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

Semiannual Technical Progress Report for the Period 03/28/1994 to 09/27/1994

By

Bruce G. Miller, David A. Bartley, Joel L. Morrison, Roger L. Poe, Reza Sharifi, Joseph F. Shepard,
Guheng Xu, and Alan W. Scaroni

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The Pennsylvania State University;**

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Paul C. Painter and Boris Veytsman

Polymer Science Program

The Pennsylvania State University; and

Donald Morrison, Donald Englehardt, and Todd M. Sommer
Energy and Environmental Research Corporation

April 14, 1995

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

For
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

By
The Consortium for Coal-Water Slurry Fuel Technology
The Pennsylvania State University
University Park, Pennsylvania

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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 two phases of the program are underway.

Activities this reporting period included performing coal beneficiation/preparation studies, conducting combustion performance evaluations, preparing retrofit engineering designs, determining retrofit economics, and installing a micronized coal-water mixture (MCWM) circuit.

Coal Beneficiation/Preparation Studies

The coal beneficiation/preparation studies involved procuring an additional coal for the program, an Indiana coal from the Lower Block seam. Float-sink testing was started in order to determine the level of cleaning needed (to produce <5% ash and <1% sulfur) prior to MCWM formulation and combustion evaluation.

Activities continued in studying conventional and fine gravity separations and surface-based cleaning processes, such as flotation and selective agglomeration. Baseline testing of a batch triboelectrostatic separator, which is being used to develop a dry coal cleaning technique, has been completed.

Combustion Performance Evaluations

A low-NO_x burner capable of firing natural gas, dry, micronized coal (DMC), and MCWM was installed on the demonstration boiler. Baseline tests firing natural gas were conducted to study boiler performance and emissions, and burner stability. This was followed by testing firing DMC.

Retrofit Engineering Designs

Work continued on completing engineering designs for a complete retrofit of a boiler located at the Naval Surface Warfare Center at Crane, Indiana to fire either MCWM or DMC. The designs are in the final review stage and include DMC preparation, fuel handling, burner, ash removal, handling, and disposal, and air pollution control systems.

Retrofit Economic Analysis

The economic analysis for retrofitting an oil-designed boiler to MCWM is being expanded to include DMC as well as precombustion strategies. The evaluation includes determining the process analysis, the environmental and regulatory impacts, the adoption of the technology, regional economic impacts, and public perception of benefits and costs.

Installation of a MCWM Preparation Circuit.

Work continued on the installation of a MCWM preparation circuit to provide fuel to the demonstration boiler. The majority of the air, water, and MCWM piping was installed, major components were fabricated or ordered, and equipment is being installed.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF FIGURES	viii
LIST OF TABLES	xiii
1.0 INTRODUCTION	1
2.0 PHASE I; TASK 1: COAL BENEFICIATION/PREPARATION.....	5
2.1 Subtask 1.1 Identify/Procure Coals	5
2.2 Subtask 1.2 Determine Liberation Potential	5
2.3 Subtask 1.3 Produce Laboratory-Scale Quantities of Micronized Coal-Water Mixtures	28
2.4 Subtask 1.4 Develop a Dry Coal Cleaning Technique	48
2.5 Subtask 1.5 Produce MCWMs and Micronized Coal from Dry, Clean Coal	55
2.6 Subtask 1.6 Produce MCWM and Dry, Micronized Coal for the Demonstration Boiler	55
3.0 PHASE I; TASK 2: COAL COMBUSTION PERFORMANCE	58
3.1 Subtask 2.1 Boiler Retrofit	58
3.2 Subtask 2.2 Fuel Evaluation in the Research Boiler	58
3.3 Subtask 2.3 Performance Evaluation of MCWM and DMC in the Demonstration Boiler	61
3.4 Subtask 2.4 Evaluate Emissions Reduction Strategies	130
4.0 PHASE I; TASK 3: ENGINEERING DESIGN	130
4.1 Subtask 3.1 MCWM/DMC Preparation Facilities	131
4.2 Subtask 3.2 Fuel Handling	131
4.3 Subtask 3.3 Burner System	131
4.4 Subtask 3.4 Ash Removal, Handling, and Disposal	131
4.5 Subtask 3.5 Air Pollution Control	132
4.6 Subtask 3.6 Integrate Engineering Analysis	132
5.0 PHASE I; TASK 4: ENGINEERING AND COST ANALYSIS	132
5.1 Subtask 4.1 Survey Boiler Population/Identify Boilers for Conversion	132
5.2 Subtask 4.2 Identify Appropriate Cost-Estimating Methodologies	132
5.3 Subtask 4.3 Estimate Basic Costs of New Technologies	132
5.4 Subtask 4.4 Process Analysis of MCWM and Dry, Micronized Coal	132
5.5 Subtask 4.5 Analyze/Identify Transportation Cost of Commercial Sources of MCWM and Cleaned Coal for Dry, Micronized Coal Production	132
5.6 Subtask 4.6 Community Spillovers	132
5.7 Subtask 4.7 Regional Market Considerations and Impacts	132
5.8 Subtask 4.8 Integrate the Analysis	132
6.0 PHASE I; TASK 5: FINAL REPORT/SUBMISSION OF DESIGN PACKAGE	132

TABLE OF CONTENTS (cont.)

			<u>Page</u>
7.0	PHASE II; TASK 1	EMISSIONS REDUCTION	133
7.1	Subtask 1.1	Evaluation of Emissions Reduction Strategies	133
7.2	Subtask 1.2	Conduct Fundamental Emissions Studies	133
7.3	Subtask 1.3	Install System on the Demonstration Boiler	133
7.4	Subtask 1.4	Evaluate Emissions Reduction System	133
	PHASE II; TASK 2	COAL PREPARATION/UTILIZATION	133
8.1	Subtask 2.1	Optimization of Particle Size Consist for MCWM Formulation	133
8.2	Subtask 2.2	Fine Grinding/Classification/Liberation	134
8.3	Subtask 2.3	Fine Gravity Concentration	139
8.4	Subtask 2.4	Agglomeration/Flotation Studies	149
8.5	Subtask 2.5	Fundamental Studies of Surface-Based Processes	152
8.6	Subtask 2.6	Column Flotation	152
8.7	Subtask 2.7	Dry Cleaning of Fine Coal	156
8.8	Subtask 2.8	MCWM Density Control	159
8.9	Subtask 2.9	Stabilization of CWM	159
9.0	PHASE II; TASK 3	COAL PRECOMBUSTION	180
9.1	Subtask 3.1	Evaluate Coal Precombustion Options	180
9.2	Subtask 3.2	Fundamental and Pilot-Scale Precombustion Studies	180
10.0	PHASE II; TASK 4	ENGINEERING DESIGN AND COST; AND ECONOMIC ANALYSIS	183
10.1	Subtask 4.1	Basic Cost Estimation of Boiler Retrofits	183
10.2	Subtask 4.2	Process Analysis	183
10.3	Subtask 4.3	Environmental and Regulatory Impacts	183
10.4	Subtask 4.4	Transportation Cost Analysis	184
10.5	Subtask 4.5	Technology Adoption	184
10.6	Subtask 4.6	Regional Economic Impacts	185
10.7	Subtask 4.7	Public Perception of Benefits and Costs	185
10.8	Subtask 4.8	Social Benefits	188
10.9	Subtask 4.9	Coal Market Analysis	188
10.10	Subtask 4.10	Engineering Design	188
10.11	Subtask 4.11	Integration of Analysis	188
11.0	PHASE II; TASK 5	FINAL REPORT/SUBMISSION OF DESIGN PACKAGE	189
12.0	MISCELLANEOUS ACTIVITIES		189
13.0	NEXT SEMIANNUAL ACTIVITIES		189
14.0	SELECTED NOMENCLATURE		190
15.0	ACKNOWLEDGMENTS		191
16.0	REFERENCES		192

TABLE OF CONTENTS (cont.)

	<u>Page</u>
Appendix A. Burner Stability Summary Test Sheets.....	197
Appendix B. Test Summary Graphs	207

LIST OF FIGURES

	<u>Page</u>
FIGURE 1-1. DOD Phase I milestone schedule	6
FIGURE 1-2. DOD Phase II milestone schedule	14
FIGURE 2-1. Effect of feed particle size on flotation of Indiana VII coal	33
FIGURE 2-2. Effect of dodecane on flotation of -65 μm Indiana VII coal.....	34
FIGURE 2-3. Effect of propylene-ethylene oxide block co-polymer on flotation of Indiana VII coal. Surfactant to dodecane ratio =0.8; dodecane = 11.2 kg/T; surfactant = Pluronic L-64.	35
FIGURE 2-4. Sedimentation/clarification results for -100 mesh Upper Freeport coal	37
FIGURE 2-5. Product size distributions after grinding the -200 mesh sample of the Taggart seam coal in a stirred ball mill at 40% solids (by weight) for various times without a dispersant	39
FIGURE 2-6. Product size distributions after grinding the -200 mesh sample the Pittsburgh seam coal in a stirred ball mill at 40% solids (by weight) for various times without a dispersant	40
FIGURE 2-7. Product size distributions after grinding the -200 mesh sample of the Lower Kittanning seam coal in a stirred ball mill at 40% solids (by weight) for various times without a dispersant	41
FIGURE 2-8. Product size distributions after grinding the -200 mesh sample of the Upper Freeport seam coal in a stirred ball mill at 40% solids (by weight) for various times without a dispersant	42
FIGURE 2-9. Product size distributions at various grinding times for the four coals plotted against the dimensionless size	43
FIGURE 2-10. Variation of the median sizes with grinding time for the four coals	44
FIGURE 2-11. Power consumption for grinding the Taggart seam coal in a stirred ball mill at 40 wt.% solids	45
FIGURE 2-12. Relationship between the specific energy input and the product median size for grinding the Taggart seam coal in a ball mill and a stirred ball mill at 40 wt.% solids.	46
FIGURE 2-13. Double stage froth flotation circuit	49

FIGURE 2-14.	Schematic diagram of the triboelectrostatic separator	50
FIGURE 2-15	Triboelectrostatic separation of the Pittsburgh seam coal (-100 mesh) using different static mixer length (nitrogen velocity = 920 cm/s; voltage = +26 kV; temperature = 24°C; humidity = 26%)	52
FIGURE 2-16	Triboelectrostatic separation of the Upper Freeport seam coal (-100 mesh) using different static mixer lengths (nitrogen velocity = 920 cm/s; voltage = +26 kV; temperature = 23°C; humidity = 20%)	53
FIGURE 2-17	Triboelectrostatic separation of the Upper Freeport, Pittsburgh, and Indiana VII seam coals (coal feed size = -100 mesh; nitrogen velocity = 920 cm/s; voltage = +kV; temperature = 23°C; humidity = 24%).....	54
FIGURE 2-18	Schematic diagram of the equipment train in the fuel preparation facility	56
FIGURE 2-19	Schematic diagram of the MCWM preparation circuit	57
FIGURE 3-1	Side view of assembled burner prior to installation into the demonstration boiler	59
FIGURE 3-2	Burner sectional view	60
FIGURE 3-3	Schematic diagrams of the natural gas burner prior to (a) and the after modification (b) and the front view of the burner (c)	62
FIGURE 3-4	The effect of oxygen concentration in the flue gas on boiler efficiency	74
FIGURE 3-5	The effect of mill air flow on boiler efficiency	75
FIGURE 3-6	The effect of firing rate on boiler efficiency	76
FIGURE 3-7	The effect of swirl on boiler efficiency	77
FIGURE 3-8	The concentration of CO and NO _x as a function of O ₂ in the flue gas	79
FIGURE 3-9	The concentration of CO and NO _x as a function of firing rate...	80
FIGURE 3-10	The effect of swirl on CO and NO _x Emissions	81
FIGURE 3-11	Example of boiler outlet temperature (°F) vs time for micronized coal testing on 8/04/94.....	91
FIGURE 3-12	Quantity of coal consumed since last convective pass soot blowing when operating from 07/13/94 to 09/02/94.....	92
FIGURE 3-13	Furnace ash blowdown system.....	94

	<u>Page</u>
FIGURE 3-14 The rate coefficient for growth of oxide scale was obtained by fitting the experimental measurements of Davies et al. ^[11] , Schmahl et al. ^[64] , Caplan and Cohen ^[5] , and Jansson and Vannerberg ^[27] , for iron oxidation at temperatures in the range from 673 to 873 K, in the presence of 1 ATM oxygen.....	98
FIGURE 3-15 Measured (open circles) and calculated (lines) erosion rates of carbon steel as functions of temperature and the jet gas oxygen content. The metal erosion rate coefficient was adjusted to fit the measurements in the nitrogen jet at the lowest temperature 450 K. The oxide erosion rate coefficient was adjusted to fit the measurements in the air jet at the highest temperature 650 K. Three exponents of oxygen partial pressure ($a=1.0, 0.5, 0.25$) were used in the calculations.....	99
FIGURE 3-16 Estimate of the erosion rate of carbon steel by fly ash and unburned char from micronized coal combustion under the following conditions: gas temperature 890 K, excess oxygen 3.4 vol%, metal temperature 550 K, tube diameter 51 mm, particle loading 3.0 g/m^3 , particle density 835 kg/m^3 , particle size $43 \text{ }\mu\text{m}$, and impaction angle 30°	101
FIGURE 3-17 Estimate of the erosion rate of carbon steel by fly ash and unburned char from micronized coal combustion under the following conditions: gas temperature 890 K, excess oxygen 3.4 vol%, metal temperature 550 K, tube diameter 51 mm, particle loading 3.0 g/m^3 , particle density 835 kg/m^3 , particle size $43 \text{ }\mu\text{m}$, and impaction angle 90°	102
FIGURE 3-18 Atomization/erosion test facility with INSITEC's Particle Counter-Sizer-Velocimeter Probe	104
FIGURE 3-19 Schematic diagram of the Delevan nozzle	105
FIGURE 3-20 Schematic diagram of the INSITEC Particle Counter-Sizer-Velocimeter Probe with laser shield	110
FIGURE 3-21 Filled contours of temperature for a slice along the center line of the demonstration boiler firing micronized-coal	123
FIGURE 3-22 Filled contours of velocity for a slice along the center line of the demonstration boiler firing micronized-coal	124

	<u>Page</u>
FIGURE 3-23 Trajectories of a selected number micronized-coal particles in the demonstration boiler	126
FIGURE 3-24 Filled contours of temperature for a slice along the center line of the demonstration boiler firing micronized-coal (after the installation of the ceramic tunnel)	127
FIGURE 3-25 Filled contours of velocity for a slice along the center line of the demonstration boiler firing micronized-coal (after installation of the ceramic tunnel)	128
FIGURE 3-26 Trajectories of a selected number micronized-coal particles in the demonstration boiler (after the installation of the ceramic tunnel)	129
FIGURE 8-1 Experimental (symbols) and simulated (lines) product size distributions after grinding the -10 mesh sample of the Taggart seam coal in a tumbling ball mill at 40% solids (by weight) for various times (74 μ m)	136
FIGURE 8-2 Simulated size distributions for the Taggart seam coal to give 80% passing 200 mesh	138
FIGURE 8-3 Back-calculated cumulative B-values for various solids concentrations of the Taggart seam coal	140
FIGURE 8-4 Experimental (symbols) and simulated (lines) product size distributions after grinding the -200 mesh sample of the Taggart seam coal in a stirred ball mill at 40% solids (by weight) for various times without a dispersant	141
FIGURE 8-5a. Probable errors for the 28 x 100 mesh coal obtained from simulations of various cyclone diameters at different flow rates and pulp splits: (cyclone diameters:——500 mm, — —350 mm, — - —250 mm, -----200mm, -----150mm).....	144
FIGURE 8-5b. Relative densities of separation for the 28x 100 mesh coal obtained from simulations of various cyclone diameters at different flow rates and pulp splits: (cyclone diameters: _____500mm, _____350mm, _____ 250mm, _____ - - 200mm, -----150mm).....	145
FIGURE 8-6 Volumetric fraction of the feed slurry reporting to the overflow of a 360 mm diameter cyclone for two medium densities ^[7]	146

	<u>Page</u>
FIGURE 8-7 Characteristic parameters for the 28x100 mesh coal obtained from simulations of a 360 mm diameter cyclone at different flow rates and pulp splits: (a) probable errors, (b) relative densities of separation	147
FIGURE 8-8 Schematic diagram of the continuous, solid-bowl centrifuge test circuit	148
FIGURE 8-9 Schematic diagram of the separator and pole pieces for magnetic fluid separation	150
FIGURE 8-10 Zeta potential of Pittsburgh seam coal as a function of pH at several concentrations of Coalmaster A-23 M.	154
FIGURE 8-11 Schematic diagram of the continuous triboelectrostatic separator	157
FIGURE 8-12 Schematic diagram of the laser sheet generator setup	158
FIGURE 8-13 Particle size distribution of micronized Taggart seam coal to be used in slurry thickening studies	160
FIGURE 8-14 Random close packing of spheres	163
FIGURE 8-15 Furnas' distributions for different n	165
FIGURE 8-16 Cumulative distribution function from equation 8-44, $K=10$..	171
FIGURE 8-17 Differential distribution function from equation 8-50, $K=10$..	172
FIGURE 8-18 Differential distribution function from equation 8-51, $K=10$..	174
FIGURE 8-19 Differential distribution function from equation 8-45, $K=10$, $\alpha=0.5$	175
FIGURE 8-20 Efficiency of packing	178
FIGURE 8-21 Preliminary data on coal particles size distribution and optimal . distributions	179
FIGURE 8-22 Photoacoustic Spectroscopy responses for a weathered coal sample (a), a fresh coal sample (b), and the difference between the weathered and fresh coal samples (a-b)	181
FIGURE 8-23 Diffuse Reflectance Spectroscopy responses for a weathered coal sample (a), a fresh coal sample (b), and the difference between the weathered and fresh coal samples (a-b)	182
FIGURE 10-1 Longwall coal production as portion of total U.S. coal production	186

LIST OF TABLES

	<u>Page</u>
TABLE 1-1. Phase I milestone description	19
TABLE 1-2. Phase II milestone description	25
TABLE 2-1. Proximate analysis and Hardgrove grindability indices of the Lower Block seam coal.....	29
TABLE 2-2. Washability analysis of the Lower Block seam coal a) crushed to a nominal -1/4"	30
TABLE 2-2. Washability analysis of the Lower Block seam coal b) crushed to a nominal -28 mesh	30
TABLE 3-1. Summary of results for boiler performance/emissions testing	71
TABLE 3-2. Summary of reproducibility analysis	73
TABLE 3-3. Summary of results for dry, micronized coal testing	83
TABLE 3-4. Summary of sootblowing frequency.....	89
TABLE 3-5. Experimental conditions and average maximum erosion rates	96
TABLE 3-6. Results of proximate and CHN analysis for Brookville seam coals	107
TABLE 3-7. CWM Formulation for Brookville coal (as of 7/14/92)	108
TABLE 3-8. Steel chemical composition (wt.%)	111
TABLE 8-1. Breakage parameters for the Taggart seam coal at various solids concentrations	137
TABLE 8-2. Breakage parameters and estimated false times for stirred ball mill ground Taggart seam coal at 40% solids	137
TABLE 8-3. Summary of the input parameters used for the batch hindered-settling model ^[31]	143
TABLE 8-4. Model parameters and the fitting errors calculated using Method I for the Upper Freeport and Pittsburgh samples	151
TABLE 8-5a. Model parameters calculated using Method II for the Upper Freeport Sample No. 2	153
TABLE 8-5b. Fitting errors calculated using Method II for the Upper Freeport Sample No. 2	153
TABLE 8-6. Effect of gas velocity on the column flotation of Upper Freeport coal at a frother concentration of 50 ppm	155
TABLE 8-7. Effect of frother concentration on the column flotation of Upper Freeport coal at a gas velocity of 2.9 cm/s	155

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 two phases of the program are underway.

