is lowered. It has been suggested that beyond the critical porosity of 0.7-0.8, the integrity of the solid matrix is lost and the particle sheds off fragments. These fragments escape and burn separately. It is important to determine the conditions under which char fragmentation is favored, since this phenomenon is useful both from the point of view of burnout and obtaining a finer fly ash.

To investigate the phenomenon of fragmentation through an analysis of the behavior of the particles in the demonstration boiler, *in situ* particle counting, sizing and velocimetry technology will be used (using an Insitec PCSV-P) to gather data on the temporal and spatial variations of the particle size distribution and number densities of the pulverized coal particles and the CWSF agglomerates. To further analyze the behavior of the particles in the boiler, it is necessary to characterize the environment inside the boiler in terms of the operational parameters. This involves the correlation of the boiler's operational parameters to the aerodynamic properties of the jet flame. These operational parameters for a pulverized coal jet flame include:

- Amount of combustion air
- Amount of fuel
- Inlet temperature of the combustion air
- Swirl number
- Amount of tertiary air and hence level of excess air

The objectives of the project recently started are focused on the phenomena taking place during the combustion of CWSF, however, the experimental techniques will be applied to the combustion of pulverized coal so that the process of combustion in the boiler will be further characterized and understood.

The operational parameters for a CWSF jet flame include all of the aforementioned parameters for PC jet flame, plus the following:

- Different atomizer guns, resulting in different spray (or jet) angles, velocities, and droplet size distributions
- Inlet temperature of the CWSF
- Pressure and temperature of the atomizing air
- Length of penetration of the atomizer gun, axially into the boiler, which will affect the boiler residence time.

To fully characterize the boiler, temperature and gas velocity profiles will be obtained for different operating conditions. Hence, in addition to the measurements carried out with the PCSV-P, suction pyrometry and pitot-tube measurements will also be performed.

The main aerodynamic properties of turbulent jet flames are: velocity, temperature and concentration. To correlate these three properties to the operational parameters of the jet, the conservation equations of mass continuity, energy and momentum (Navier-Stokes equations) will be applied to the jet flame, to obtain expressions for velocity, temperature and concentration of the jet.

Computational Modeling of Natural Gas Combustion in the Demonstration Boiler

To further enhance the theoretical understanding of the furnace environment in the demonstration boiler, the fundamental equations governing the fluid flow (the mass continuity equation, the energy equation and the Navier-Stokes equations) are solved employing a computational code (FLUENT, developed by Creare Inc.) which uses a finite difference numerical procedure. The numerical technique involves the subdivision of the domain of interest into a finite number of control volumes or cells. The partial differential equations are discretized over these cells to obtain sets of simultaneous algebraic relations. Because of the non-linearity and interdependence of the differential equations, an iterative solution has to be adopted.

The fluid is regarded as a continuum and is solved in an Eulerian frame of reference in the manner described above. Where a second, disperse phase is present a Lagrangian approach is preferred. Particles or droplets are followed by means of a particle tracking technique in which the equations of motion along with any auxiliary relations which may be in effect, are integrated with respect to time.

In order to fire pulverized coal or CWSF, the furnace environment in the boiler is initially heated by firing natural gas. Consequently, a two-dimensional model for the combustion of natural gas in the boiler has been set up employing FLUENT. In order to save considerable CPU time and to facilitate quick iterations, only a horizontal slice of the furnace environment is modeled with the assumption that the values of gas velocity, temperature, turbulence intensity, etc. in this slice are characteristic of the entire volume of the furnace. The validity of this assumption will be tested by repeating the calculations for different slices and finally by setting up a three-dimensional model for the combustion of natural gas in the boiler.

The details of the calculated flow field in the boiler are shown by means of graphical plots (Figures 3-4 to 3-13). The solution domain, including the grid locations, is displayed graphically in Figure 3-4. In Figure 3-5, the vector plot indicating the magnitude of the resultant velocity at each point in the flow field is shown. The vectors are scaled in length according to the magnitude of the velocity. Figures 3-6 to 3-9 the profiles of the u-velocity (*i.e.*, the x-component of the velocity), and concentration profiles of natural gas, air and the combustion products are illustrated. The profiles are interpreted by noting that the dashed line refers to the datum location. The distance between the dashed line and the solid line indicates the magnitude of the variable being plotted. In the case of the profiles of u velocity, where the solid line is to the right of the datum line, the