To achieve the objectives of the program, a team of researchers was assembled and the current members of the Consortium are from Penn State (Energy and Fuels Research Center (EFRC), Mineral Processing Section, Fuel Science Program, Department of Mineral Economics, and Polymer Science Program) and the Energy and Environmental Research Corporation (EER). AMAX Research and Development Center was a member but withdrew. ABB Combustion Engineering was invited and Research-Cottrell Companies will be invited.

Phase I activities are focused on developing clean, coal-based combustion technologies for the utilization of both micronized coal-water mixtures (MCWMs) and dry, micronized coal (DMC) in fuel oil-designed industrial boilers. Phase II research and development 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 Phases I and II 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 MCWM 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. Following is an outline of the project tasks that comprise Phase I:

Task 1: Coal Beneficiation/Preparation

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

Task 2: Combustion Performance Evaluation

- Subtask 2.1 Boiler Retrofit
- Subtask 2.2 Fuel Evaluation in the Research Boiler

- Subtask 2.3 Performance Evaluation of the MCWM and DMC in the Demonstration Boiler
- Subtask 2.4 Evaluate Emissions Reductions Strategies
- Subtask 2.5 Project Management and Support

Task 3: Engineering Design

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

Task 4: Engineering and Economic Analysis

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

Task 5: Final Report/Submission of Design Package

The Phase I activities include:

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

Task 2: The EFRC is conducting the combustion performance evaluation with assistance from EER and Penn State's Fuel Science Program. The technical aspects of converting a fuel oil-designed boiler at a DOD facility 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, MCWM and DMC will be evaluated in EFRC's 15,000 lb

steam/h watertube boiler. EER will provide a proven coal-designed burner for retrofitting Penn State's boiler. In addition, EER 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 MCWM 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 for 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 MCWM 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 MCWM 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 objectives of Phase II are to: (a) extend the Phase I boiler retrofit options by including designs to achieve further reductions in gaseous and particulate emissions, (b) prepare and characterize fuels compatible with coal precombustors, and (c) investigate precombustion as a means of using high ash, high sulfur coals. This will be achieved through a combination of fundamental, pilot-scale, and demonstration-scale studies, an engineering design and cost analysis for retrofitting a DOD boiler with a precombustor, and an economic analysis of the wide scale use of the technologies within DOD. Phase II consists of five tasks as outlined below:

Task 1. Emissions Reduction

- Subtask 1.1 Evaluation of Emissions Reduction Strategies
- Subtask 1.2 Fundamental Emissions Studies
- Subtask 1.3 Installation of an Emissions Reduction System on the Demonstration Boiler
- Subtask 1.4 Evaluation of an Emissions Reduction System

Task 2. Coal Preparation/Utilization

- Subtask 2.1 Optimization of Particle Size Consist for CWM Formulation
- Subtask 2.2 Fine Grinding/Classification/Liberation

- Subtask 2.3 Fine Gravity Concentration
- Subtask 2.4 Agglomeration/Flotation Studies
- Subtask 2.5 Fundamental Studies of Surface-Based Processes
- Subtask 2.6 Column Flotation
- Subtask 2.7 Dry Cleaning of Fine Coal
- Subtask 2.8 CWM Density Control
- Subtask 2.9 Stabilization of CWM

Task 3. Coal Precombustion

- Subtask 3.1 Evaluation of Coal Precombustion Options
- Subtask 3.2 Fundamental and Pilot-Scale Precombustion Studies

Task 4. Engineering Design and Cost; and Economic Analysis

- Subtask 4.1 Determination of Basic Cost Estimation of Boiler Retrofits
- Subtask 4.2 Determination of Process Analysis
- Subtask 4.3 Determination of Environmental and Regulatory Impacts
- Subtask 4.4 Determination of Transportation Cost Analysis
- Subtask 4.5 Determination of Technology Adoption
- Subtask 4.6 Determination of Regional Economic Impacts
- Subtask 4.7 Determination of Public Perception of Benefits and Costs
- Subtask 4.8 Determination of Social Benefits
- Subtask 4.9 Determination of Coal Market Analysis
- Subtask 4.10 Engineering Design
- Subtask 4.11 Integration of Analyses

Task 5. Final Report/Submission of Design Package

The Phase II activities include:

Task 1: In Task 1, strategies will be developed to provide for ultra-low emissions when firing coal-based fuels in industrial-scale boilers. Emissions to be addressed include SO₂, NO_x, fine particulate matter (<10 µm), and air toxics (volatile organic compounds and trace metals). Post-combustion and during-combustion technologies to reduce SO₂ and NO_x emissions from coal-fired industrial boilers will be investigated. Novel technologies that are under development but are not commercially available will be evaluated as well as proven technologies such as limestone/lime injection, selective catalytic reduction, and nonselective catalytic reduction. Options to remove the submicron particulates will also be investigated. In addition, methods to remove air toxics from the flue gas, such as scrubbing, will be investigated.

Task 2: Emphasis in Task 2 will be on the refinement and optimization of coal grinding and CWM preparation procedures, and on the development of advanced processes for beneficiating high ash, high sulfur coals. CWM formulation is still an art and there is a clear need for scientifically-based guidelines for slurry design. This involves determining the optimum particle size distribution, how and why the optimum particle size distribution varies from coal to coal, and the specific roles of chemical dispersing and stabilizing agents. Extensive, physical pre-cleaning of coal is especially important in small-boiler applications. The research effort will build on work conducted in Phase I and will be carried out in concert with the efforts in combustion engineering, emissions control and cost analysis.

Task 3: Two coal precombustion options will be investigated as retrofit technologies for industrial boilers. One is to utilize a slagging combustor to remove a majority of the ash as a liquid slag upstream of the boiler. The second option is a gasifier that produces a clean fuel for subsequent combustion in the boiler.

Task 4: An engineering design and cost analysis, and technology assessment of slagging combustion and gasification will be performed. This will be done to compare coal cleaning costs for producing low sulfur, low ash coals fired in conventional burners to the additional capital costs associated with technologies utilizing high ash, high sulfur coals (coals that have undergone less cleaning). The boiler selected for the Phase I conversion will be used for the Phase II analysis.

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 and pollution control system will be submitted. These will include the engineering design and economic analysis.

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

2.0 PHASE I, TASK 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 test plan called for five coals to be identified and procured. This was completed the previous semiannual reporting period. However, because the retrofit design (Task 3) is being conducted on a boiler located in Indiana, a second coal from Indiana has been identified and samples have been procured to determine liberation potential and cleaning strategies. The coal is from the Lower Block seam and has been designated II-3.

2.2 Subtask 1.2 Determine Liberation Potential

Float-sink testing continued on the recently acquired Lower Block seam coal sample to determine the level of cleaning needed to achieve the required grade of <5% ash and <1% total sulfur. The results of the proximate and sulfur analyses and Hardgrove Grindability Index are

Task 1 - Coal Beneficiation/Preparation 1992

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Figure 1-1. DOD Phase I Miles

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Task 1 - Coal Beneficiation/Preparation (cont.)

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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

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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 EER

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Subtask 2.3.27 Comparison of Performance of Three Tube Materials

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Subtask 2.5.5 Budget Management / Project Administration

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Task 3 - Engineering Design

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Subtask 3.1 Micronized CWSF Dry, Micronized Coal Preparation Facilities

Subtask 3.1.1 Design of MCWSF Facility -
PSU

Subtask 3.1.2 Design of Dry, Micronized Coal
Preparation System - EER /
PSU

Subtask 3.2 Fuel Handling

Subtask 3.2.1 Design of Fuel System - EER

Subtask 3.2.2 Technical Support and Fuel
System Design - PSU

Subtask 3.3 Burner System

Subtask 3.3.1 Burner Design - EER

Subtask 3.3.2 Auxiliary Component Design -
EER

Subtask 3.4 Ash Removal, Handling and
Disposal

Subtask 3.4.1 Design of Ash System - EER

Subtask 3.5 Air Pollution Control

Subtask 3.5.1 Design of Emission Control -
EER

Subtask 3.6 Integrate Engineering Design

Subtask 3.6.1 Integrate System Components

Subtask 3.7 Project Management and Support

Subtask 3.7.1 Project Management and
Technical Advisement

Subtask 3.7.2 Penn State Technical Review

Subtask 3.7.3 Drafting / Technical
Secretarial Support

Subtask 3.7.4 Budget Management / Project
Administration

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**Task 5 - Final Report/ Submission of
DesignPackage**

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**Subtask 5.1 Industrial Participants
Submission**

**Subtask 5.2 Penn State Technical
Preparation**

**Subtask 5.3 Report Preparation Support
Services**

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Task 1. Emissions Reductions

Subtask 1.1 - Evaluate Emissions Reductions Strategies

Subtask 1.2 - Conduct Fundamental Emissions Studies

Subtask 1.3 - Install System on Demonstration Boiler

Subtask 1.4 - Evaluate Emissions Reduction System

Figure 1-2. DOD Phase II Milestone Schedule

Task 2. Coal Preparation / Utilization

Subtask 2.1 - Optimization of Particle Size Consist for Slurry Formulation

Subtask 2.2 - Fine Grinding / Classification / Liberation

Subtask 2.3 - Fine Gravity Concentration

Subtask 2.4 - Agglomeration / Flotation Studies

Subtask 2.5 - Fundamental Studies of Surface-Based Processes

Subtask 2.6 - Column Flotation

Subtask 2.7 - Dry Cleaning of Fine Coal

Subtask 2.8 - Slurry Density Control

Subtask 2.9 - Stabilization of CWSF

Task 3. Coal Precombustion

Subtask 3.1 - Evaluate Coal Precombustion Options

Subtask 3.2 - Conduct Fundamental and Pilot-Scale Studies

Subtask 3.2.1 - Fluidized Bed Gasification

Subtask 3.2.2 - Slagging Combustion

Task 4. Engineering Design and Cost and Economic Analysis

Subtask 4.1 - Basic Cost Estimation of Boiler Retrofits

Subtask 4.2 - Process Analysis

Subtask 4.3 - Environmental and Regulatory Impacts

Subtask 4.4 - Transportation Cost Analysis

Subtask 4.5 - Technology Adoption

Subtask 4.6 - Regional Economic Impacts

Subtask 4.7 - Public Perception of Benefits and Costs

Subtask 4.8 - Social Benefits

Subtask 4.9 - Coal Market Analysis

Subtask 4.10 - Engineering Design

Subtask 4.11 - Integration of Analyses

Table 1-1. Phase I. 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	05/01/93	08/10/93
Subtask 1.1, No. 5	Procure samples	06/01/93	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	06/01/93
Subtask 1.2.1, No. 2	Analysis of Type I complete	06/15/93	07/27/93
Subtask 1.2.1, No. 3	Analysis of Type II complete	09/30/93	09/30/93
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	07/01/93	09/30/93
Subtask 1.2.2, No. 3	Analysis of Type III complete	09/30/93	09/30/93
Subtask 1.3. Produce Laboratory-Scale Quantities of MCWM			
Subtask 1.3.1, No. 1	Identify Cleaning Strategies	10/30/93	10/30/93
Subtask 1.3.2. Evaluate Conventional Gravity Separations			
Subtask 1.3.2, No. 1	Test work on Type I complete	09/01/93	09/01/93
Subtask 1.3.2, No. 2	Test work on Type II complete	04/30/94	04/30/94
Subtask 1.3.2, No. 3	Test work on Type III complete	04/30/94	04/30/94
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	02/02/93
Subtask 1.3.3, No. 4	Preliminary centrifuge data evaluation	01/31/94	01/31/94
Subtask 1.3.3, No. 5	Procure continuous centrifuge	08/01/93	07/14/93
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	07/29/93
Subtask 1.3.3, No. 9	Procure variable speed pump	08/01/93	07/29/93
Subtask 1.3.3, No. 10	Preliminary test work complete	04/01/94	05/31/94
Subtask 1.3.4. Evaluate Advanced Froth Flotation			
Subtask 1.3.4, No. 1	Reagent selection	06/01/93	06/01/93
Subtask 1.3.4, No. 2	Initiate test work on Type II samples	06/15/93	08/31/93
Subtask 1.3.4, No. 3	Initiate test work on Type III samples	07/01/93	06/15/93

<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	09/30/94	
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	11/30/94	
Subtask 1.3.5. Evaluate Column Flotation			
Subtask 1.3.5, No. 1	Complete column design	05/01/93	05/01/93
Subtask 1.3.5, No. 2	Procure bubble generators	06/01/93	06/01/93
Subtask 1.3.5, No. 3	Complete column fabrication	07/31/93	09/01/93
Subtask 1.3.5, No. 4	Complete test work	05/31/94	05/31/94
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	09/30/94	
Subtask 1.3.6, No. 5	Complete preliminary test work on Type III samples	09/15/93	09/15/93
Subtask 1.3.6, No. 6	Complete detailed studies on Type II samples	03/01/94	03/01/94
Subtask 1.3.7. Investigate Solid-Liquid Separations			
Subtask 1.3.7, No. 1	Preliminary evaluation complete	09/30/93	09/30/93
Subtask 1.3.7, No. 2	Initiate studies on test coals	09/30/93	09/30/93
Subtask 1.3.7, No. 3	Complete studies on test coals	09/30/94	
Subtask 1.3.8. Select Cleaning Flowsheet(s)			
Subtask 1.3.8, No. 1	Establish flowsheet for Type I sample	12/01/93	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	10/31/94	
Subtask 1.3.9, No. 2	Complete for Type II samples	12/31/94	
Subtask 1.3.9, No. 3	Complete for Type III samples	12/31/94	
Subtask 1.3.10. Investigate Conventional Ball Milling			
Subtask 1.3.10, No. 1	Complete test work for Type I samples	07/31/93	07/31/93
Subtask 1.3.10, No. 2	Complete test work for Type II samples	10/31/93	10/31/93
Subtask 1.3.10, No. 3	Complete test work for Type III samples	10/31/93	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	04/30/94	04/30/94
Subtask 1.3.11, No. 3	Complete test work on Type II samples	05/15/94	06/15/94
Subtask 1.3.11, No. 4	Complete test work on Type III samples	05/31/94	06/30/94
Subtask 1.3.12. Investigate Attrition Milling			
Subtask 1.3.12, No. 1	Establish test procedure	04/30/94	05/31/94
Subtask 1.3.12, No. 2	Evaluate preliminary data	09/30/94	
Subtask 1.3.12, No. 3	Complete evaluation	10/31/94	

<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	09/15/94	
Subtask 1.3.13, No. 2	Type II produced	10/31/94	
Subtask 1.3.13, No. 3	Type III produced	11/30/94	
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	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	05/15/93
Subtask 1.4.1, No. 3	Procure pilot-scale jet mill	05/30/93	05/30/93
Subtask 1.4.1, No. 4	Procedure established for Type III samples	08/31/93	08/31/93
Subtask 1.4.1, No. 5	Produce micronized product for dry beneficiation studies	11/01/93	11/01/93
Subtask 1.4.2. Deagglomeration Studies			
Subtask 1.4.2, No. 1	Establish standardized test procedure	07/31/94	09/15/94
Subtask 1.4.2, No. 2	Initiate humidity and reagent testing	09/30/94	
Subtask 1.4.2, No. 3	Procure laser diagnostic system	10/15/93	02/08/94
Subtask 1.4.2, No. 4	Complete humidity testing	10/01/94	
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	08/31/93
Subtask 1.4.3, No. 4	Complete testing	06/30/94	06/30/94
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	11/01/94	
Subtask 1.5.2, No. 1	Product MCWM from Dry, Clean Coal	12/01/94	
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	09/30/93
Subtask 1.6.2, No. 1	Complete CWM Preparation Facility	07/31/93	07/31/93
Subtask 1.6.2, No. 2	Procure automated valves	09/01/94	09/01/94
Subtask 1.6.2, No. 3	Install CWM equipment	11/01/94	
Subtask 1.6.3, No. 1	Shakedown CWM circuit	02/01/95	
Subtask 1.6.4, No. 1	Coal Cleaning	06/01/95	
Subtask 1.6.5, No. 1	Coal Micronizing	01/01/95	
Subtask 1.6.6, No. 1	MCWM Preparation	06/01/95	

<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	06/01/95	
Subtask 1.7.2, No. 1	Drafting/Technical Secretary Support	06/01/95	
Subtask 1.7.3, No. 1	Budget Management/Project Administration	06/01/95	
Task 2. Combustion Performance Evaluation			
Subtask 2.1. Boiler Retrofit			
Subtask 2.1.1, No. 1	Finalize burner/atomizer design	05/31/93	11/01/93
Subtask 2.1.2, No. 1	Procure and install burner	05/01/94	05/15/94
Subtask 2.1.3, No. 1	Optimize burner firing dry, micronized coal	07/31/94	07/31/94
Subtask 2.1.4, No. 1	Optimize burner firing CWM	01/01/95	
Subtask 2.2. Fuel Evaluation in Research Boiler			
Subtask 2.2.1, No. 1	Test sample of Type I CWM	10/31/94	
Subtask 2.2.2, No. 1	Test sample of Type II CWM	11/31/94	
Subtask 2.2.3, No. 1	Test sample of Type III CWM	12/31/94	
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	100-hour milestone firing dry, micronized coal	07/19/94	07/19/94
Subtask 2.3.2, No. 1	200-hour milestone firing dry, micronized coal	07/28/94	07/28/94
Subtask 2.3.3, No. 1	300-hour milestone firing dry, micronized coal	08/05/94	08/05/94
Subtask 2.3.4, No. 1	400-hour milestone firing dry, micronized coal	08/22/94	08/22/94
Subtask 2.3.5, No. 1	500-hour milestone firing dry, micronized coal	08/30/94	08/30/94
Subtask 2.3.6, No. 1	600-hour milestone firing dry, micronized coal	09/14/94	09/14/94
Subtask 2.3.7, No. 1	700-hour milestone firing dry, micronized coal	09/30/94	
Subtask 2.3.8, No. 1	800-hour milestone firing dry, micronized coal	10/14/94	
Subtask 2.3.9, No. 1	900-hour milestone firing dry, micronized coal	10/25/94	
Subtask 2.3.10, No. 1	1,000-hour milestone firing dry, micronized coal	11/09/94	
Subtask 2.3.11, No. 1	Technical Advisement by EER	12/31/94	
<u>MCWM Testing</u>			
Subtask 2.3.12, No. 1	100-hour milestone firing micronized CWM	03/01/95	
Subtask 2.3.13, No. 1	200-hour milestone firing micronized CWM	03/11/95	
Subtask 2.3.14, No. 1	300-hour milestone firing micronized CWM	03/23/95	
Subtask 2.3.15, No. 1	400-hour milestone firing micronized CWM	04/01/95	
Subtask 2.3.16, No. 1	500-hour milestone firing micronized CWM	04/11/95	
Subtask 2.3.17, No. 1	600-hour milestone firing micronized CWM	04/23/95	
Subtask 2.3.18, No. 1	700-hour milestone firing micronized CWM	05/01/95	
Subtask 2.3.19, No. 1	800-hour milestone firing micronized CWM	05/11/95	
Subtask 2.3.20, No. 1	900-hour milestone firing micronized CWM	05/23/95	
Subtask 2.3.21, No. 1	1,000-hour milestone firing micronized CWM	06/01/95	
Subtask 2.3.22, No. 1	Technical advisement by EER	06/01/95	
<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	03/01/94

<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	10/15/93
Subtask 2.3.25, No. 2	Compare heat transfer surface performance firing micronized dry coal and CWM	05/01/95	
Subtask 2.3.26, No. 1	Develop procedure for determining optimum convective section gas velocity	02/28/94	03/01/94
Subtask 2.3.27, No. 1	Comparison of performance of three tube materials	05/01/95	
Subtask 2.4. Evaluate Emissions Reduction Strategies			
Subtask 2.4.1, No. 1	Determine emissions from micronized coal testing	01/01/95	
Subtask 2.4.2, No. 1	Determine emissions from CWM testing	06/01/95	
Subtask 2.5. Project Management and Support			
Subtask 2.5.1, No. 1	Project management and advisement	06/01/95	
Subtask 2.5.2, No. 1	Staff supervision, test planning, and quality control	06/01/95	
Subtask 2.5.3, No. 1	Data reduction and interpretation	06/01/95	
Subtask 2.5.4, No. 1	Drafting/technical secretarial support	06/01/95	
Subtask 2.5.5, No. 1	Budget management/project administration	06/01/95	
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 PSU	12/31/94	
Subtask 3.1.2, No. 1	Design of dry micronized coal preparation system by EER	09/01/94	07/15/94
Subtask 3.2. Fuel Handling			
Subtask 3.2.1, No. 1	Design of fuel system by EER	09/01/94	07/15/94
Subtask 3.2.2, No. 1	Technical support and design of fuel system by PSU	09/01/94	07/15/94
Subtask 3.3. Burner System			
Subtask 3.3.1, No. 1	Design of burner by EER for selected boiler	09/01/94	07/15/94
Subtask 3.3.2, No. 1	Design of auxiliary components by EER	09/01/94	07/15/94
Subtask 3.4. Ash Removal, Handling, and Disposal			
Subtask 3.4.1, No. 1	Design of ash system by EER	09/01/94	07/15/94
Subtask 3.5. Air Pollution Control			
Subtask 3.5.1, No. 1	Design of emission control by EER	09/01/94	07/15/94
Subtask 3.6. Integrate Engineering Design			
Subtask 3.6.1, No. 1	Integrate system components	09/01/94	07/15/94

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 3.7. Project Management and Support			
Subtask 3.7.1, No. 1	Project management and technical advisement	12/31/94	
Subtask 3.7.2, No. 1	Penn State technical review	12/31/94	
Subtask 3.7.3, No. 1	Drafting/technical secretarial support	12/31/94	
Subtask 3.7.4, No. 1	Budget management/project administration	12/31/94	
Task 4. Engineering and Economic Analysis			
Subtask 4.1, No. 1 Survey Boiler Population/Identify Boilers for Conversion		09/01/94	
Subtask 4.2, No. 1 Identify Appropriate Cost-Estimating Technologies		05/31/93	09/01/93
Subtask 4.2, No. 2 Prepare Final Draft		01/31/94	01/31/94
Subtask 4.3, No. 1 Estimate Basic Costs of New Technologies		12/31/93	12/31/93
Subtask 4.3, No. 2 Prepare Final Draft		09/01/94	
Subtask 4.4. Process Analysis of MCWM and Dry, Micronized Coal			
Subtask 4.4.1, No. 1	Penn State Analysis	09/01/94	
Subtask 4.4.2, No. 1	Industrial Participants Assistance/Advisement	09/01/94	
Subtask 4.5, No. 1 Analyze/Identify Transportation Cost of Commercial Sources of MCWM and Cleaned Coal for Dry, Micronized Coal Production		12/31/93	
Subtask 4.6, No. 1 Determine Community Spillovers		12/31/93	12/31/93
Subtask 4.7, No. 1 Regional Market Considerations and Impacts		01/31/94	01/31/94
Subtask 4.8. Integrate the Analysis			
Subtask 4.8.1, No. 1	Penn State Review of Industrial Participants Contribution	09/01/94	
Subtask 4.8.2, No. 1	Penn State Integration of the Analysis	09/01/94	
Subtask 4.8.3, No. 1	Industrial Participants Assistance in Preparing, and Review of, the Integrated Analysis	09/01/94	
Subtask 4.9. Project Management and Support			
Subtask 4.9.1, No. 1	Project Management and Advisement	09/01/94	
Subtask 4.9.2, No. 1	Drafting/Technical Secretarial Support	09/01/94	
Subtask 4.9.3, No. 1	Budget Management/Project Administration	09/01/94	
Task 5. Final Report/Submission of Design Package			
Subtask 5.1, No. 1	Industrial Participants Submission to Penn State/Review Final Package	06/01/95	
Subtask 5.2, No. 1	Penn State Technical Preparation	06/01/95	
Subtask 5.3, No. 1	Report Preparation Support Services	06/01/95	

Table 1-2. Phase II. Milestone Description

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Task 1. Emissions Reduction			
Subtask 1.1. Evaluation of Emissions Reduction Strategies			
Subtask 1.1, No. 1	Receive proposals for pollution control system	12/01/93	12/01/93
Subtask 1.1, No. 2	Select pollution control system	01/01/94	02/01/94
Subtask 1.1, No. 3	Complete summary report of pollution control technologies	12/31/94	
Subtask 1.2. Conduct Fundamental Emissions Studies			
Subtask 1.2, No. 1	Complete testing on gasifier, down-fired combustor, and research boiler	10/31/94	
Subtask 1.2, No. 2	Complete testing on demonstration boiler and slagging combustor	12/31/94	
Subtask 1.2, No. 3	Prepare summary of emissions studies	02/01/95	
Subtask 1.3. Install System on Demonstration Boiler			
Subtask 1.3, No. 1	Order pollution control system	09/01/94	
Subtask 1.3, No. 2	Complete installation of system	01/01/95	
Subtask 1.4. Evaluate Emissions Reduction System			
Subtask 1.4, No. 1	Shakedown system	02/01/95	
Subtask 1.4, No. 2	Complete system evaluation	07/01/95	
Task 2. Coal Preparation/Utilization			
Subtask 2.1. Optimization of Particle Size Consist for Slurry Formulation			
Subtask 2.1, No. 1	Samples of fine and coarse slurry components prepared	04/30/94	05/30/94
Subtask 2.1, No. 2	Rheological characterization of components completed	10/31/94	
Subtask 2.1, No. 3	Models for rheology of binary mixtures developed	09/30/94	
Subtask 2.1, No. 4	Optimization studies complete	10/31/94	
Subtask 2.2. Fine Grinding/Classification Liberation			
Subtask 2.2, No. 1	Grinding kinetics data for wet ball milling obtained	04/30/94	04/30/94
Subtask 2.2, No. 2	Wet classifier performance evaluated	10/15/94	
Subtask 2.2, No. 3	Dry classifier performance evaluated	04/30/94	06/30/94
Subtask 2.2, No. 4	Grinding kinetics data for stirred media milling obtained	05/31/94	05/31/94
Subtask 2.2, No. 5	Closed-circuit jet-milling data obtained	10/31/94	
Subtask 2.2, No. 6	Slurry production simulations initiated	06/30/94	06/30/94
Subtask 2.2, No. 7	Liberation data on Type III coal obtained	04/30/94	04/30/94
Subtask 2.3. Fine Gravity Concentration			
Subtask 2.3, No. 1	Initiate magnetic fluid separation of Type III coal	07/31/94	08/15/94
Subtask 2.3, No. 2	Complete batch centrifuge testing	04/30/94	06/30/94
Subtask 2.3, No. 3	Continuous centrifuge test rig set-up	09/30/94	
Subtask 2.3, No. 4	Initiate magnetite classification studies	10/15/94	
Subtask 2.3, No. 5	Initiate separations of Type III coals	11/30/94	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Subtask 2.3, No. 6	Initiate micronized coal classification studies	12/31/94	
Subtask 2.3, No. 7	Evaluate dense-medium separation data	01/31/95	
Subtask 2.3, No. 8	Evaluate size classification data	02/28/95	
Subtask 2.4. Agglomeration/Flotation Studies			
Subtask 2.4, No. 1	Set-up device to size separate flotation products of micronized coal	12/31/93	12/31/93
Subtask 2.4, No. 2	Set-up equipment for larger scale tests using 2.2 cu.ft. flotation cells	04/30/94	04/30/94
Subtask 2.4, No. 3	Conduct agglomeration-flotation tests for micronized Type III coal	09/30/94	
Subtask 2.4, No. 4	Conduct agglomeration-flotation tests in larger cells	12/31/94	
Subtask 2.4, No. 5	Determine parameters for scale-up	03/31/95	
Subtask 2.5. Fundamental Studies of Surface-Based Processes			
Subtask 2.5, No. 1	Conduct interface characterization studies to determine flotation reagent-coal interactions	06/30/94	06/30/94
Subtask 2.5, No. 2	Measure contact angles in the coal-oil-surfactant-water system	09/30/94	
Subtask 2.5, No. 3	Determine effect of surfactants on slurry stability	10/31/94	
Subtask 2.6. Column Flotation			
Subtask 2.6, No. 1	Test work on Type II coals	11/30/94	
Subtask 2.6, No. 2	Test work on Type III coals	09/30/94	
Subtask 2.6, No. 3	Determine scale-up parameters	03/31/95	
Subtask 2.7. Dry Cleaning of Fine Coal			
Subtask 2.7, No. 1	Complete evaluation of Type III coal in batch separator	04/30/94	05/31/94
Subtask 2.7, No. 2	Integration of closed dry grinding circuit with TES	12/31/94	
Subtask 2.7, No. 3	Initiate investigation of continuous TES	04/01/94	06/30/94
Subtask 2.7, No. 4	Complete charge measurements on Type II coal	10/15/94	
Subtask 2.7, No. 5	Complete charge measurements on Type III	11/15/94	
Subtask 2.8. Slurry Density Control			
Subtask 2.8, No. 1	Evaluate procedures for reversible flocculation of fine coal	09/30/94	
Subtask 2.8, No. 2	Establish process engineering for thickening of fine-coal slurries	10/31/94	
Subtask 2.9. Stabilization of CWSF			
Subtask 2.9, No. 1	Complete stabilization study	10/31/94	

<u>Milestone</u>	<u>Description</u>	<u>Planned Completion Date</u>	<u>Actual Completion Date</u>
Task 3. Coal Precombustion			
Subtask 3.1. Evaluate Coal Precombustion Options			
Subtask 3.1, No. 1	Receive proposals for slagging combustor	12/01/93	01/07/94
Subtask 3.1, No. 2	Select slagging combustor	10/01/94	
Subtask 3.1, No. 3	Complete summary report of precombustion technologies	10/01/94	
Subtask 3.2. Fundamental and Pilot-Scale Precombustion Studies			
Subtask 3.2.1. Fluidized-Bed Gasification			
Subtask 3.2.1, No. 1	Erosion and deposition measurements in boiler firing CFB gasifier products	10/01/94	
Subtask 3.2.1, No. 2	Modeling of erosion and deposition of ash and sorbent fines from the CFB gasifier	12/31/94	
Subtask 3.2.1, No. 3	Complete fundamental studies	05/31/95	
Subtask 3.2.1, No. 4	Complete pilot-scale studies	07/01/95	
Subtask 3.2.2. Slagging Combustion			
Subtask 3.2.2, No. 1	Erosion and deposition measurements in boiler fitted with slagging precombustor	11/30/94	
Subtask 3.2.2, No. 2	Modeling and erosion of deposition of micron and submicron size ash from the slagging combustor	01/31/95	
Subtask 3.2.2, No. 3	Complete fundamental studies	01/31/95	
Subtask 3.2.2, No. 4	Complete pilot-scale studies	02/28/95	
Task 4. Engineering Design and Cost; and Economic Analysis			
Subtask 4.1. Determine Basic Cost Estimation of Boiler Retrofits		10/01/94	
Subtask 4.2. Determine Process Analysis		10/01/94	
Subtask 4.3. Determine Environmental and Regulatory Impacts		02/01/95	
Subtask 4.4. Determine Transportation Cost Analysis		10/01/94	
Subtask 4.5. Determine Technology Adoption		10/01/94	
Subtask 4.6. Determine Regional Economic Impacts		10/01/94	
Subtask 4.7. Determine Public Perception of Benefits and Costs		03/01/95	
Subtask 4.8. Determine Social Benefits		10/01/94	
Subtask 4.9. Determine Coal Market Analysis		10/01/94	
Subtask 4.10. Complete Engineering Design		12/31/94	
Subtask 4.11. Complete Integration of Analyses		12/31/94	
Task 5. Final Report/Submission of Design Package		07/01/95	

given in Table 2-1. As reported previously, the float-sink testing procedure for a Type II coal involves crushing the coal to top sizes of 1/4" and 28 mesh followed by sizing and float-sink separation of each size fraction at various relative densities. A detailed description of the procedure is given elsewhere^[1].

As seen in Table 2-2, this coal sample would require almost no cleaning to meet product specifications with 99% yield of less than 5% ash and 0.6% sulfur at a nominal size of -1/4". Hence, this coal could be classified as a Type I coal. As reported previously, a Type I coal is one which can meet the specifications at high yield with little or no cleaning; a Type II coal can be cleaned by conventional means and can meet the specifications at fairly high yield; and a Type III coal can be cleaned to meet the specifications but only at low yield using conventional cleaning technology. If desired, a superclean coal of less than 3% ash can be produced with 70% yield. By reducing the top size to 28 mesh, the yield can be increased to 95% for the same ash content at a separation density of 1.60. The sulfur content of the product did not vary with the density of separation. However, this coal sample contains a low sulfur content (0.7%) and can meet the sulfur specification at any density.

Liberation Modeling

During this period, work continued on developing the crusher-liberation model. Emphasis was on the fitting of functional forms -

- probability of breakage
- primary breakage distribution
- primary breakage distribution of mineral matter
- liberation

to the experimental data and developing the parameter variation pattern of these functions, while preserving the mass balance of the original mineral matter content.

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

Conventional Gravity Separations

The application of conventional gravity separations to the Type II and Type III coals has been evaluated using the washability data obtained for each of the test coals. The data were interpolated as appropriate and then used in conjunction with existing computer simulation procedures^[2]. The separations were made on the nominal 1/4"x28 mesh size fraction using performance data obtained by the USBM for dense-medium cyclone operations.

Table 2-1. Proximate Analysis and Hardgrove Grindability Indices of the Lower Block Seam Coal.

<u>Proximate Analysis</u>	<u>As received</u>	<u>Dry basis</u>
Moisture %	11.9	--
Volatile %	30.4	34.5
Fixed Carbon %	51.5	58.5
Ash %	6.1	7.0
Total Sulfur %	0.7	0.8
Hardgrove Grindability Index	45	

Table 2-2. Washability analysis of the Lower Block seam coal.

a) crushed to a nominal -1/4".