Figure 3-4. The finite difference grid for the 2 dimensional solution domain

Figure 3-5. The velocity vectors in the demonstration boiler during the combustion of natural gas

Figure 3-6. Profiles of u-velocity

Figure 3-7. Concentration of profiles of fuel species (on a mass basis)

Figure 3-8. Concentration profiles of oxidant species (on a mass basis)

Figure 3-9. Concentration profiles of combustion products (on a mass basis)

Figure 3-10. Contours of u-velocity

Figure 3-11. Concentration contours of fuel species (on a mass basis)

Figure 3-12. Concentration contours of oxidant species (on a mass basis)

Figure 3-13. Concentration contours of combustion products (on a mass basis)

u-velocity is positive and when it is to the left the u-velocity is negative. Figures 3-10 to 3-13 show that the contours of the u-velocity, and species concentrations are drawn at equal intervals distributed between the minimum and maximum values of the variable throughout the flow field.

Having characterized the combustion of natural gas in the boiler, the next stage of this modeling work entails the injection of pulverized coal particles and CWSF droplets into the furnace and following their combustion histories.

Experimental

Local particle behavior has received significant attention from a modeling perspective, however, it is only beginning to be addressed experimentally due primarily to the lack of instrumentation to carry out such studies. The objectives of the experimental section of this study is twofold.

Firstly, to obtain information on velocity, size distribution and number density of pulverized coal particles in the boiler. These measurements will provide validation data for the three-dimensional codes being developed to model pulverized coal combustion.

The second objective of this research is to look at the phenomenon of fragmentation during the devolatilization of CWSF and examine the hypothesis used to explain this phenomenon. In the event that this proves difficult to accomplish, the process of fragmentation during char burnout will be investigated. In fact due to the time scales involved (ms-s), it seems logical to investigate fragmentation during devolatilization and char burnout concurrently.

The phenomenon of fragmentation has never been investigated in an industrial-sized boiler and the above hypothesis has been developed out of the work done on numerous bench-scale experiments. Consequently, in the event that fragmentation does occur during devolatilization of CWSF in the demonstration boiler, factors other than the angular velocity of the agglomerates may be responsible for the break up of the agglomerates. These factors may include the degree of swirl and the turbulence intensity of the jet flame.

PCSV Technology

The PCSV (developed by Insitac, Inc.) is an *in situ* instrument capable of measuring the concentration number density, size distribution, and velocity of disperse particles (see Figure 3-14).

Particle sizes are inferred from the amplitude of the near-forward scattered He-Ne laser beam. For this application two laser beams will be used separately, one with a 25 μm beam waist used to size particles in the range 0.4-2 μm and the second with a 250 μm beam waist used to size particles in the range 2-140 μm .

Light scattered from the particles passing through the sample volume of the beam waist is collected over a solid angle and monitored with a photomultiplier tube. The size and the trajectory of the particles affect the maximum amplitude of the detected pulses in known ways. As long as

Figure 3-14. The components of PCSV

the particles are small compared with the beam waist, Mie theory predicts their size dependence. Trajectory dependencies are calculated by a statistical technique based on the following assumptions: 1) the average flux of particles of a given diameter does not vary spatially over the width of the beam and 2) a large number of particles of each size are detected. Using this statistical technique, particle size distributions are calculated from the measured frequency of pulses of each amplitude.

Individual pulse duration is related to the known width of the beam waist and is used to calculate the particle speed. A distribution of the particle speeds is measured and the median of this distribution is used to calculate the particle number densities.

The PCSV system specifications are:

Specification	
Size range	General capability from 0.20 to 200 μm
Concentration	Absolute particle concentrations up to 10 g^7/cm^3 for sub-micron range or up to 10 g/m^3 for supermicron range
Speed	0.1-400 m/s
Particle type	Solid, liquid, composite, volatile or nonvolatile
Particle environment	No sample conditioning required, capability to make in-line measurements of particles in gas or liquid carriers over a wide range of pressure and temperatures
Accuracy	Typically $\pm 10\%$ of indicated size
Calibration	Calibrated with monodispersed polystyrene latex spheres , standard polydispersed aerosols, and Insitac Reference Reticle
Particle pulse rate	Up to 500 kHz

3.4 Evaluate Emissions Reductions Strategies

No work was scheduled or conducted this reporting period.