Rel. Den.	+1/4"			1/4"x28 Mesh			28x100 Mesh			-100 Mesh			Composite		
	Wt.,%	Ash,%	T.S.%	Wt.,%	Ash,%	T.S.%	Wt.,%	Ash,%	T.S %	Wt.,%	Ash,%	T.S %	Wt.,%	Ash,%	T.S %
1.3 F	59.3	2.15	0.64	12.7	1.47	0.64	0.22	-	0.73	0.10	-	0.70	33.1	1.64	0.62
1.4 F	87.2	3.54	0.62	65.9	2.54	0.60	13.3	1.34	0.62	14.8	1.40	0.43	70.6	2.89	0.58
1.5 F	94.1	4.34	0.62	89.0	3.29	0.59	81.4	3.26	0.61	65.3	2.12	0.46	89.8	3.72	0.58
1.6 F	95.2	4.50	0.62	94.6	3.84	0.59	87.3	3.97	0.60	82.9	2.69	0.40	94.0	4.09	0.58
2.0 F	99.4	5.40	0.65	98.3	4.56	0.62	94.6	4.32	0.53	95.7	4.40	0.43	98.5	4.93	0.60
2.0 S	100.	5.70	0.72	100.	5.40	0.71	100.	9.38	0.86	100.	7.75	0.65	100.	5.87	0.69
Wt.,%	46.5			43.5			5.2			4.7			100.0		

b) crushed to a nominal -28 mesh

Rel. Den.	28x100 Mesh			-100 Mesh			Composite		
	Wt.,%	Ash,%	T.S.%	Wt.,%	Ash,%	T.S.%	Wt.,%	Ash,%	T.S %
1.3 F	60.3	2.45	0.62	9.3	0.61	0.59	44.7	1.71	0.61
1.4 F	83.5	2.57	0.63	83.8	1.89	0.59	83.6	2.10	0.62
1.5 F	92.5	3.30	0.62	91.5	2.54	0.59	92.2	2.77	0.61
1.6 F	96.1	4.06	0.60	94.8	2.10	0.58	95.7	2.70	0.59
2.0 F	98.8	5.07	0.61	97.7	4.32	0.68	98.4	4.53	0.63
2.0 S	100.	6.40	0.78	100.	5.87	0.91	100.	6.23	0.82
Wt.,%	69.5			30.5			100.0		

The following results were obtained for the test coals:

Coal	Relative Density of Separation	Yield, %	Ash, %	Total Sulfur, %
Lower Kittanning	1.33	48.6	5.0	0.80
Indiana VII	1.35	59.2	4.9	0.39
Upper Freeport	1.33	47.5	4.5	0.99

In each case, approximately 50% of the feed coal reported to the clean coal stream. For the Lower Kittanning and Indiana VII seam coals, the ash content was the limiting factor in producing a specification product, while the sulfur content of the clean coal prevented a higher yield for the Upper Freeport seam coal.

For the Pittsburgh seam coal (Type III), the necessary sulfur reduction could only be obtained by crushing to -100 mesh. Therefore this coal was not evaluated, since the treatment of this size range would not be considered as conventional processing, at least for gravity concentration operations.

Fine Gravity Separations

The production of a compliance product from a Type II or a Type III coal will require crushing to achieve additional liberation of the clean coal from the mineral matter particles, resulting in an increase in the quantity of material that must be treated by the fine coal cleaning processes. As demonstrated above, this fraction may range from approximately 50% for the Type II coals to 100% for the Type III coals. In many cases, separations must be made at low relative densities (<1.35) to achieve the required ash and pyritic sulfur rejection. As such, dense-medium processes would be preferred since they are able to make sharp separations at low relative densities. Furthermore, they can be controlled with considerable precision, enabling them to clean coals containing large amounts of near-gravity material.

Centrifugal Separations

The baseline testing of the "batch" centrifuge using the +0.025 mm (+500 mesh) Upper Freeport seam coal was completed. As was shown in the previous report^[3], it was possible to separate fine coal using the batch centrifuge. The design of the unit limited an extensive investigation of the test conditions, in particular the effect of process variable interactions. However, the detailed test program will be conducted using the continuous, high-speed solid-bowl centrifuge.

Tests were made with the batch unit to demonstrate the advantage of using a dense-medium based separation system compared to a water-only system. When using the water-only system, a

clean coal yield of 15.4% was obtained with an ash content of 4.9%. On the other hand, when using a dense medium of 1.30, the yield increased to 63.1% at an ash content of 4.7%. These results indicate that centrifugal dense-medium separation may be a viable alternative for producing the specification coal.

Work also continued on examining changes in dense-medium separator performance using the batch hindered-settling model. This model is useful for analyzing the effects of changes in operating conditions on separation efficiency as given by the fractional recovery curves. However, the model would need to be revised before it can be used directly for the prediction of dense-medium centrifuge separations.

Surface-Based Cleaning Processes

Advanced Froth Flotation

Flotation tests were continued with Type II coals to obtain the target ash concentration (< 5.0 %) in the froth product. The results of ash rejection are presented in Figures 2-1 and 2-2 for the Indiana VII coal. The results in Figure 2-1 show that recoveries were generally low and the ash content much too high. Although the recoveries could be increased with addition of dodecane, the results were not satisfactory as shown in Figure 2-2 for the -65 μm feed. The results were similar for both the -600 and -150 μm feeds when the amount of collector was increased. However, a substantial improvement occurred when using the block co-polymer of propylene and ethylene oxide as the promotor, as can be seen from the results in Figure 2-3. In the presence of 11.2 kg/T collector and a surfactant to collector ratio of 0.8, the ash content decreased to less than 4.0 % at a combustible matter recovery greater than 90 %. This positive effect of collector and surfactant concentration is being further evaluated.

A different strategy was required to clean coal from the Lower Kittanning seam since earlier studies had shown that this coal floats readily but the ash content of the product was greater than the target. Therefore, a change in flotation circuit was considered. This approach was used because the effect of particle size on coal flotation is complex. With a decrease in particle size, the degree of liberation increases making it possible to reject the ash-forming minerals. At the same time, the rate of flotation decreases, however. To achieve the desired goal, an integrated flotation-comminution scheme in which the raw coal is first floated at minus 28 mesh and the froth product is ground to minus 200 mesh is being proposed. The re-ground coal will be floated to produce a low-ash clean coal and a middling product. Preliminary studies have been conducted to determine viability of this approach and the results are being analyzed.

Column Flotation

The test work on the column instrumentation, including the data acquisition system, has been completed. The column was filled with water and the output from the axial pressure sensors were recorded. These were compared with the estimated hydrostatic pressures. In general, the

Figure 2-1. EFFECT OF FEED PARTICLE SIZE ON FLOTATION OF INDIANA VII COAL

Figure 2-2. EFFECT OF DODECANE ON FLOTATION OF -65 μm INDIANA VII COAL

Figure 2-3. EFFECT OF PROPYLENE-ETHELENE OXIDE BLOCK CO-POLYMER ON FLOTATION OF INDIANA VII COAL.
Surfactant to dodecane ratio = 0.8; dodecane = 11.2 kg/T; surfactant = Pluronic L-64.

axial pressure measurements decreased with increasing column height as predicted by theory. These measurements will be used in the calculation of the pulp-froth interface.

Selective Agglomeration

The use of small additions of oil for selectively agglomerating fine coal particles is being investigated with a view to its use as a precursor to separation by flotation. Research in this area is being conducted in conjunction with a separate project, directly supported by the USDOE.

Studies of the fundamental processes involved in agglomerate formation and growth were described in a previous report^[3]. A sequential process was suggested which involves emulsification of the oil, agglomerate growth and breakage and a final, agglomerate-compaction step. Pre-emulsification of the oil, prior to addition to the coal suspension has been shown to enhance agglomeration rates, especially at very low oil concentrations (less than 0.5 %) and to provide improved control over the growth process. The role of surfactants is currently being investigated with regard to both agglomerate formation and the control of hydrophobicity. Preliminary investigations of the use of froth flotation for separation of the agglomerates from the aqueous/dispersed mineral phase are being initiated in order to complete the Phase I effort in this area.

Solid-Liquid Separations

The need for solid-liquid separations to control slurry density following coal cleaning and/or size reduction steps was discussed in the previous report^[3]. Typically, the greatest need for slurry thickening is likely to occur subsequent to cleaning steps such as fine gravity separation or flotation but prior to final grinding. Based on available technology, these steps will generally be performed on coal ground to about -100 mesh. A series of sedimentation/clarification tests have been performed on -100 mesh samples of the Upper Freeport coal (III-1). Settling behavior was evaluated from measurements of suspension turbidity as a function of settling time. The turbidity measurements were carried out using a Hach Model 2100A turbidimeter on samples taken from the suspensions at a fixed depth of 7 cm. The results are shown in Figure 2-4. It is clear that rapid, efficient settling can be obtained at pH 7 which is close to the point of zero charge of this coal^[3]. The results also indicate that the thickened coal can be readily redispersed simply by adjusting the slurry pH. The surface charging characteristics of the other test coals are currently being evaluated through measurements of Electrokinetic Sonic Amplitude (ESA). Such measurements will provide the basis for predicting sedimentation behavior for these coals.

Figure 2-4. SEDIMENTATION / CLARIFICATION RESULTS FOR -100 MESH UPPER FREEPORT COAL

Stirred Media Milling

Tests were conducted using a laboratory horizontal stirred ball mill (Dyno-Mill). It consists of a water-jacketed stainless-steel grinding chamber of 0.6 liter volume and a stirrer shaft with 4 agitating disks and is equipped with a feed inlet and outlet for continuous closed-loop operation, providing the capability of continuous closed-loop operation. The standard grinding tests were performed in the batch mode, without slurry circulation, in order to evaluate breakage behavior in the absence of complications due to materials transport effects. Stainless steel beads of 1/16 inch diameter were used as grinding media. The grinding tests were conducted with a 80% loading of media on a bulk volume basis and a slurry of 114 g of coal and 171 g of water (40% solids by weight). The mill was operated at 3000 rpm.

The coal was ground for various times using a new sample for each test. The products were screened at 400 mesh. The +400 mesh size fractions were dried, followed by dry screening. Any -400 mesh material was combined with the wet-screened fines and then analyzed using a Microtrac SRA and SPA. The overall size distribution was calculated by combining the sieve size and Microtrac size based on the material balance and a sieving/Microtrac conversion factor.

Figures 2-5 to 2-8 show the size distributions of the four test coals obtained for various grinding times. It can be seen that the size distribution becomes progressively finer in a parallel manner, a trend very similar to the typical batch grinding data in a ball mill. However, the overall shape of the size distribution is steeper than the ball mill grinding products at the same solids concentration. For example, the Gaudin-Schumann slope of the Taggart seam coal is about 0.8 for the stirred ball mill, compared to 0.72 for ball milling. Also, unlike the ball mill products, the shape of the size distribution is similar regardless of coal type. This is more evident in Figure 2-9 where the size distributions are plotted against the dimensionless size (x/x_{50}). It can be seen that all the size distribution data collapsed into a single curve. The implication is that the median size (x_{50}) can be used as a characteristic parameter to describe the grinding products.

Figure 2-10 shows the variation of median size with grinding time for the four coals. It can be seen that the median size decreased in a linear manner with grinding time when plotted on a log-log scale. Also, there is a general trend for a given grinding time; the median coal particle size decreases as the HGI of the coals increases. Figure 2-11 shows the power consumption over the grinding period for the Taggart seam coal. Except for the initial period of grinding, the power consumption remains fairly constant with an average value of 0.132 kW. The specific energy requirements (kWh/T) for grinding to different product sizes are illustrated in Figure 2-12. It can be seen that a single relationship (commonly known as Charles' energy-size relationship) can be applied to size reduction in both the ball mill and the stirred-media mill. In this particular case, reducing the product size by a factor of 10 requires about 80 times more energy.

Figure 2-5. PRODUCT SIZE DISTRIBUTIONS AFTER GRINDING THE -200 MESH SAMPLE OF THE TAGGART SEAM COAL IN A STIRRED BALL MILL AT 40% SOLIDS (BY WEIGHT) FOR VARIOUS TIMES WITHOUT A DISPERSANT

Figure 2-6. PRODUCT SIZE DISTRIBUTIONS AFTER GRINDING THE -200 MESH SAMPLE OF THE PITTSBURGH SEAM COAL IN A STIRRED BALL MILL AT 40% SOLIDS (BY WEIGHT) FOR VARIOUS TIMES WITHOUT A DISPERSANT

Figure 2-7. PRODUCT SIZE DISTRIBUTIONS AFTER GRINDING THE -200 MESH SAMPLE OF THE LOWER KITTANNING SEAM COAL IN A STIRRED BALL MILL AT 40% SOLIDS (BY WEIGHT) FOR VARIOUS TIMES WITHOUT A DISPERSANT

Figure 2-8. PRODUCT SIZE DISTRIBUTIONS AFTER GRINDING THE -200 MESH SAMPLE OF THE UPPER FREEPORT SEAM COAL IN A STIRRED BALL MILL AT 40% SOLIDS (BY WEIGHT) FOR VARIOUS TIMES WITHOUT A DISPERSANT

Figure 2-9. PRODUCT SIZE DISTRIBUTIONS AT VARIOUS GRINDING TIMES FOR THE FOUR COALS PLOTTED AGAINST THE DIMENSIONLESS SIZE

Figure 2-10. VARIATION OF THE MEDIAN SIZES WITH GRINDING TIME FOR THE FOUR COALS

Figure 2-11. POWER CONSUMPTION FOR GRINDING THE TAGGART SEAM COAL IN A STIRRED BALL MILL AT 40 WT. % SOLIDS

Figure 2-12. RELATIONSHIP BETWEEN THE SPECIFIC ENERGY INPUT AND THE PRODUCT MEDIAN SIZE FOR GRINDING THE TAGGART SEAM COAL IN A BALL MILL AND A STIRRED BALL MILL AT 40 WT. % SOLIDS

Laboratory-Scale Production of CWM

The laboratory production of CWM is subdivided into the following three tasks: 1) formulation of the CWM, 2) cleaning the coal feedstock, and 3) preparing barrels quantities (e.g., 3 to 4 fifty-five gallon drums) of CWM for determining atomization behavior and combustion performance prior to the pilot-scale production. The status of these three subtasks is presented below.

The objective of the bench-scale CWM formulation is to determine the components of the CWM (e.g., solids loading, additive concentration, coal particle top size, coal particle size distribution) that will make a CWM with pre-specified properties (e.g., viscosity and stability). The generic CWM specification that is targeted throughout the CWM formulation efforts is presented below.

Targeted Specifications Used in the CWM Formulation Efforts

CWM Parameter	Targeted Specification
Coal Particle Size (Top Size)	100 % Passing 200 μm (~ 65 mesh)
Coal Particle Size Distribution	Broad, Optimize Using Farris-Furnace Equation
CWM Apparent Viscosity	Less Than 500 cp. at 100 sec^{-1} at 25° C
CWM Flow Behavior	Yield Psuedoplastic
Solids Loading	Maximize While Meeting Viscosity Specification (Minimum Solids Loading is Set at 50 wt. %)
CWM Stability	Maximize Stability (Greater Than 80% Penetration Without the Use of a Stabilizer)
CWM Sedimentation Type	Softpack

The first coal being formulated into a CWM is the Taggart coal seam since its inherent sulfur (< 1.0 wt.%) and ash (< 5.0 wt.%) contents already meet the coal quality specifications without cleaning. The formulation of the Taggart into a CWM is approximately 50% complete. Solids loading, dispersant concentration, slurry pH, and stabilizer concentration are currently being systematically varied while maintaining an optimum coal particle size distribution (as defined by the Farris-Furnas equation) in an effort to produce a CWM having an acceptable apparent viscosity and stability.

Concurrent with the formulation of the Taggart coal, construction of a double stage froth flotation circuit has begun. This froth flotation circuit will be used to prepare the necessary clean coal feedstock for the CWM formulation efforts and the feedstocks to prepare barrel quantities of CWM for atomization and combustion performance testing. A pre-ground ball mill product will be used as the froth flotation feedstock and will be stored in an existing 500 gallon feed tank equipped

with a mixer. The coal will be wet ground continuously in a 2 x 4' tumbling overflow ball mill without using additives (e.g., grinding aides, pH modifier) and milled at approximately 50 to 55 wt.% solids and then pumped to a 500 gallon feed tank. The slurry will then be pumped from the 500 gallon feed tank to a 20 gallon head tank where water will be added to dilute the solids loading from 50 to 55 wt.% solids to approximately 5 wt.% at a flow rate of approximately 8 gpm. The collector (oil emulsion) and the frother (MIBC) will be added to the head tank which will discharge the overflow by gravity directly into rougher cells. The rougher concentrate will then be pumped to a 20 gallon head tank which will discharge into cleaner cells. The cleaner cell concentrate will then be dewatered using a duplex 24" pan filter and then the filter cake air dried. A schematic diagram of the froth flotation circuit is shown in Figure 2-13. The following is the status of key equipment items:

- Constructed/Refurbished

- a 2 x 4' ball mill that is needed to provide the coal feedstock to the froth flotation circuit has been designed and construction is nearly 85% completed
- a Moyno pump that will be used with the 500 gallon feed tank was identified from equipment donated by CE
- materials needed to fabricate the two 20 gallon head tanks were ordered and received
- the tables for the rougher and cleaner cells were designed and constructed
- the control system to operate the froth flotation circuit was designed
- the duplex vacuum pan filters were refurbished and connected to the in-house vacuum system

- Purchased

- a 500 gallon feed tank
- the tanks for the froth flotation reagents were ordered and received
- the rougher and cleaner froth flotation cells were obtained
- the froth pump was ordered and received

The production of barrel quantities of CWM will begin upon completion of the 2 x 4' ball mill and the double stage froth flotation circuit.

2.4 Subtask 1.4 Develop a Dry Coal Cleaning Technique

The baseline testing of the batch triboelectrostatic separator has been completed. A schematic diagram of the triboelectrostatic separator is shown in Figure 2-14. For these series of tests, the gap between the separator plates was kept constant at 115 mm. The coal sample was fed by vibrating feeder to the tribocharger/separator over a 5-10 minute period. After the test was completed, the plates were removed and the coal and refuse 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 and total sulfur content.

Figure 2-13. DOUBLE STAGE FROTH FLOTATION CIRCUIT

Figure 2-14. SCHEMATIC DIAGRAM OF THE TRIBOELECTROSTATIC SEPARATOR

As noted in the previous report, the yield of the Pittsburgh seam coal was quite low (~25%). In an attempt to improve the yield of this coal, a longer in-line static mixer was tested. The new mixer was also constructed of copper. It was 61 cm long, with a nominal inside diameter of 1.25 cm. This mixer had 16 elements compared to the 6 element mixer used in the previous testing. The -100 mesh Pittsburgh seam coal was tested under the conditions as noted above. A comparison of the results from both mixers is given in Figure 2-15.

The longer mixer had a dramatic effect on the yield of the clean coal product, which increased to ~73%. This was achieved without an increase in the ash content of the clean coal (~4%), although the total sulfur content increased from 0.8% to approximately 1.1%. One explanation for the increase in yield would be the higher probability of coal to copper contact using the longer mixer. This would increase the opportunity for the coal particles to acquire a surface charge.