4.0 TASK 3: ENGINEERING DESIGN

EER visited Penn State to inspect Penn State's demonstration boiler site and fuel preparation facility, discuss various aspects of the designs (MCWSF and dry, micronized coal) to be completed, and receive guidance for the upcoming design efforts (The designs will be started after receiving official approval from DOE -- see Section 4.1.). Discussions centered around MCWSF storage, handling, and combustion, and dry, micronized coal preparation. Penn State provided EER with recommendations for the designs.

5.0 TASK 4: ENGINEERING AND COST ANALYSIS

5.1 Subtask 4.1 Survey Boiler Population/Identify Boilers for Conversion

Boiler Selection

Penn State visited several military installations and has had discussions with both civilian and military personnel regarding the use of coal in the military (Miller, et al., 1993b). Figure 5-1

Figure 5-1. Candidate boilers and test coals

shows the final candidates along with the coals to be tested in the program. As a consequence of this activity, Penn State recommended to DOE the Naval Surface Warfare Center at Crane, Indiana as the site for the retrofit designs in Phase I of the DOD program.

The Crane facility has several boilerhouses, one of which contains three boilers that are good candidates for conversion. There are three Cleaver Brooks D-type watertube boilers firing natural gas with No. 6 fuel oil backup. Two of the boilers were installed in 1989 and have a firing rate of 25.2 million Btu/h. The third boiler was installed in 1972 and has a firing rate of 18 million Btu/h. The boilers are good candidates for a retrofit design. The two larger boilers have been installed such that they are raised off of the floor by ~1.5', which would facilitate ash removal from the convective pass. There is space outside the building to accommodate coal (or coal-water slurry fuel) and ash storage and handling. In addition, there is a rail spur that services the building. Only two of the three boilers are operated simultaneously. Steam demand is based upon the number of orders for filling bombs.

The Crane facility is a good choice for the retrofit for the following reasons:

- The boilers are of a size which is representative of many military boilers.
- The boilers are good candidates from a technical viewpoint as discussed above.
- The installation is located in the coal fields of a coal-producing state.

5.2 Subtask 4.2 Identify Appropriate Cost Estimating Methodologies

No work was conducted in Subtask 4.2 during this reporting period.

5.3 Subtask 4.3 Estimate Basic Costs of New Technologies

No work was conducted in Subtask 4.3 during this reporting period.

5.4 Subtask 4.4 Process Analysis of MCWSF and Dry, Micronized Coal

The objective in developing a cost minimizing model for retrofitting an existing oil-fired boiler to fire coal-water slurry fuel is based on the flexibility the facility to be retrofitted has in deciding on the level of retrofit. The decision to convert to MCWSF should take into consideration the useful life of the plant, the degree (or extent) of retrofit required, and the nature of financing. Two types of models have been developed: 1) Spreadsheet models, of a linear programming nature, using Microsoft Excel 4.0, and 2) Linear programming models using the general algebraic modeling system (GAMS). Stochastic analysis was performed using Crystal Ball, a forecasting and risk management program for the Macintosh, developed by Comtech Services, Inc. The models are based on Carpenter & Berg (1984), Combustion Engineering (1989), and the cost analysis for firing coal-water slurry fuel, oil, and natural gas at Penn State (Miller, et al., 1993a). The models are structured along the lines of the first two references and utilize cost data from the third. The cost data is for a 15,000 lb steam/hr boiler at Penn State. This Penn State data was used because it is more current than those of the two other references, and the boiler size is more representative of the DOD boilers under consideration than the other two references.

The total capital requirement (TCR) has been modeled in this report as a function of boiler derated capacity (BDC). The modeling of the TCR is based on the Penn State cost data and other conservative assumptions. Important factors in the analyses are: the expected life of the boiler plant, its size (or capacity), degree of derating desired, differential fuel costs. The models show that some boilers will realize a net benefit from retrofitting while others would not. This is dependent on the economic factors of interest but in general, the larger the boiler (in terms of capacity), the more economically feasible is the retrofit consideration (i.e. economies of scale are present). Also the longer the useful life, the greater the benefits from retrofitting. The differences in net benefits with size suggests that DOD can consider a gains from retrofitting distribution scheme, in which the gains from retrofitting large (and more economic) boilers is given to boiler plants that will realize some operational gains by retrofitting but cannot afford the capital costs. This analysis assumes that boilers face uniform constraints, which is not really the case. In addition, the smaller the boiler plant capacity, the lesser should be the degree of retrofit desired. With increasing DFC, increasing expected boiler plant life, and increasing boiler plant size, it appears that it would make both engineering and economic sense to install new MCWSF boilers than to retrofit existing oil-fired boilers. A stochastic analysis of retrofitting gave an average payback period of 7.5 years for a 50,000 lb steam/hr boiler plant under the assumptions employed. A sensitivity analysis showed that the MCWSF price had the most influence on the analysis. This really translates to mean that the DFC has the most influence since fuel oil price was kept constant.