Tests were then run on the Upper Freeport coal using the 16 element mixer. In this case, the longer mixer had less of an impact on the separation but still increased the clean coal yield approximately 5% (Figure 2-16). Again the cumulative ash remained constant (~4.3%), while the total sulfur content of the clean coal increased slightly from 1.05 to 1.15%. The small increase in yield with the number of elements and length of the static mixer suggests that the Upper Freeport seam coal acquires a charge more readily than that of the Pittsburgh seam coal. Based on these results, all subsequent testing was done with the 16 element static mixer.

The next set of tests was run with the Indiana VII seam coal. The results for this coal were compared to those obtained for the Pittsburgh and Upper Freeport seam coals and are shown in Figure 2-17. The yield for the three coals is constant up to a plate length of ~16 cm. Beyond 16 cm, the yield changes with the Pittsburgh seam coal having a final yield of 73%, followed by the Indiana coal at 68%, and the Upper Freeport coal at 64%. These results suggest that the surface charge is independent of coal type up to 16 cm. At the longer distances, the charge on the Indiana and Upper Freeport seam coals diminishes more quickly than that on the Pittsburgh seam coal. The ash content of all three coals was the same, while the total sulfur of the Pittsburgh coal was slightly less than that of the Upper Freeport. The sulfur content of the Indiana coal is not shown because of the low amount (~0.5%) in the feed.

A float-sink analysis of the clean coal and refuse products was initiated for each coal. The material was collected over plate distances that corresponded to the samples collected for the ash and sulfur analyses. Analysis of these results is in progress.

In electrostatic separation, it is desirable that the coal be thoroughly dispersed before and after tribocharging so that the particles appear in the gas stream as single particles rather than as agglomerates of two or more particles. It was reported^[4-6] that the deagglomeration of particulates can be achieved by the use of a fluidized bed. In this technique, the powder to be

Figure 2-15. TRIBOELECTROSTATIC SEPARATION OF THE PITTSBURGH SEAM COAL (-100 mesh) USING DIFFERENT STATIC MIXER LENGTHS (Nitrogen Velocity = 920 cm/s; Voltage = ± 26 kV; Temperature = 24°C; Humidity = 26%)

Figure 2-16. TRIBOELECTROSTATIC SEPARATION OF THE UPPER FREEPORT SEAM COAL (-100 mesh) USING DIFFERENT STATIC MIXER LENGTHS
 (Nitrogen Velocity = 920 cm/s; Voltage = ± 26 kV;
 Temperature = 23°C; Humidity = 20%)

Figure 2-17. TRIBOELECTROSTATIC SEPARATION OF THE UPPER FREEPORT, PITTSBURGH, AND INDIANA VII SEAM COALS IN A 16 ELEMENT MIXER

(Coal Feed Size = -100 mesh; Nitrogen Velocity = 920 cm/s;
Voltage = ± 26 kV; Temperature = 23°C; Humidity = 24%)

dispersed is introduced into a fluidizing bed of beads (bronze or brass beads), which are larger than the powder, and the fluidizing action of these beads disperses the powder as individual particles. A small test unit is currently being designed for use in this part of the testing.

The argon laser has been received. This unit will be used primarily as part of the test circuit for studying charging effects. However, it will also be used in some phases of the deagglomeration testing. The laser setup is described under Phase II.

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

No work was conducted in Subtask 1.5.

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 (containing MCWM and DMC preparation circuits) associated with the demonstration boiler (15,000 lb steam/h boiler). There are two circuits in the facility, one for producing DMC and one for producing MCWM. The construction of the fuel preparation facility that will contain the MCWM preparation circuit and the DMC circuit was previously completed.

Dry, Micronized Coal Preparation Circuit

The DMC preparation circuit is complete, has undergone shakedown, and is currently in use. A schematic diagram of the DMC equipment train in the fuel preparation facility is shown in Figure 2-18.

MCWM Preparation Circuit

Figure 2-19 is a schematic diagram of the MCWM circuit, which is under construction. The process flow sheet, engineering design, and final cost determinations were completed.

The following is the status of key items that have been, or are in the process of being installed/constructed:

Constructed/Refurbished

- Water lines and nozzles (to clean the pipe trench) have been installed in the pipe trench in the FPF;
- CWM tank stands were constructed for Tanks T1 and T4 (see Figure 2-19 for tank description);
- Tanks T1 and T4 were mounted on the stands;
- Mixer mounts were constructed for Tanks T1 and T4 and a mixer was mounted on Tank T1;

Figure 2-18. SCHEMATIC DIAGRAM OF THE DRY, MICRONIZED COAL EQUIPMENT TRAIN IN THE FUEL PREPARATION FACILITY

- Piping for compressed air and water lines was installed to the areas in the FPF where each major piece of equipment (pumps, tanks, sand mill, etc.) will be sited;
- MCWM lines were installed in the FPF and from the FPF to the boiler room;
- A flush water (water/coal mixture produced from purging lines in the boiler room) return line was installed from the boiler room to Tank T4;
- Air, water, and drain piping was installed for the sand mill;
- Moyno pumps that were received from CE were identified for Tanks T1 and T4 and put into place;
- Refurbishing of the 4 x 8' Centrix ball mill has begun. Allis Mineral Systems of York, Pennsylvania is currently fabricating a new main bearing for the ball mill. Orders for a new lubrication system and 50 hp motor have been placed. Installation of these components and controls for the ball mill will be subcontracted to the Beitzel Corporation;
- Electrical conduit and wiring was installed on the mixers;
- Construction started on the sump under the ball mill;
- The Quality Assurance (QA) room was set up which included mounting cabinets, installing a sink, and setting up a computer; and
- A ladder was constructed and installed for access to a storage area above the QA room.

Procured

- Pneumatic valves for tanks T1, T2, T3, and T4 have been ordered;
 - Stainless steel wiring for the sump on the ball mill was procured; and
 - A new hydraulic system was ordered for the sand mill (which was donated by CE) because the existing system could not be repaired;
- Orders were placed for the remaining major pieces of equipment (tanks, moyno pumps, mixers). These equipment will be installed upon receipt.

3.0 PHASE I, TASK 2: COAL COMBUSTION PERFORMANCE

3.1 Subtask 2.1 Boiler Retrofit

In this subtask, EER designed and constructed a Low-NO_x burner capable of firing natural gas, DMC, and MCWM is to be designed and constructed for Penn State's 15,000 lb steam/h demonstration boiler. The burner was delivered and installed in May 1994. Side and sectional views of the burner are shown in Figures 3-1 and 3-2, respectively.

3.2 Subtask 2.2 Fuel Evaluation in the Research Boiler

No combustion tests were conducted during this reporting period. The boiler was experiencing tube leaks and therefore was recently retubed. The boiler is currently undergoing shakedown prior to beginning testing

Figure 3-1. SIDE VIEW OF ASSEMBLED BURNER PRIOR TO INSTALLATION INTO THE DEMONSTRATION BOILER

Figure 3-2. BURNER SECTIONAL VIEW

3.3 Subtask 2.3 Performance Evaluation of MCWM and DMC in the Demonstration Boiler

Activities in Subtask 2.3 included preliminary tests of the EER burner with pulverized coal, conducting baseline tests firing natural gas, conducting DMC testing, addressing deposition in the furnace and convective pass during coal firing, evaluating erosion-corrosion and deposition characteristics when firing coal in an oil-designed boiler, determining the erosion characteristics of materials subjected to atomized MCWM, and conducting theoretical and experimental studies of particle behavior in the demonstration boiler. These activities are discussed in the following subsections.

Initial Evaluation of the EER Burner in the Demonstration Boiler

During this reporting period, the EER burner was installed, operated on natural gas, and initially tested with DMC. These tests were performed prior to conducting the DMC testing. A summary of activities conducted from May (when the burner was installed) through September is presented.

May Activities

During the month of May, activities included removing the ABB Combustion Engineering (CE) HEACC burner (DOE Project DE-AD22-91PC91160), installing and shaking down the EER burner, and starting construction of the MCWM preparation circuit. The MCWM preparation circuit construction progress was presented in Section 2.6 and is not discussed in this section; rather, a day-by-day synopsis of activities associated with the boiler is presented:

- May 2 -- Work started on dismantling the CE burner from the boiler.
- May 3 -- Work was completed dismantling the CE burner from the boiler. The boiler was prepared for installing the EER burner.
- May 4 -- Work began on installing the EER burner into the boiler.
- May 5 and 6 -- Work continued on installing the EER burner.
- May 9 -- Refractory work started in the boiler. Work started on installing the tertiary and secondary air dampers in the windbox.
- May 10 -- Completed installation of the EER burner. Refractory work inside the boiler was completed. The coal feed line was connected and work was completed on the secondary and tertiary air controls. The boiler was operated on gas. The flame was long and narrow and pulled into the convective pass. The boiler was unstable with high CO concentration measured.
- May 11 -- The EER burner was modified with holes drilled into the radial section of the burner. (The axial gas ports shown in Figure 3-3 were ultimately plugged and new holes drilled on the radial side of the burner as described during the following

Figure 3-3. SCHEMATIC DIAGRAMS OF THE NATURAL GAS BURNER PRIOR TO (a) AND AFTER MODIFICATION (b) AND THE FRONT VIEW OF THE BURNER (c)

days.) The boiler was operated on gas. The flame was wider but still did not fill the burner throat.

- May 12 -- The boiler was operated on gas and the flame was unstable. High CO concentration was recorded and the flame entered the convective section.
- May 13 -- The boiler was operated on coal only for 5 1/2 hours. Data and samples were collected. The flame appeared acceptable; however, during this initial test period air was introduced into the center of the burner, which will not be the standard operating procedure (as this portion of the burner is reserved for the MCWM nozzle). Coal combustion efficiency was 96-97%.
- May 16 -- The burner was modified by drilling additional holes in the radial section of the burner to obtain a stable gas flame. Twenty-four holes were drilled radially and eight axial holes were welded shut leaving sixteen axial holes open. The gas flame still was unstable.

Personnel worked most of the day cleaning the site.

- May 17 -- The burner was modified by drilling all 24 holes on the radial section to #16 size and plugging four of the axial holes leaving 12 axial holes open. A yellow flame without any turbulence was observed.
- May 18 -- The burner was modified by plugging four more axial holes, leaving eight holes open. No modifications were made to the radial section. The burner was operated on gas but the flame was highly unstable. The burner poorly mixed the gas and air for combustion. As previously observed, a long narrow flame exited the convective section with high CO concentration recorded.
- May 19 -- The burner was modified by plugging 2 more axial holes, leaving 6 holes open. No modifications were made on the radial section. The boiler was operated on gas. The burner center started showing signs of turbulence. A large soot build-up was observed on the boiler tubes and at end of the burner.
- May 20 -- The burner was modified again. Holes on the radial part of the burner were drilled larger at 7/32", while plugging two holes on the axial part, leaving 4 holes open. A compressed air line was broken on campus. The boiler was operated at 1400 hours after the compressed air problem was fixed. The flame was yellow and short with maximum swirl. The flame appeared to look better than earlier observations.
- May 23 -- The temporary wall in the boiler was removed prior to starting the natural gas baseline testing. The inside of the boiler was cleaned and the burner was modified by plugging the 4 remaining holes on the axial section of the burner.

- May 24 -- The breaching next to the convective pass was cleaned and sampled. The vortex steam flow meter was repaired and the transducer lines were cleaned.
- May 25 -- Attempts were made to operate boiler on gas only. Personnel continued modifying the burner and attempted to light on gas. Modifications included moving the defuser ring 1/4" from center of the radial holes; adjusting dampers; and drilling four 1/4" holes in the axial end. The flame remained unstable on gas.
- May 26 -- The flame remained unstable. The burner was modified to correct the flame problems by drilling every other radial hole to either 7/32" or 15/64". Work started on installing a coal-slurry line from the boiler room to the coal preparation building. This was in addition to the ongoing construction effort in the Fuel Preparation Facility.
- May 27 -- Most operating personnel were on vacation; work continued on the MCWM circuit.
- May 30 -- Memorial Day vacation
- May 31 -- Most operating personnel were on vacation; work continued on the MCWM circuit.

June Activities

During the month of June, activities included characterizing the natural gas valve, conducting some coal shakedown tests, and starting a natural gas baseline test matrix. A day-by-day synopsis of the boiler operation for June is:

- June 1 -- Preliminary gas firing of the boiler to characterize the burner.
- June 2 -- Characterized O₂ settings by comparing firing rate and O₂ content while operating the boiler on gas. Instrument and Control group on site checking for gas leaks in the analyzer bank.
- June 3 -- Continued characterizing the O₂ settings. Adjusted natural gas characterizing valve.
- June 6 -- Instrument and Control group corrected calibration problems with the analyzers in the morning. Increased gas rate to check O₂ content at various rates to check repeatability. An attempt to fire coal only failed.
- June 7 -- Attempts to take boiler on coal failed due to low u.v. signal. Slag accumulated on the burner tip which was corrected by removing the end ring. The boiler was then cooled down to make modifications to the u.v. scanner positioning.
- June 8 -- Removed the old u.v. scanner tube and replaced it with a larger diameter tube (from 1.5" to 3.5") in order to increase the field of view. Refractory was replaced around the new tube inside the boiler.

- June 9 -- Installed a new Fire-Eye U.V. Scanner and prepared the boiler for operation. The boiler was operated on gas to observe the u.v. readings.
- June 10 -- The damper positions were characterized to find the optimal positions. An attempt to fire the boiler on 100% coal failed. Began venting steam from the boiler in order to enter the boiler to clean the walls prior to beginning the natural gas baseline testing. The testing was conducted with clean boiler walls.
- June 13 -17 -- The steam lines on the East end of Campus were shut off for repairs. Consequently, the boiler could not be operated. Activities included MCWM circuit construction.
- June 20 -- Attempted to operate the boiler but there was a problem with the main control panel controls. Instrument and Control group corrected the problem. The boiler was operated on gas to characterize its operation.
- June 21 -- The natural gas baseline testing started. A description of the tests and the results are presented in the following subsection. The boiler operation involved two shifts per day. Two tests were completed.
- June 22 -- Two natural gas baseline tests were completed.
- June 23 -- Two natural gas baseline tests were completed.
- June 24 -- Two natural gas baseline tests were completed.
- June 27 -- Problems were encountered with the gas analyzers. Testing was put on hold while the analyzers were repaired. Equipment maintenance was conducted during the down time.
- June 28 -- A natural gas baseline test was conducted with suction pyrometry heat flux measurements performed.
- June 29 -- A natural gas baseline test was conducted during the first shift. Burner stability tests were conducted by varying secondary and tertiary air swirl and flows.
- June 30 -- Burner stability tests were conducted by varying secondary and tertiary air swirl and flows.

July Activities

During the month of July, activities included completing the natural gas baseline test matrix and stability testing. A day-by-day synopsis of the boiler operation for July is:

- July 1 -- No testing due to insufficient personnel.
- July 4 -- No testing due to Holiday.
- July 5 -- Testing was terminated during a natural gas baseline test because the University was experiencing problems with its deaerator tank and repairs were necessary. Repairs were completed by the Office of Physical Plant late in the day.

- July 6 -- A natural gas baseline test was conducted with heat flux measurements performed.
- July 7 -- Two natural gas baseline tests were completed.
- July 8 -- A natural gas baseline test was conducted.
- July 11 -- No testing was conducted. Maintenance on the boiler and data acquisition was conducted in preparation for tests firing coal without natural gas support. A furnace ash blowdown (FAB) system was assembled to entrain ash and unburned carbon from the furnace floor. A discussion of the system is contained in a latter subsection. The initial system was a prototype using carbon steel to determine optimum location and operability characteristics.
- July 12 -- Personnel finished work on the FAB system. A new coal curve for the screw feeder was generated. The boiler was operated on coal with the intent of characterizing the operation of the boiler and the burner.
- July 13 -- Two hours of gas supported coal firing was conducted as well as 2 hours on coal only. Data and samples were collected. The burner performed poorly regardless of damper, swirl, and burner core positions. Burner performance could not be improved by varying damper, swirl, and burner core positions.
- July 14 -- The burner core ramp was reinstalled. The boiler was operated for 3 hours on 100% coal firing. Data and samples were collected. Coal combustion efficiency ranged from 93-95% with an average of 94%. The ramp appeared to improve flame stability.
- July 15 -- The boiler was fired for 2 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 94-95% with an average of 94.6%.
- July 18 -- The boiler was fired for 3 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 93.2-94.5% with an average of 93.8%. Monthly equipment maintenance was also conducted.
- July 19 -- The boiler was fired for 8 hours on 100% coal. Data and samples were collected.
- July 20 -- The boiler was fired on 100% coal until the current shipment of coal was depleted (3 hours). A delivery of Brookville seam coal was received which was coal remaining from testing conducted in 1992. A new coal curve for the screw feeder was generated.
- July 21 -- The boiler was fired for 3 hours on 100% coal. Data and samples were collected. The boiler was shut down due to problems with the coal processing

system. The cage mill vibrated severely and appeared greatly out of balance. Repairs and maintenance on coal processing system were performed.

- July 22 -- Personnel continued maintenance on the cage mill. The surge bin was emptied in search of debris that may have caused the cage mill to malfunction. Common building brick pieces were discovered in the coal. Also, nuts, bolts, washers, and nails were discovered on the magnets located throughout the coal processing system. No determination was made of the cause of the cage mill malfunction.
- July 25 -- The cage mill was balanced (by TCS, Inc. personnel) using a dynamic balance. The system was brought on line but the cage mill malfunctioned again. Another large building brick was found in the coal processing system. The bricks were being inadvertently loaded with the coal at the coal storage facility. After discussions with the facility, the problem was remedied.
- July 26 -- Personnel finished coal processing system maintenance.
- July 27 -- The FAB system was replaced and one sparge pipe was observed to be cracked and broken. A new coal curve for the screw feeder was generated. Four hours of 100% coal firing was conducted. Data and samples were collected.
- July 28 -- The boiler was fired for 10 hours on 100% coal. Data and samples were collected.
- July 29 -- The boiler was fired for 10 hours on 100% coal. Data and samples were collected.

August Activities

During the month of August, the boiler was fired at 100% coal for initial burner characterization. High, erratic CO readings were observed after July 27. In particular, the CO readings periodically showed dramatic upward spikes that were sometimes off-scale. To account for these spikes, the goal of gas and coal testing after August 22 was to isolate the cause of the erratic operation. A day-by-day synopsis of the activities associated with the boiler is presented:

- August 1 -- The boiler was fired for 5 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 93.3-94.0% with an average of 93.8%. Test was terminated due to poor coal feed. The burner ramp was moved outward on the coal gun allowing the gun a greater range of distance within the furnace. The cage mill periodically shut down due to coal clogging.
- August 2 -- No testing conducted because OPP shut down the compressed air to throughout the University to repair the air compressors. During this time, EFRC performed system maintenance.

- August 3 -- Poor coal feed experienced in the morning. In the afternoon, the boiler was fired for 6 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 91.8-94.1% with an average of 93.5%.
- August 4 -- The boiler was fired for 10 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 94.9-96.2% with an average of 95.1%. During the 10 hour coal run, the cage mill required maintenance due to clogging.
- August 5 -- The boiler was fired for 1 hour on 100% coal. One set of data along with one ash and one coal sample was collected. Coal combustion efficiency was 94.6%. In the morning, there were problems with the gas analyzers and in the afternoon the boiler was shut-down due to low feed water temperature.
- August 8 -- Attempted to operate the boiler on coal but no testing was conducted. Low feed water temperature continued to be a problem. The cage mill required maintenance due to clogging.
- August 9 -- No testing was conducted and monthly maintenance was performed. A new coal curve for the screw feeder was generated.
- August 10 -- An additional coal curve for the screw feeder was generated. The boiler was fired for 2 hours on 100% coal. Data and samples were collected.
- August 11 -- The boiler was fired for 8 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 92.3-94.6% with an average of 94.0%. The Pennsylvania Department of Environmental Resources visited the site as part of their regional meeting.
- August 12 -- No testing was conducted because OPP requested that the demonstration boiler not be operated while they operate their two boilers in the East Campus Steam Plant (ECSP) as part of their summer operation. OPP was concerned that there may be insufficient compressed air at the ECSP for operating OPP's two boilers and EFRC's boiler simultaneously.
- August 15 -- No testing was conducted because OPP was operating the ECSP boilers. The boiler was not operated for the week of August 15 to 19.
- August 16 -- Maintenance on the Redler conveyor was conducted. Because of discrepancies (between OPP and EFRC) in total compressed air usage by the demonstration boiler system, EFRC decided to install an orifice meter into the compressed air line entering the demonstration boiler house. Piping needed for installing the orifice plate was fabricated.
- August 17 -- Work continued on installing the orifice plate on the main air line entering the boiler room.

- August 18 -- Fabrication of a new FAB system was started and installation of the orifice plate and a capsuhelic gauge was completed.
- August 19 -- Fabrication of the new FAB system continued.
- August 22 -- Fabrication of the new FAB system was completed.
- August 23 -- The boiler was fired for 5 hours on 100% gas. The objectives of this test were to observe CO emissions to ensure that the analyzer was working properly, and to observe the burner stability.
- August 24 -- No testing conducted because a steam line was cut on campus as part of a building project. A new coal curve for the screw feeder was generated.
- August 25 -- The boiler was fired for 2 hours on 100% coal. Data and samples were collected. The purpose of this test was to observe CO emissions and burner stability.
- August 26 -- No testing conducted. A delivery of coal was received and a new coal curve for the screw feeder was generated. Personnel installed a new bearing on the ash conditioning screw. The SO₂ analyzer was not operating properly and the booster fan was not operating.
- August 29 -- The SO₂ analyzer was repaired and Beitzel Corporation personnel were on site and repaired the booster fan. The boiler was operated for two hours on coal with gas support.
- August 30 -- The boiler was fired for 9 hours on 100% coal. Data and samples were collected. The test objective was to characterize the boiler operation with and without the MCWM atomizer (which was inserted in the burner core to inject atomizing air through the gun into the center of the flame).
- August 31 -- The boiler was fired for 9 hours on 100% coal. Data and samples were collected. The objective of the test was to repeat the August 30 testing.

September Activities

The boiler was shutdown most of September due to construction by OPP on steam lines. Most of the work for the month was repair and maintenance of equipment. Also, preliminary engineering work was conducted throughout the month on a new coal delivery system (surge bin and weigh-belt feeder). A day-by-day synopsis of the activities associated with the boiler is presented:

- September 1 -- The boiler was fired for 1 hour on 100% coal. No written data or samples were collected. Test was terminated due to erratic CO readings. Installed a 3/4" probe inside the burner core.
- September 2 -- The boiler was fired for 4 hours on 100% coal. Data and samples were collected. Coal combustion efficiency ranged from 92.4-93.0% with an average

of 92.7%. The burner was removed, centering pins were installed on end of burner, and the burner ramp was fixed.

- September 5 -- University Holiday; Labor Day- No work completed.
- September 6-30 -- No testing was conducted. The boiler was not be operated because of steam line work conducted by the University.

Natural Gas Baseline Testing

A series of tests was conducted to evaluate the performance of the burner while firing natural gas. This was done to verify natural gas firing capabilities and characterize the burner on natural gas prior to beginning coal firing. The objective of the testing was to evaluate the effect of excess oxygen, firing rate, and tertiary and secondary air swirl on boiler efficiency and emissions, and to determine the burner stability as a function of tertiary and secondary air degree of swirl and flow.

Table 3-1 contains a summary of the tests (boiler performance/emissions) except for the stability tests which are presented later. Each boiler performance/emissions test was conducted over a five to six hour period with maximum tertiary and secondary air swirl. The tests are presented in chronological order and the planned test conditions are briefly described below.

- June 20 -- High firing rate; 2% O₂
- June 21 -- High firing rate; 3% O₂
- June 21 -- High firing rate; 2% O₂; repeat of June 20 (reproducibility test)
- June 22 -- High firing rate; 1% O₂
- June 22 -- ~60% firing rate; 2% O₂
- June 23 -- ~80% firing rate; 2% O₂
- June 23 -- Lowest firing rate achievable when firing at 3% O₂
- June 24 -- High firing rate; 2% O₂; 2-hour test
- June 24 -- Lowest firing rate achievable when firing at 1% O₂
- June 28 -- High firing rate; 3% O₂; heat flux and suction pyrometry data obtained
- June 29 -- High firing rate; 2% O₂; minimal transport air
- July 6 -- High firing rate; 3% O₂; heat flux data obtained (This test was a repeat of the June 28 test after it was observed that the steam drum pressure was 183 psig instead of ~200 psig which is the normal operating pressure.)
- July 7 -- High firing rate; 2% O₂; minimum tertiary and secondary air swirl
- July 7 -- High firing rate; 2% O₂; medium tertiary and secondary air swirl
- July 8 -- High firing rate; 2% O₂; minimal transport air (This test was a repeat of the June 29 test after it was observed that the steam drum pressure was 178 psig instead of ~200 psig which is the normal operating pressure.)

Table 3-1. Summary of Results for Boiler Performance/Emissions Testing

[illegible]

Reproducibility Analysis

Three test conditions were used to evaluate the reproducibility of the boiler efficiency in order to draw conclusions about the effect of varying operating parameters on boiler efficiency. A summary of the results from the three pairs of tests is contained in Table 3-2. Note that the steam production is not reported for the tests conducted on June 28 and 29 because the steam drum pressure was below the normal operating pressure, which resulted in a larger quantity of steam produced for the same firing rates. The steam pressure was lower on these two days because foreign debris became lodged in the steam drum outlet regulator/valve and hindered the closing of the valve. The valve was removed and cleaned on July 1 and steam drum pressures of ~200 psig were obtained for the remaining tests.

The absolute differences between the boiler efficiencies for the three sets of data were 0.01, 0.37, and 0.52%. It was decided that the largest difference, 0.52%, would be used to determine if differences in boiler efficiencies were significant when evaluating the effect of varying operating parameters on boiler efficiency.

Boiler Performance

The effects of the oxygen concentration in the flue gas (excess air), mill (coal transport) air flow rate, firing rate, and secondary and tertiary swirl on boiler efficiency are shown in Figures 3-4 to 3-7, respectively. In Figure 3-4, the boiler efficiencies ranged from ~82.5 to 83.6% and exhibited a decreasing trend in boiler efficiency as O₂ concentration was increased (as would be expected) from ~1.2 to 1.8%, but exhibited variability in the data from 1.8 to ~3.0% O₂.

The boiler efficiency was plotted as a function of mill air, which varied considerably in order to maintain burner stability and targeted O₂ concentrations, to determine if the quantity of mill air affected boiler efficiency. As seen in Figure 3-5, there was no observed relationship between boiler efficiency and mill air flow.

The effect of firing rate on boiler efficiency is shown in Figure 3-6. The boiler efficiency exhibited a decreasing trend, from ~84.3 to 83.0%, as the firing rate was increased from ~10.2 to 15.2 million Btu/h (MM Btu/h). At 16.5 MM Btu/h, there was much variability in the boiler efficiency as it ranged from ~82.5 to 83.6%.

The effect of secondary and tertiary air swirl on boiler efficiency is shown in Figure 3-7. The boiler efficiency tends to decrease as the swirlers are moved from their maximum to minimum position; however, the differences are subtle (0.8% is the maximum) and may not be significant except when comparing the maximum swirl result to that of the minimum swirl. The differences between the maximum and medium swirl results (0.46 and 0.62 with an average of 0.54%) are very similar to the largest reproducibility difference (discussed above) of 0.52%. This indicates that there may not be any difference in data for the two swirl settings. Likewise, the difference between the medium and minimum swirl results is 0.18%, which is less than 0.52% indicating that

Table 3-2. Summary of Reproducibility Analysis

Date	28-Jun	6-Jul	Average
Test			
Targeted Pct O2	3% O2;	3% O2;	
Targeted Firing Rate; MM Btu/h	16.6	16.6	
Notes	Probe Meas.		
O2; %	2.21	2.27	2.24
CO; ppm	30	17	23
NOx; ppm	108	97	103
Firing rate; MM Btu/h	16.57	16.55	16.56
Boiler efficiency; %	82.86	82.87	82.86
Steam flow rate; lb/h	Not App.	14,556	Not App.
Steam drum pressure; psig	183	213	198
Date	29-Jun	8-Jul	Average
Test			
Targeted Pct O2	2% O2;	2% O2;	
Targeted Firing Rate; MM Btu/h	16.6	16.6	
Notes	low mill air	low mill air	
O2; %	1.55	1.79	1.67
CO; ppm	6	40	23
NOx; ppm	103	86	94
Firing rate; MM Btu/h	16.57	16.52	16.54
Boiler efficiency; %	83.24	82.87	83.06
Steam flow rate; lb/h	Not App.	15,015	Not App.
Steam drum pressure; psig	178	208	193
Date	20-Jun	21-Jun	Average
Test		B	
Targeted Pct O2	2% O2;	2% O2;	
Targeted Firing Rate; MM Btu/h	16.6	16.6	
Notes			
O2; %	2.05	1.98	2.01
CO; ppm	33	44	39
NOx; ppm	40	91	65
Firing rate; MM Btu/h	16.54	16.59	16.56
Boiler efficiency; %	83.08	83.60	83.34
Steam flow rate; lb/h	15,290	15,138	15,214
Steam drum pressure; psig	205	203	204

Figure 3-4. THE EFFECT OF OXYGEN CONCENTRATION IN THE FLUE GAS ON BOILER EFFICIENCY

**Figure 3-5. THE EFFECT OF MILL AIR FLOW ON
BOILER EFFICIENCY**

Figure 3-6. THE EFFECT OF FIRING RATE ON BOILER EFFICIENCY

Figure 3-7. THE EFFECT OF SWIRL ON BOILER EFFICIENCY

there is not an affect of swirl setting on boiler efficiency. However, the differences between the maximum and minimum swirl settings is 0.64 and 0.80% which is significant when comparing to 0.52%. Hence, the degree of swirl has an effect on boiler efficiency when comparing the extreme cases.

Emissions

The effects of excess air (O_2 concentration), firing rate, and secondary and tertiary swirl on CO and NO_x emissions are shown in Figures 3-8 to 3-10, respectively. None of these operating conditions affected the emissions significantly except for very low O_2 concentration ($\sim 1.1\%$) where the CO concentration increased from the typical <40 to 140 to 300 ppm. The concentration of NO_x was consistently in the ~ 90 to 100 ppm range. It should be noted that during the last week of testing (which includes the minimum and medium swirl test days) the continuous on-line analyzer was not operational and CO readings were obtained using a portable analyzer. Consequently, CO data was recorded every 30 minutes and averaged as compared to the normal mode of operation which is averaging data obtained from a data acquisition system which logs data every 30 seconds. Variability in the CO data in Figure 3-10 may be due to the limited number of data points obtained.

Burner Stability

A series of eight tests was conducted to evaluate the stability of the burner when varying the secondary and tertiary air dampers and swirl. This was done to characterize the burner prior to firing coal. The tests that were conducted are:

Matrix Number	Tertiary Air Damper Setting	Secondary Air Damper Setting	Tertiary Air Swirl	Secondary Air Swirl
1	Maximum	<i>Varied</i>	Maximum	Maximum
2	<i>Varied</i>	Maximum	Maximum	Maximum
3	Maximum	Maximum	Maximum	<i>Varied</i>
4	Maximum	Maximum	<i>Varied</i>	Maximum
5	<i>Varied</i>	Maximum	Minimum	Minimum
6	Maximum	<i>Varied</i>	Maximum	Minimum
7	<i>Varied</i>	Maximum	Maximum	Minimum
8	Maximum	<i>Varied</i>	Maximum	Minimum

Appendix A contains summary tables from the testing with a brief discussion given below. In Test Matrix #1, the secondary air damper was incrementally closed until the secondary air flow was zero. The burner stability was very good. Normally the tertiary air-to secondary air (TA/SA) ratio is ~ 2.6 and this ratio increased to 8.5 until the secondary air damper was closed. The O_2

Figure 3-8. THE CONCENTRATION OF CO AND NO_x AS A FUNCTION OF O₂ IN THE FLUE GAS

Figure 3-9. THE CONCENTRATION OF CO and NO_x AS A FUNCTION OF FIRING RATE

Figure 3-10. THE EFFECT OF SWIRL ON CO AND NO_x EMISSIONS

concentration decreased from 3.3 to ~2.3% with no affect on CO concentration and burner stability.

In Test Matrix #2, the tertiary air damper was incrementally closed until it was approximately half closed (TA/SA ratio was ~1.6). At this point, the O₂ concentration was very low and the CO concentration increased significantly. Because the bulk of the combustion air is tertiary, the burner stability is very sensitive to the tertiary air damper setting as the damper reaches its midpoint.

In Test Matrix #3, the secondary air swirl was incrementally changed from its maximum setting to its minimum setting. Some pulsing of the flame was noticed as the swirl approached its minimum setting; however, the burner stability was still good.

In Test Matrix #4, the tertiary air swirl was incrementally changed from its maximum setting to its minimum setting. The flame started to approach the rear boiler wall and the flame was pulsing as the swirl approached its minimum setting; however, the burner stability was still good.

In Test Matrix #5, the tertiary air swirl was left at its minimum position and the tertiary air damper was incrementally closed. Similarly to Matrix Test #2, the burner became unstable (pressure fluctuations and high CO concentration) as the TA/SA ratio approached ~1.7.

In Test Matrix #6, the tertiary air swirl was left at its minimum position and the tertiary air damper setting was at 100% open while the secondary air damper was incrementally closed. Closing the secondary air damper completely had minimal affect on burner stability.

In Test Matrix #7, the tertiary air damper was incrementally closed while the secondary air damper was 100% open, tertiary air swirl was maximum, and secondary air swirl was minimum. At this set of conditions, the tertiary air damper was about 50% closed when the burner became unstable.

In Test Matrix #8, the secondary air damper was incrementally closed while the tertiary air damper was 100% open, tertiary swirl was maximum, and the secondary swirl was minimum. No problems in burner stability were encountered.

In summary, the burner was very stable regardless of secondary and tertiary air swirl or the amount of secondary air introduced into the boiler. Only when closing the tertiary air damper, and hence limiting the quantity of combustion air into the boiler, did the burner become unstable. The burner exhibited flexibility in damper and swirl settings.