The variables which most strongly influence the economic feasibility of retrofitting to fire MCWSF are the differential fuel cost, total or specific capital requirement, payback period, boiler derated capacity, and the discount rate. There are economies of scale in retrofitting. The DFC is the major driving force of retrofitting, and a DFC of at least \$1.50 is preferred. DOD can consider a gains from retrofitting distribution scheme in which the gains from retrofitting large (and more economic boilers) is given to boiler plants that will realize some gains by retrofitting but cannot afford the capital costs. DOD must consider using a desired payback period longer than the usual industry payback period. The desired payback period can be reduced with increases in the differential fuel cost. Technological improvements that lead to reduction in boiler capacity losses would reduce the capital requirement for retrofitting and also encourage retrofitting. It may be the case that beyond a certain BDC level it may not be economical to continue to invest in technology and research into boiler capacity losses due to retrofitting. Depending on the sizes of DOD boilers, it may well be the case that DOD will have to set a desirable payback period close to the useful plant life. Given the uncertainties in a study of this kind, the desirable PP should be considerably or significantly less than the useful plant life. The cost models developed in this work can be applied to other coal-based fuels with some modifications. It takes as input, technical and

economic data and outputs the variables required for an economic analysis of retrofitting to fire the alternate fuel. Such studies will demonstrate the competitive advantage (if any) of MCWSF.

The GAMS models currently give net present values of retrofitting. They can be modified to yield payback periods as well. The GAMS models analyses are more general and should be used for centralized decision making, while the spreadsheet models are more suitable for specific site decision-making. A combination of net present value and payback period is often used to make commercial investment decisions. In this case, when the output of the GAMS models is payback periods, as well as their current output, they will become invaluable as decision aids on retrofitting. Note that an oil price of \$5.00/MM Btu was used; however, the current price of oil is about \$3.00/ MM Btu. This demands a delivered MCWSF price of at most \$1.50 MM Btu to be competitive. This price is lower than our current cost estimates for producing and delivering slurry. Therefore, given current oil prices, the preliminary analysis indicates there is little economic incentive to retrofit. The DOD regulation discount rate of 4% makes retrofitting more attractive, and a report of the analysis using this discount rate will soon be made available.

5.5 Subtask 4.5 Analyze/Identify Transportation Cost of Commercial Sources of MCWM and Cleaned Coal for Dry, Micronized Coal Production

No work was conducted in Subtask 4.5 during this reporting period.

5.6 Subtask 4.6 Determine Community Spillovers

No work was conducted in Subtask 4.6 during this reporting period.

5.7 Subtask 4.7 Regional Market Considerations and Impacts

An input-output model for an 8-county region surrounding the Crane Naval Weapons Center has been constructed using the IMPLAN Modeling System. A regional I-O table for 1990 and a set of multipliers are presented in Tables 5-1 and 5-2, respectively. The research team is in the process of verifying the data in the tables by checking with local sources of information.

To complete Phase I, regional I-O tables will be used to determine the economic impacts of using MCWM and MPC at Crane and two or three other sites. The impacts of adoption of these combustion technologies on all DOD boilers within the state of Pennsylvania will also be analyzed. Simulations will be performed with both an I-O model and a computable general equilibrium model. The results will be compared to assess the relative strengths of these two modeling approaches.

The empirical specification of a computable general equilibrium model for Pennsylvania has been completed. The construction of this model is nearly completed. It will prove especially useful in performing economic impact assessments of widespread adoption of new coal utilizing technologies.

Table 5-1. Input-Output Table for the Crane, Indiana Region, 1990
(MM \$1990)

INDUSTRY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	FINAL DEMAND (Includes Crane NSWC)	TOTAL OUTPUT
1. Agriculture	66.3	*	*	2.3	104.7	0.6	0.2	*	*	0.1	14.0	1.8	0.5	*	319.7	510.3
2. Coal Mining	0.1	1.0	*	*	*	0.2	*	2.2	*	*	*	*	0.3	*	117.6	121.5
3. Other Mining	0.2	*	25.2	2.2	0.6	8.6	0.1	0.1	*	*	*	*	0.1	*	353.0	393.9
4. Construction	6.8	1.0	1.8	1.1	2.6	22.4	14.7	14.4	0.9	1.8	40.1	15.0	39.4	*	603.1	764.8
5. Non-durable Manufacturing	4.4	0.5	0.9	5.5	43.4	39.5	0.9	0.4	0.1	4.0	11.7	6.8	1.3	*	850.3	969.8
6. Durable Manufacturing	1.9	0.4	1.3	36.0	3.4	334.2	1.8	0.2	0.1	0.8	21.1	10.3	0.6	*	2839.9	3251.9
7. Transport/Communication	9.0	0.5	4.1	16.0	17.0	54.1	25.0	2.3	0.1	5.0	17.1	7.6	2.3	*	265.6	425.6
8. Electric Services	5.2	1.3	5.0	1.7	7.2	26.9	1.5	*	*	3.2	5.9	4.6	7.6	*	96.0	166.3
9. Other Utilities	0.6	*	1.8	0.4	2.1	8.9	0.1	8.0	0.8	0.4	1.0	1.5	11.1	*	40.5	77.2
10. Trade	7.1	0.7	1.1	32.9	12.4	80.3	2.1	0.4	0.1	0.5	10.2	3.5	1.3	*	433.3	586.4
11. Services	22.7	2.4	5.0	52.4	15.0	89.3	17.5	2.8	0.3	15.6	107.9	41.1	4.3	*	2133.4	2509.6
12. Health, Social Services	0.8	*	0.1	*	1.0	3.4	0.3	0.1	*	0.2	2.1	2.2	0.1	*	603.7	614.2
13. Government Enterprises	4.4	0.5	2.2	2.1	6.5	22.6	2.4	2.5	0.2	3.3	14.3	9.5	5.5	*	182.4	258.4
14. Adjustment & Other	*	*	*	*	*	*	*	*	*	*	*	*	*	*	11.7	7.1
Total Imports	224.4	20.8	150.8	319.5	456.2	1411.6	92.0	35.2	55.2	50.2	333.4	173.8	49.3	0.0	[3372.5]**	0.0
Total Value Added	152.5	92.1	193.8	285.2	295.9	1140.9	266.3	97.5	19.3	500.8	1927.6	335.5	134.6	13.1	0.0	[5455.0]*
Errors & Omissions	4.1	0.3	0.8	7.6	1.8	8.3	0.6	0.2	0.1	0.5	3.4	1.1	0.2	-6.0	0.0	0.0
Total Industry Outlays	510.3	121.5	393.9	764.8	969.8	3251.9	425.6	166.3	77.2	586.4	2509.6	614.2	258.4	7.1	8850.3	10657.0

*Less than \$0.05 million

**Not part of column total

Table 5-2. Employment Multipliers

Indiana \$MM 1990 Employment Multipliers

Invert Report #606 7/8/93

	Sector	Direct	Indirect	Induced	Total	Type I	Type III
1	Agg 1 Agriculture	15.6891	5.5983	8.7867	30.0741	1.3568	1.9169
37	Agg 2 Coal Mining	9.3913	1.3757	4.4442	15.2112	1.1465	1.6197
38	Agg 3 Other Mining	2.2313	1.2799	4.3566	4.8679	1.5736	2.1816
48	Agg 4 Construction	14.8449	4.7897	8.1045	27.7390	1.3226	1.8686
58	Agg 5 Non-Durable Mfg.	7.7411	4.3859	5.0056	17.1326	1.5666	2.2132
133	Agg 6 Durable Mfg.	9.5663	3.8940	5.5560	19.0163	1.4071	1.9878
433	Agg 7 Transport/Commun.	13.9290	3.3480	7.1314	24.4084	1.2404	1.7523
443	Agg 8 Electric Services	3.9147	3.2226	2.9460	10.0833	1.8232	2.5757
444	Agg 9 Other Utilities	2.6431	.5425	1.2308	4.4165	1.2053	1.6709
447	Agg 10 Trade	33.7340	1.2997	14.7360	49.7697	1.0385	1.4754
454	Agg 11 Services	27.2261	2.2970	12.4181	41.9413	1.0844	1.5405
490	Agg 12 Health, Soc. Serv.	28.2149	3.7919	13.4628	45.4696	1.1344	1.6115
510	Agg 13 Government	16.6697	4.7773	9.0211	30.4681	1.2866	1.8278
524	Rest of the World Industry	.0000	.0000	.0000	.0000	1.2866	1.8278
525	Household Industry-low Income	230.9353	.0000	97.6771	328.6124	1.0000	1.4230
528	Inventory Valuation Adjustment	.0000	.0000	.0000	.0000	1.0000	1.4230