Micronized Coal Testing

Micronized coal testing was conducted in May and from July 13, 1994 to September 2, 1994. A summary of the results for the testing performed from July to September is given in Table 3-3. Over 1,200 hours of the DMC demonstration have been performed with 200 hours of micronized coal-fired testing conducted during this reporting period. The testing was conducted to optimize the burner firing coal and determine burner performance firing micronized coal. The

Summary Sheet

TEST/DESCRIPTION:	13-Jul #1 Gas Support	13-Jul #2 Coal Only	14-Jul #3 Gas Support	14-Jul #4 Coal Only	15-Jul #5 Coal Only	18-Jul #6 Coal Only
WATER/STEAM SIDE						
Steam flow rate; lb/h	11,830	8,868	12,877	12,446	11,164	12,063
Water temperature into boiler; °F	209	207	208	209	207	209
Drum pressure; psig	209	204	213	211	209	208
Calorimeter temperature; °F	215	305	203	294	288	307
Steam temperature; °F	384	381	385	385	384	384
Steam quality; %	94.39	99.51	93.72	98.93	98.58	99.66
Blowdown rate; lb/h	3,170	3,131	3,196	3,182	3,171	3,159
AIR,FUEL, FLUE GAS SIDE						
Natural gas flow rate; lb/h;MMBtu/h	280;6.58	0;0	140;3.29	0;0	0;0	0;0
Coal flow rate; lb/h,MMBtu/h	534	977	780	1,113	1,120	1,117
Air temperature entering air heater; °F	93	154	137	135	172	87
Air temperature leaving air heater; °F	366	392	405	411	417	409
Air temperature into boiler; °F	338	362	373	381	387	378
Furnace outlet temperature; °F	529	528	577	565	553	587
Gas temperature leaving air heater; °F	336	352	387	377	383	372
Bagfilter inlet temperature; °F	328	346	379	371	376	362
Bagfilter outlet temperature; °F	299	310	330	325	339	324
Combustion air flow; lb/h	12,880	12,646	13,180	13,571	14,221	13,601
Boiler draft; in H ₂ O	0.01	-0.03	0.01	-0.01	-0.02	0.02
Boiler efficiency; %	84.1	82.1	83.5	83.9	83.5	83.6
Mill air flow rate; ACFM;lbs/hr	354;1,608	317;1,432	350;1,599	348;1,576	380;1,728	353;1,591
Mill inlet temperature; °F	94	98	93	96	95	99
Mill outlet temperature; °F	185	215	205	208	201	209
Burner inlet temperature; °F	152	181	172	174	182	180
Natural gas temperature; °F	82	97	82	79	94	90
Coal combustion efficiency; %	92.6	92.6	94.4	94.0	94.6	93.8
EMISSIONS						
O ₂ ; %	3.2	4.3	3.6	3.2	3.9	3.3
CO; ppm	52	1,454	122	193	123	286
CO ₂ ; %	13.4	14.7	14.7	16.0	15.1	16.0
SO ₂ ; ppm	219	479	354	496	514	499
NO _x ; ppm	446	298	540	536	538	541
ECONOMIC ANALYSIS DATA						
ID fan power consumption; Amperage	32.0	30.3	31.0	31.2	30.4	31.0
FD fan power consumption; Amperage	12.0	12.0	11.5	11.6	11.4	12.0
Pulverizer power consumption; Amperage	85	90	95	95	95	95
Booster fan power consumption; Amperage	4.0	5.3	6.0	5.7	5.9	5.7
Ash collection power consumption; Amperage Not Measured(NM)		NM	NM	NM	NM	NM
Crusher power consumption; Amperage	NM	NM	NM	NM	NM	NM
Redler conveyor power consumption; Amperage	NM	NM	NM	NM	NM	NM
Feed screw power consumption; Amperage	1.8	1.8	1.8	1.8	1.80	1.80
Feedwater pump power consumption; Amperage	18.0	16.9	18.0	18.7	15.3	17.4
Total air usage; scfm (Pilot burner)	25	31	40	36	26	38
Maximum load ; %	79.4	59.5	86.4	83.5	74.9	81.0

Table 3-3. Summary of Results for Dry, Micronized Coal-Fired Testing

Summary Sheet

TEST/DESCRIPTION:	19-Jul 7 Coal Only	20-Jul 8 0800 hrs Gas Support	20-Jul 9 0945 hrs Gas Support	21-Jul 10 Coal Only	27-Jul 11 Coal Only	28-Jul 12 Coal Only
WATER/STEAM SIDE						
Steam flow rate; lb/h	12,269	12,048	11,956	11,754	12,486	11,888
Water temperature into boiler; °F	209	209	204	209	210	209
Drum pressure; psig	206	208	206	200	204	199
Calorimeter temperature; °F	306	203	203	306	306	305
Steam temperature; °F	383	384	383	383	382	380
Steam quality; %	99.59	93.74	93.73	99.62	99.62	99.55
Blowdown rate; lb/h	3,142	3,159	3,142	3,118	3,126	3,087
AIR,FUEL, FLUE GAS SIDE						
Natural gas flow rate; lb/h;MMBtu/h	0;0	313;7.35	326;7.66	0;0	0;0	0;0
Coal flow rate; lb/h,MMBtu/h	1,294	639	639	1,172	1,174	1,174
Air temperature entering air heater; °F	92	84	89	88	75	110
Air temperature leaving air heater; °F	403	383	392	402	397	424
Air temperature into boiler; °F	374	353	363	372	365	394
Furnace outlet temperature; °F	585	563	572	584	571	582
Gas temperature leaving air heater; °F	370	356	364	369	361	385
Bagfilter inlet temperature; °F	360	346	353	359	353	379
Bagfilter outlet temperature; °F	322	304	315	318	314	335
Combustion air flow; lb/h	15,818	15,415	15,783	14,388	14,220	14,221
Boiler draft; in H ₂ O	0.01	-0.01	-0.01	-0.09	-0.02	-0.01
Boiler efficiency; %	84.0	83.3	83.3	80.7	82.9	81.1
Mill air flow rate; ACFM;lbs/hr	361;1,627	352;1,619	362;1,657	386;1,744	418;1,916	424;1,927
Mill inlet temperature; °F	99	88	90	98	89	94
Mill outlet temperature; °F	208	184	185	189	179	181
Burner Inlet temperature; °F	183	148	153	170	166	169
Natural gas temperature; °F	92	80	82	90	77	82
Coal combustion efficiency; %	94.3	90.1	90.1	90.5	92.8	91.3
EMISSIONS						
O ₂ ; %	3.3	3.7	3.8	3.4	3.3	3.2
CO; ppm	161	34	28	192	158	1,070
CO ₂ ; %	16.0	15.5	15.5	15.6	16.1	15.9
SO ₂ ; ppm	481	121	125	490	456	426
NO _x ; ppm	573	444	404	553	594	512
ECONOMIC ANALYSIS DATA						
ID fan power consumption; Amperage	30.9	32.0	32.0	31.2	31.5	30.3
FD fan power consumption; Amperage	12.08	12.4	12.4	12.4	12.31	11.58
Pulverizer power consumption; Amperage	95	95	95	95	90	92
Booster fan power consumption; Amperage	5.7	5.5	5.5	6.1	7.4	7.4
Ash collection power consumption; Amperage	NM	NM	NM	NM	NM	NM
Crusher power consumption; Amperage	NM	NM	NM	NM	NM	NM
Redler conveyor power consumption; Amperage	NM	NM	NM	NM	NM	NM
Feed screw power consumption; Amperage	1.8	1.8	1.8	1.8	1.8	1.8
Feedwater pump power consumption; Amperage	19.2	20.0	20.0	18.6	18.3	17.9
Total air usage; scfm (Pilot burner)	26.94	25	25	25	27	31
Maximum load ; %	82.3	80.9	80.2	78.9	83.8	79.8

Summary Sheet

TEST/DESCRIPTION:	29-Jul 13 Coal Only	1-Aug 14 Coal Only	3-Aug 15 Coal only	4-Aug 16 Coal only	4-Aug 17 Coal only
WATER/STEAM SIDE					
Steam flow rate; lb/h	11,679	11,471	12,074	12,194	12,656
Water temperature into boiler; °F	209	210	209	206	205
Drum pressure; psig	196	204	197	201	191
Calorimeter temperature; °F	304	306	306	305	302
Steam temperature; °F	379	382	380	380	375
Steam quality; %	99.51	99.61	99.59	99.53	99.39
Blowdown rate; lb/h	3,064	3,126	3,077	3,110	3,028
AIR,FUEL, FLUE GAS SIDE					
Natural gas flow rate; lb/h;MMBtu/h	0;0	0;0	0;0	0;0	0;0
Coal flow rate; lb/h,MMBtu/h	1,174	1,174	1,129	1,129	1,129
Air temperature entering air heater; °F	119	118	132	132	131
Air temperature leaving air heater; °F	433	428	417	412	408
Air temperature into boiler; °F	403	394	390	386	385
Furnace outlet temperature; °F	582	578	578	581	575
Gas temperature leaving air heater; °F	393	388	385	386	382
Bagfilter inlet temperature; °F	388	382	378	377	375
Bagfilter outlet temperature; °F	344	342	338	337	334
Combustion air flow; lb/h	14,540	14,353	13,535	13,741	13,475
Boiler draft; in H ₂ O	-0.01	-0.01	-0.01	0.00	0.00
Boiler efficiency; %	81.1	82.9	82.8	84.0	84.0
Mill air flow rate; ACFM;lbs/hr	488;2,214	489;2,222	294;1,327	324;1,467	308;1,383
Mill inlet temperature; °F	96	95	99	96	101
Mill outlet temperature; °F	171	171	213	201	208
Burner inlet temperature; °F	165	166	179	177	179
Natural gas temperature; °F	89	89	92	87	93
Coal combustion efficiency; %	91.7	93.8	93.5	95.3	94.9
EMISSIONS					
O ₂ ; %	3.6	3.8	3.5	4.0	3.7
CO; ppm	1,121	536	260	132	277
CO ₂ ; %	15.8	15.3	15.4	15.1	15.3
SO ₂ ; ppm	426	291	400	368	442
NO _x ; ppm	529	554	618	651	671
ECONOMIC ANALYSIS DATA					
ID fan power consumption; Amperage	30.3	30.5	30.4	31.0	31.0
FD fan power consumption; Amperage	11.6	11.6	11.7	11.9	11.9
Pulverizer power consumption; Amperage	93	82	88	88	91
Booster fan power consumption; Amperage	10.3	10.8	5.4	5.5	5.5
Ash collection power consumption; Amperage	NM	NM	NM	NM	NM
Crusher power consumption; Amperage	NM	NM	NM	NM	NM
Redler conveyor power consumption; Amperage	NM	NM	NM	NM	NM
Feed screw power consumption; Amperage	1.8	1.8	1.8	1.8	1.8
Feedwater pump power consumption; Amperage	17.7	18.3	17.8	17.9	17.1
Total air usage; scfm (Pilot burner)	28	29	28	28	28
Maximum load ; %	78.4	77.0	81.0	81.8	84.9

Table 3-3. Summary of Results for Dry, Micronized Coal-Fired Testing

Summary Sheet

TEST/DESCRIPTION:	5-Aug 18 Coal only	10-Aug 19 Coal Only	11-Aug 20 Coal Only	25-Aug 21 Coal Only	30-Aug 22 w/o gun
WATER/STEAM SIDE					
Steam flow rate; lb/h	9,686	11,993	13,097	11,526	12,016
Water temperature into boiler; °F	117	220	215	217	218
Drum pressure; psig	209	206	207	211	212
Calorimeter temperature; °F	304	306	306	208	208
Steam temperature; °F	382	382	383	383	386
Steam quality; %	99.49	99.61	99.61	93.99	93.98
Blowdown rate; lb/h	3,170	3,145	3,149	3,187	3,190
AIR,FUEL, FLUE GAS SIDE					
Natural gas flow rate; lb/h;MMBtu/h	0;0	0;0	0;0	0;0	0;0
Coal flow rate; lb/h,MMBtu/h	1,170	1,166	1,165	1,135	1,134
Air temperature entering air heater; °F	98	128	128	144	158
Air temperature leaving air heater; °F	403	414	411	419	415
Air temperature into boiler; °F	375	382	385	386	384
Furnace outlet temperature; °F	572	142	159	570	554
Gas temperature leaving air heater; °F	368	382	387	381	382
Bagfilter inlet temperature; °F	364	376	380	374	378
Bagfilter outlet temperature; °F	326	335	339	331	337
Combustion air flow; lb/h	15,196	14,344	13,908	14,001	13,468
Boiler draft; in H ₂ O	0.00	-0.01	0.01	0.02	0.02
Boiler efficiency; %	83.7	83.2	82.7	81.2	82.6
Mill air flow rate; ACFM;lbs/hr	311;1,409	303;1,389	283;1432	343;1569	327;1494
Mill inlet temperature; °F	97	90	95	90	91
Mill outlet temperature; °F	205	195	210	212	204
Burner inlet temperature; °F	175	172	182	178	173
Natural gas temperature; °F	74	83	81	81	79
Coal combustion efficiency; %	94.6	94.2	93.8	91.9	93.2
EMISSIONS					
O ₂ ; %	4.7	3.6	3.3	3.8	3.1
CO; ppm	165	509	496	473	439
CO ₂ ; %	14.6	15.5	15.8	15.1	16.4
SO ₂ ; ppm	535	376	401	322	-247
NO _x ; ppm	610	583	665	494	507
ECONOMIC ANALYSIS DATA					
ID fan power consumption; Amperage	30.5	30.6	31.8	29.9	30.3
FD fan power consumption; Amperage	12.0	12.0	12.09	11.46	11.6
Pulverizer power consumption; Amperage	87	95	103	83	91
Booster fan power consumption; Amperage	5.2	5.4	5.4	5.8	5.3
Ash collection power consumption; Amperage	NM	NM	NM	NM	NM
Crusher power consumption; Amperage	NM	NM	NM	NM	NM
Redler conveyor power consumption; Amperage	NM	NM	NM	NM	NM
Feed screw power consumption; Amperage	1.8	1.8	1.8	1.8	1.8
Feedwater pump power consumption; Amperage	18.5	19.3	17.5	16.7	17.4
Total air usage; scfm (Pilot burner)	28	22	28	27	27
Maximum load ; %	65.0	80.5	87.9	77.4	80.6

Summary Sheet

TEST/DESCRIPTION:	30-Aug 23 w/ gun	31-Aug 24 w/ gun	31-Aug 25 w/o gun	2-Sep 26 Coal Only
WATER/STEAM SIDE				
Steam flow rate; lb/h	11,439	11,462	11,271	11,600
Water temperature into boiler; °F	218	196	164	189
Drum pressure; psig	211	213	212	212
Calorimeter temperature; °F	211	215	230	203
Steam temperature; °F	385	385	385	384
Steam quality; %	94.17	94.41	95.27	93.73
Blowdown rate; lb/h	3,180	3,196	3,191	3,192
AIR,FUEL, FLUE GAS SIDE				
Natural gas flow rate; lb/h;MMBtu/h	0;0	0;0	0;0	0;0
Coal flow rate; lb/h,MMBtu/h	1,134	1,134	1,134	1,132
Air temperature entering air heater; °F	171	167	166	160
Air temperature leaving air heater; °F	420	420	426	417
Air temperature into boiler; °F	393	391	401	386
Furnace outlet temperature; °F	559	559	578	555
Gas temperature leaving air heater; °F	381	382	392	380
Bagfilter inlet temperature; °F	376	376	385	378
Bagfilter outlet temperature; °F	332	331	341	334
Combustion air flow; lb/h	13,790	13,860	13,894	13,005
Boiler draft; in H ₂ O	-0.03	-0.02	-0.03	0.05
Boiler efficiency; %	80.3	80.6	83.1	82.4
Mill air flow rate; ACFM;lbs/hr	333;1505	333;1517	333;1518	289;1316
Mill inlet temperature; °F	98	93	94	93
Mill outlet temperature; °F	208	203	204	217
Burner inlet temperature; °F	180	171	176	177
Natural gas temperature; °F	85	81	85	71
Coal combustion efficiency; %	90.2	90.4	93.8	92.7
EMISSIONS				
O ₂ ; %	3.5	3.4	3.5	2.7
CO; ppm	332	462	234	420
CO ₂ ; %	15.9	16.2	16.2	17.1
SO ₂ ; ppm	-247	-246	-246	-245
NO _x ; ppm	427	416	544	639
ECONOMIC ANALYSIS DATA				
ID fan power consumption; Amperage	29.4	30.0	30.0	30.0
FD fan power consumption; Amperage	11.5	11.4	11.5	11.3
Pulverizer power consumption; Amperage	87	89	85	92
Booster fan power consumption; Amperage	5.3	5.3	5.3	5.3
Ash collection power consumption; Amperage	NM	NM	NM	NM
Crusher power consumption; Amperage	NM	NM	NM	NM
Redler conveyor power consumption; Amperage	NM	NM	NM	NM
Feed screw power consumption; Amperage	1.8	1.8	1.8	1.8
Feedwater pump power consumption; Amperage	17.1	17.5	17.5	20.5
Total air usage; scfm (Pilot burner)	27	26	27	40
Maximum load ; %	76.8	76.9	75.6	77.9

primary objectives during the micronized coal testing were to increase coal combustion efficiency and to determine the cause for excessive CO formation and fluctuations.

The average coal combustion efficiencies (for 26 tests), when firing 100% coal, ranged from ~91 to 95%. The average CO concentration is not reported for many of the tests in Table 3-3 because the CO concentration fluctuated significantly and was off the scale of the data acquisition system ($>2,000$ ppm) and hence, the averages are skewed low. This extreme fluctuating can be seen in the figures contained in Appendix B which are plots of the CO and O₂ concentrations as a function of time for the tests conducted from July 13, 1994 to September 2, 1994. In an attempt to increase combustion efficiency and reduce the CO concentration, the quantity of secondary and tertiary air and their degree of swirl were varied, a burner ramp was installed, and air was introduced into the center of the burner. In addition, test data was provided to EER for support in determining the cause of the excessive CO emissions. Work is in progress to determine the cause of the CO fluctuations and to increase the coal combustion efficiency.

Furnace and Convective Pass Deposition

A concern when firing coal in a boiler designed for fuel oil is the effect of the inorganic portion of the coal on deposition and erosion. This section describes the effect of deposition while erosion is addressed in a subsequent section. A summary of convective pass soot blowing that was done during this reporting period is contained in Table 3-4. Table 3-4 gives the boiler outlet, baghouse inlet, and baghouse outlet temperatures prior to, during, and after soot blowing. Each soot blowing event is given by date and time as well as the coal usage since the last soot blowing event occurred.

The boiler outlet and baghouse inlet temperatures were monitored and the convective pass steam sootblower was operated when the boiler outlet temperature was ~600°F. The baghouse inlet temperature would approach 400°F as the boiler outlet temperature reached 600°F and this is the upper limit set for comfortable operation.

Figure 3-11 is a plot of boiler outlet temperature history for a day of operation. Figure 3-11 is a plot of boiler outlet temperature as a function of data acquisition data point (time) and shows when coal feed was started (time 50), the period of cofiring coal and natural gas where the total firing rate was held constant and the coal feed was increased as the natural gas was decreased (approximately the next 100 data points), the switch to 100% coal (approximately time 175), four convective pass and furnace floor blowdowns, and the termination of the test (approximately time 800). Similar plots are contained in Appendix B for each day of operation.

Plots such as Figure 3-11 illustrate the time/temperature history of the boiler outlet temperature but do not give a quantitative indication of the severity of deposition. The data in Table 3-4 are presented graphically in Figure 3-12 to show the extent of deposition that was experienced.