Note: The induced and total components are based upon the Type III multipliers.

5.8 Integrate the Analysis

No work was scheduled or conducted this reporting period.

6.0 TASK 5: FINAL REPORT/SUBMISSION OF DESIGN PACKAGE

No work was conducted on Task 5.

7.0 MISCELLANEOUS ACTIVITIES

A DOD/DOE Information Transfer Session was held at Penn State July 9, 1993 to review the Phase I work being conducted at Penn State. Penn State personnel gave thirteen presentations covering Tasks 1, 2, and 4. Attendees from DOD and DOE were Mike Lin (U.S. Corps of Engineers Construction Engineering Research Laboratory) and John Winslow (U.S. DOE, Pittsburgh Energy Technology Center).

8.0 REFERENCES

Austin, L.G., C.H. Lee, F. Concha, and P.T. Luc'kie, "Hindered Settling and Classification Partition Curves," accepted for publication in **Minerals and Metallurgical Processing**.

Capes, C.E., J.D. Hazlett, and B.L. Ignasick, "Novel Application of Oil Agglomeration Technology for Coal Preparation, Upgrading of Low Quality Fuels and Environmental Clean-up", in **Eleventh International Coal Preparation Congress**, Tokyo, Japan, October 22-25, (1990).

Carpenter, R.G., and R.D. Berg, "The Conversion of Industrial Oil-Fired Boilers to Coal-Water Slurry," **Sixth Int. Symp. on Coal Slurry Comb. and Tech.**, pp. 51-66 (1984).

Clayfield, E.J., E.C. Lumb and P.H. Mackey, **J. Coll. Interf. Sci.**, 37, 382 (1971).

Combustion Engineering, Inc., "Combustion and Fuel Characterization of Coal-Water Fuels" Volumes 2-6, Final Report," U.S. Department of Energy, Pittsburgh Energy Technology Center, DE-AC22-82PC50271 (February 1989).

Cross, M., "Prediction of the Voidage of Packed Beds", in **Agglomeration '85 Proceedings of the 4th International Symposium on Agglomeration**. (C.E.Capes, ed), Toronto, Canada, (1985).

Davies, M.H., M.T. Simnad, and C.E. Birchenall, **Journal of Metals, Transactions, AIME**, p. 889, 1951.

Fowkes, F.M., **Ind. Eng. Chem.**, 54, 40 (1964).

Gregory, J., **J. Coll. Interf. Sci.**, 138 (1981).

Hamaker, H.C., "The London-van der Waals Attraction between Spherical Particles," **Physica**, 4, 1058 (1937).

Hogg, R., Healy, T.W., and D.W. Fuerstenau, "Mutual Coafulation of Colloidal Dispersions", **Trans. Faraday Soc.**, 62 (1638).

Hunter, R.J., **Zeta Potential in Colloid Science**, Academic Press, London.

Israelachvili, J.N., **Intermolecular and Surface Forces**, Academic Press, New York, (1985).

Ityokumbul, M.T., "A New Modelling Approach to Flotation Column Design," **Minerals Engineering**, 5, 585-593 (1992).

Ityokumbul, M.T., "Maximum Gas Velocity in Column Flotation," **Minerals Engineering**, in press (1993).

Klima, M.S., and P.T. Luckie, "Application of an Unsteady-State Pulp-Partition Model to Dense-Medium Separations," **Coal Prep.**, 6, 227-240 (1989).

Klima, M.S., and P.T. Luckie, "Use of an Unsteady-State Pulp-Partition Model to Investigate Multiple Variable Interactions," **Coal Prep.**, 8, 185-193 (1990).

Lee, C.H., "Modeling of Batch Hindered Settling," PhD Thesis, The Pennsylvania State University (1989).

Link, T., R.P. Killmeyer, R. Elstrodt, and N. Haden, "Initial Study of Dry Ultrafine Coal Beneficiation Utilizing Triboelectrostatic Charging with Subsequent Electrostatic Separation," **DOE/PETC/TR-90/11**, 19 pp. (1990).

Melhotra V.P., K.V.S. Sastry and B.W. Morey, "Review of Oil Agglomeration Techniques for Processing of Fine Coals", **International Journal of Mineral Processing**, 11 (3), 175-201 (1983).

Miller, B.G., and A.W. Scaroni, "The Pennsylvania State University's Superclean Coal-Water Slurry Demonstration Program," **Proceedings of the Fifteenth Int. Conf. on Coal and Slurry Tech.**, Coal & Slurry Technology Association, Washington, D.C., p. 77 (1990a).

Miller, B.G., and A.W. Scaroni, "Superclean Coal-Water Slurry Combustion Testing in an Oil-Fired Boiler," **6th Annual Coal Prep., Util., and Environ. Control Contractors Conf.**, U.S. Department of Energy, Pittsburgh Energy Technology Center, Pittsburgh, Pennsylvania, p. 81 (1990b).

Miller, B.G. A.W. Scaroni, S.A. Britton, D.A. Clark, J.L. Morrison, S.V. Pisupati, R.L. Poe, P.M. Walsh, R.T. Wincek, and J. Xie "Superclean Coal-Water Slurry Combustion Testing in an Oil-Fired Boiler, Technical Report for Phases I-III," U.S. Department of Energy, Pittsburgh Energy Technology Center, DE-FC22-89PC88697, (1993a).

Miller, B.G., A.W. Scaroni, R. Hogg, S. Chander, M.T. Ityokumbul, M.S. Klima, P.T. Luckie, A. Rose, T.J. Considine, R.L. Gordon, K. McClain, P.M. Walsh, P.C. Painter, M.J. Rini, M. Jha, D. Morrison, R. Melick, and T. Sommer, "The Development of Coal-Based Technologies for Department of Defense Facilities," U.S. Department of Energy, Pittsburgh Energy Technology Center, DE-FC22-92PC92162, (May 13, 1993b).

Napper, D.A., **Polymeric Stabilization of Colloidal Dispersions**, Academic Press, New York, (1983).

Overbeek, J.Th.G., in **Colloid Science, I.** (H.R. Kruyt, ed.) Elsevier, Amsterdam, (1952).

Overbeek, J.Th.G, **J. Chem. Soc. Faraday Trans. 1**, 84, 3079 (1988).

Pawlak, W., K. Szymocha, Y. Briker and B. Ignasiak, "High-sulphur Coal Upgrading by Improved Oil Agglomeration", in **Third International Conference on Processing and Utilization of High-sulfur Coals**, Ames, IA, (1989).

Scheffler, P., and P. Zahr, "Wet Classification at Cut Points Below 10 Microns," **World Mining**, 50-53 (March 1980).

Schenkel, J.H., and J.A. Kitchener, **Trans Faraday Soc.** 56, 161 (1960).

Simmons, F.J., and D.V. Keller, "Two Ton-per-day Production of Otisca T-process Ultra-clean Coal/water Slurry", **Tenth International Coal Preparation Congress**, Edmonton, Alberta, Canada (1986).

Smellie, R.H., and V.K. LaMer, "Flocculation, Subsidence and Filtration of Phosphate Slimes, VI, A Quantitative Theory of Filtration of Flocculated Suspensions," **J. Colloid Sci.**, 23, 589 (1958).

Visser, J., **Adv. Coll. Interf. Sci.**, 3, 331 (1972).

Walker, M.S., A.L. Devernoe, and W.S. Urbanski, "Separation of Non-Magnetic Minerals Using Magnetic Fluids in a Flow-Through MHS Rotor," **Minerals and Metallurgical Processing**, 209-214 (November 1990).

Ynchausti, J.A., J.D. McKay, and D.G. Foot, Jr., "Column Flotation Parameters - Their Effects," in **Column Flotation '88** (K.V.S. Sastry, ed.), SME Littleton, CO, Chap. 18, 157-172 (1988).

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