Table 3-4. Summary of Sootblowing Frequency

Soot Blowdown		Temp Prior to Blowdown			Temp during Blowdown			Temp Following Blowdown			coal use since Last soot blow- down (lbs)	Other Blowdowns	
Date	Time	B.O.	BH In	BH Out	B.O.	BH In	BH Out	B.O.	BH In	BH Out		Pneumatic*	Floor**
13-Jul	15:00	620	372	325	511	350	320	535	325	296	2,767	07:10	
14-Jul	12:00	611	399	349	561	393	346	570	370	341	4,300	12:00	
15-Jul	14:30	602	401	352	548	372	344	540	380	343	5,645	14:30	
18-Jul	18:40	613	374	330	546	299	295	562	312	305	7,746	18:40	
19-Jul	06:49	535	304	220	527	310	240	535	325	260	950	06:49	
19-Jul	16:07	598	367	324	535	346	310	560	350	315	10,404	16:07	
20-Jul	07:00	430	258	202	507	263	206	536	284	215	3,361	07:00	
21-Jul	07:05	458	263	185	523	276	195	540	288	208	2,067	07:05	
21-Jul	16:50	561	334	292	528	332	292	541	331	293	7,532	16:50	
27-Jul	18:30	589	358	320	541	353	319	557	350	317	2,854	18:30	
28-Jul	07:00	545	314	242	516	320	251	534	325	260	1,761	07:00	
28-Jul	13:20	612	372	337	538	366	333	545	364	330	5,557	13:20	
28-Jul	15:05	605	385	344	552	380	340	563	338	338	2,348	15:05	
28-Jul	16:50	599	380	343	550	375	338	562	375	336	2,055	16:50	
28-Jul	18:35	601	384	342	552	381	340	567	382	338	2,055	18:35	
29-Jul	07:00	582	348	269	531	359	287	550	364	300	1,761	07:00	
29-Jul	10:00	602	381	339	554	372	334	564	370	331	1,982	10:00	
29-Jul	12:00	600	380	342	507	367	335	552	370	332	2,348	12:00	
29-Jul	13:00	608	382	346	542	379	340	551	381	339	1,174	13:00	
29-Jul	14:00	600	386	349	541	380	344	562	382	342	2,153	14:00	
29-Jul	16:45	599	386	347	554	383	343	568	383	341	2,251	16:45	
29-Jul	18:30	600	386	346	558	382	342	568	382	339	2,055	18:30	
29-Jul	21:00	NO RECORDED DATA									1,859	21:00	
1-Aug	07:25	403	385	325	389	383	328	387	386	332	245	07:25	
1-Aug	09:25	593	378	335	540	375	334	563	375	335	1,912	09:25	
1-Aug	11:05	591	379	343	544	378	340	569	379	339	1,761	11:05	
1-Aug	13:05	595	380	346	544	378	343	566	379	341	2,348	13:05	
1-Aug	14:15	589	378	345	518	374	339	556	375	339	1,370	14:15	
1-Aug	16:20	584	365	332	547	305	315	542	300	312	1,487	16:20	
3-Aug	11:50	600	378	341	544	373	338	554	373	337	2,993	11:50	
3-Aug	13:40	597	377	345	517	371	341	554	370	337	2,069	13:40	
3-Aug	16:10	591	375	341	532	369	336	553	368	333	2,822	16:10	
3-Aug	18:40	597	375	341	537	371	337	558	371	336	2,822	18:40	

Table 3-4. Summary of Sootblowing Frequency

Soot Blowdown		Temp Prior to Blowdown			Temp during Blowdown			Temp Following Blowdown			coal use since Last soot blow- down (lbs)	Other Blowdowns	
Date	Time	B.O.	BH In	BH Out	B.O.	BH In	BH Out	B.O.	BH In	BH Out		Pneumatic*	Floor**
3-Aug	20:50	576	365	320	535	367	324	486	347	323	1,561	20:50	
4-Aug	09:30	582	370	332	538	371	331	564	372	332	Not Recorded	09:30	
4-Aug	13:30	598	378	340	541	373	338	566	373	336	6,168	13:30	
4-Aug	16:00	592	373	336	540	370	332	559	370	331	2,822	16:00	
4-Aug	18:45	596	376	337	521	369	33	552	368	331	3,010	18:45	
4-Aug	20:45	NO RECORDED DATA									1,561	20:45	
5-Aug	14:15	602	381	340	540	374	337	572	362	331	2,440	14:15	
5-Aug	17:03	580	353	313	528	345	312	472	296	299	2,301	17:03	
8-Aug	17:24	***	374	314	***	367	322	***	360	322	4,126	17:24	
10-Aug	15:15	***	376	340	***	369	333	***	369	333	2,754	15:15	
10-Aug	17:15	***	368	325	***	373	327	***	356	327	1,593	17:15	
11-Aug	09:35	***	389	337	***	375	336	***	370	332	2,131	09:35	
11-Aug	11:35	***	385	338	***	376	337	***	379	336	2,330	11:35	
11-Aug	12:45	***	388	341	***	379	340	***	379	338	1,359	12:45	
11-Aug	13:55	***	382	341	***	374	340	***	374	339	1,359	13:55	
11-Aug	15:10	***	384	342	***	379	340	***	379	339	1,457	15:10	
11-Aug	16:45	***	386	343	***	377	340	***	376	337	1,845	16:45	
11-Aug	18:10	***	384	339	***	375	338	***	371	336	1,651	18:10	
25-Aug	16:05	615	402	348	550	382	345	554	376	340	6,078	16:05	
25-Aug	17:36	590	384	348	535	382	345	563	384	346	1,236	17:36	
25-Aug	19:15	586	393	352	520	381	348	555	380	343	1,783	19:15	
30-Aug	10:06	582	389	334	504	375	335	525	370	332	3,549	10:06	
30-Aug	12:04	571	388	343	504	376	342	543	374	338	2,268	12:04	
30-Aug	14:30	574	392	347	514	377	343	539	373	339	2,835	14:30	
31-Aug	07:15	591	364	293	581	386	335	595	395	346	6,256	07:15	
31-Aug	12:40	508	365	302	504	371	333	520	380	342	5,012	12:40	
31-Aug	15:40	541	371	311	532	368	329	555	376	338	3,402	15:40	
1-Sep	10:18	565	364	295	520	360	306	537	361	311	3,875	10:18	
2-Sep	10:50	588	388	338	520	373	334	542	370	331	5,560	10:50	
2-Sep	12:25	578	388	339	531	379	338	548	378	336	1,792	12:25	

*Pneumatic blowdown is sootblowing of the heat-pipe heat exchanger

**Floor blowdown is blowdown of the furnace floor

***Data acquisition system turned off

Figure 3-11. Example of Boiler Outlet Temperature (°F) vs Time for Micronized Coal Testing on 8/04/94

Figure 3-12 is a plot of coal consumed since the last soot blowdown when using the Brookville seam coal. It must be noted that soot blowing routinely occurred at the beginning and end of most days and was not strictly a function of boiler outlet temperature. Noting this, between 2,000 and 3,000 lb of coal were consumed between sootblowing events. This is similar to testing that occurred prior to the installation of the EER burner during which a burner test program was conducted in the boiler firing micronized coal using an ABB Combustion Engineering Systems' burner in another DOE-funded program (DE-AC22-91PC91160)^[7].

During the ABB CE burner demonstration, testing was stopped because a significant quantity of ash was building up on the floor and walls of the furnace which had to be removed. As a consequence of this buildup, a manufacturer of commercial soot blowing systems was approached for options to keep the ash entrained. Their recommendation of retractable soot blowers was not adopted and Penn State designed a floor blast system. A schematic diagram of a prototype system is shown in Figure 3-13. The system consists of two pipes that are located on the furnace floor with a series of holes directed towards the furnace floor. A small quantity of air is constantly passed through the pipe to keep it cool. Whenever the sootblower in the convective pass is operated, the floor is also blown down. Several variations of the system have been tried where the hole size, height of the pipes above the floor, and the compressed air impact area on the floor has been varied. Preliminary results are encouraging; the ash has been entrained and the boiler has not been shut down due to excessive build up. The initial prototypes were constructed out of carbon steel (to use an inexpensive material of construction) while determining optimum design and operating conditions. Further evaluation of the system is ongoing.

Evaluate Erosion-Corrosion and Deposition Characteristics

Recent work is an expansion of a study that was conducted in a previous DOE program (DE-FC22-89PC88697) in which a coal-water fuel was fired in the demonstration boiler. During the recent micronized coal testing in the boiler, erosion of tube material by ash and unburned carbon was measured in the convective section. The changes in erosion rate with temperature and oxygen concentration were compared with the values calculated by the erosion-oxidation model. The gas velocity dependence of erosion was predicted for a practical set of micronized coal combustion and convection section conditions.

Experimental

The measurements were made in the convective section of the demonstration boiler after retrofitting it to fire micronized coal. Particles collected in the baghouse consisted of 37 wt% ash and 63 wt% unburned carbon. The apparent density of the particles was 835 kg/m³, determined from their settled volume, assuming a voidage of 0.42^[8]. The volume-based mean size of the baghouse catch was 43 μm .

Boiler Cleaned on July 12 and furnace air blast system was installed

Figure 3-12. QUANTITY OF COAL CONSUMED SINCE LAST CONVECTIVE PASS SOOT BLOWING WHEN OPERATING FROM 07/13/94 TO 09/02/94

Figure 3-13. FURNACE ASH BLOWDOWN SYSTEM

The probe was placed in a cavity in the convection section intended for a small superheater. The conditions of the combustion products at this location were: the flue gas temperature 890 K, convective section gas velocity 3.1 m/s, and particle concentration 3.0 g/m³. Details of the construction of the probe may be found in a separate publication^[9]. Erosion was accelerated under the inference of a high velocity jet oriented with its axis parallel to the flue gas flow and perpendicular to the surface of a carbon steel sample. The initial average gas velocity at the orifice was 200 m/s. The jet entrains surrounding particles, and accelerates them toward the surface.

Each sample was exposed to the effects of the jet and particles for 2 hours. After a test, the shape of the surface of the sample was measured using a profilometer and the erosion craters and surface structure were examined using a scanning electron microscope. Conditions which were varied during the tests were metal temperatures (450, 550, and 650 K) and jet gases (nitrogen, 3 vol% O₂ in N₂, and air). Some oxygen was present as an impurity in the nitrogen gas, at a typical level of 3 ppm.

The maximum erosion depths in each surface profile were converted to time-averaged rates, assuming constant rate of material loss over the 2 hour exposure period. The averages of these maximum rates, with estimates of their uncertainties, are listed in Table 3-5. The results show that: in the nitrogen jet, the erosion rate increased with increasing metal temperature; in the presence of 3 vol% O₂ in N₂ as the jet gas, the erosion rate first increased, then decreased with increasing metal temperature; and under the air jet erosion was slow at all three metal temperatures.

Model

A model was developed to relate the accelerated measurements to erosion expected in a boiler over longer periods of time, under normal operating conditions. In order to extract meaningful quantitative information from the measurements under the accelerating jet, two separate processes were modeled: the first is the behavior of the particles in the jet; and the second is the erosion-oxidation of the target^[10, 11].

Particle Trajectories

The gas flow in the accelerating jet is initially moving in the same direction as the surrounding flue gas and particles. The jet impinges on the flat surface of the specimen and flows away radially in all directions. It was assumed that particles cross the boundary of the jet with velocity equal to the mean velocity of flue gas, and that the particle flux on arrival at the jet boundary is the same as that in the free stream. Influences of the entrained particles on the gas flow in the jet were neglected.

The motion of the particles was described by subjecting them to the mean and fluctuating components of the gas velocity, assuming that the fluctuating components were normally distributed in both axial and radial directions with standard deviations proportional to the mean

Table 3-5. Experimental Conditions ^a and Average Maximum Erosion Rates.

Average Erosion Rates ^b ± Uncertainty (μm/hour)	Metal Temperature, K (°F)		
	450 (350)	550 (530)	650 (710)
Jet Gas, vol % O ₂ in N ₂			
< 0.1 ^c	0.70 ± 0.10	2.10 ^d ± 0.10	2.90 ^d ± 0.10
3	0.70 ± 0.10	1.30 ± 0.10	0.80 ± 0.20
21	0.65 ± 0.15	0.85 ± 0.15	0.80 ^d ± 0.10

^aInitial jet velocity at the orifice was 200 m/s; exposure time was 2 hours.

^bThe rate was averaged over the 2 hour exposure period using the maximum depths of the erosion crater on the right and left sides of the jet axis.

^cA typical value of 3 vol ppm O₂ as impurity was the supplier's specification.

^dCoal firing rate dropped to 13.3 MMBtu/h; the rate in all other cases was 15.0 MMBtu/h.

velocity components^[12]. A second-order Runge-Kutta scheme was used to solve the equations of motion^[13], using time steps on the order of 10^{-6} s. About 2,700 trajectories were calculated for each particle size and experimental condition. Integration of the energy distributions over particle size gives the radial distribution of energy delivered to the surface by all particles.

Erosion-Oxidation

The system under consideration is a carbon steel surface undergoing simultaneous erosion and oxidation. Oxide and metal are removed in series, their proportions depending upon the rate of oxidation of iron to oxide scale. A model for erosion-oxidation was proposed with the following features: 1. Metal exhibits ductile erosion at a rate which increases with temperature. 2. Oxide behaves as a brittle material, having an erosion rate independent of temperature. 3. Oxide and metal are eroded from the surface in series. 4. Oxide is strongly attached to the metal. 5. Oxide forms according to the parabolic rate law, at a rate increasing with the oxygen partial pressure. 6. Interference from particles sticking to the surface is incorporated in the erosion rate coefficients. The rate coefficient for growth of oxide scale was obtained by fitting, to the model, the experimental measurements of others^[14-17] for iron oxidation at temperatures in the range from 673 to 873 K, in the presence of 1 atm oxygen, as shown in Figure 3-14. Magnetite was assumed to be the major component of the scale, in the conversion of oxide weight per unit area to thickness. The rate constant was further assumed to be proportional to the a th power of oxygen partial pressure, $P_{O_2}^a$, where the value of a is an adjustable parameter to be determined.

The model parameters were determined using the erosion depth and properties of particles colliding with the target at a distance of 2 mm from the jet axis: the ratio of the integrated energy of impaction to the initial energy of particles suspended in the flue gas was 21; the average impaction angle, weighted according to the size distribution and collision efficiency, was 81° ; the mean size of the impacting particles was $51\text{ }\mu\text{m}$, and their impaction efficiency was 0.59. The collision frequency based on the mean size of impacting particles was $95 \times 10^6\text{ Hz/m}^2$. The area of oxide removed by a single impact, which was adjusted to fit the data, was 25 times the cross section area of the mean size of particles. This value for the area, which gave the best fit to the data, is quite sensitive to the value chosen for the metal oxidation rate coefficient. The time interval between impacts removing the scale from an area of 25 times the particle cross section area, was 0.12 s. The effect of particle erosivity was incorporated in the erosion rate coefficient: the rate coefficient for metal erosion was adjusted to fit the measurement in the nitrogen jet at the lowest temperature (450 K); and the rate coefficient for oxide erosion was adjusted to fit the measurement in the air jet at the highest temperature (650 K). As shown in Figure 3-15a, the erosion of carbon steel in the presence of the nitrogen jet increased with increasing metal temperature. In the presence of the air

Figure 3-14. THE RATE COEFFICIENT FOR GROWTH OF OXIDE SCALE WAS OBTAINED BY FITTING THE EXPERIMENTAL MEASUREMENTS OF DAVIES et al. [11], SCHMAHL et al. [64], CAPLAN AND COHEN [5], AND JANSSON AND VANNERBERG [27] FOR IRON OXIDATION AT TEMPERATURES IN THE RANGE FROM 673 TO 873 K, IN THE PRESENCE OF 1 ATM OXYGEN

Figure 3-15. MEASURED (open circles) AND CALCULATED (lines) EROSION RATES OF CARBON STEEL AS FUNCTIONS OF TEMPERATURE AND THE JET GAS OXYGEN CONTENT. The metal erosion rate coefficient was adjusted to fit the measurements in the nitrogen jet at the lowest temperature 450 K. The oxide erosion rate coefficient was adjusted to fit the measurements in the air jet at the highest temperature 650 K. Three exponents ($a=1.0, 0.5, 0.25$) of oxygen partial pressure were used in the calculations.

jet, erosion was less dependent of temperature, as shown in Figure 3-15c. All the curves for different volume fractions of oxygen, from 3 ppm to 21%, were calculated using the erosion rate coefficients determined from the nitrogen and air jets. Three different exponents ($a = 0.25, 0.5$, and 1) of the oxygen partial pressure were used to determine the oxygen pressure dependence in the oxidation rate constant.

Results and Discussion

The characteristic dependence of erosion on temperature shown by the calculations in Figures 3-15a to 3-15c arises from the model as follows. At the low end of the temperature range, the oxidation rate of carbon steel is slow, the oxide layer is very thin, the erosion behavior is that of bare metal, and the erosion rate therefore increases with increasing temperature. Because the oxidation rate is so slow, oxygen partial pressure has little effect on the steady oxide thickness or erosion rate, as shown by comparison of the measurements at 450 K in nitrogen, 3% oxygen, and air in Figures 3-15a to 3-15c.

As temperature is increased, the oxidation rate increases, with a corresponding increase in the steady thickness of oxide scale. When the temperature and oxygen pressure are sufficiently high, oxide begins to make a significant contribution to eroded volume. Over most of the temperature range investigated, the oxide is more resistant to erosion than metal, therefore, as the contribution of oxide to eroded volume increases, with increasing temperature and/or oxygen partial pressure, the erosion rate declines.

When the oxidation rate is sufficiently high, and the scale thick enough that erosion is confined to the oxide layer, the erosion rate becomes that characteristic of pure oxide, independent of temperature. This is the situation under the most oxidizing conditions, on the right hand side of Figures 3-15b and 3-15c. As shown by the calculations for different volume fractions of oxygen, decreasing the exponent of oxygen partial pressure dependence in the oxidation rate constant shifts the transition from metal to oxide erosion regimes toward lower temperature. The observed erosion rate suggests the square root dependence of oxidation on oxygen partial pressure.

Using the experimentally determined values for the erosion rate coefficients and the oxidation rate constant which fit the measurements, the erosion-oxidation loss was calculated for a tube of diameter 51 mm at temperature of 550 K. The typical conditions in the convective section of the boiler during pulverized coal combustion are: gas temperature 890 K, excess oxygen 3.4 vol%, particle loading 3.0 g/m^3 , particle density 835 kg/m^3 , and particle size of $43 \text{ }\mu\text{m}$. The impaction efficiency on the tube was obtained using the correlations of Israel and Rosner^[18], as described by Walsh and Serafini^[19]. Ductile erosion of metal and brittle erosion of oxide are expected to be most rapid at impaction angles of 30° and 90° , respectively. Their erosion rates as a function of convection section gas velocity are shown in Figures 3-16 and 3-17.

Figure 3-16. ESTIMATE OF THE EROSION RATE OF CARBON STEEL BY FLY ASH AND UNBURNED CHAR FROM MICRONIZED COAL COMBUSTION UNDER THE FOLLOWING CONDITIONS: GAS TEMPERATURE 890 K, EXCESS OXYGEN 3.4 VOL%, METAL TEMPERATURE 550 K, TUBE DIAMETER 51 mm, PARTICLE LOADING 3.0 g/m^3 , PARTICLE DENSITY 835 kg/m^3 , PARTICLE SIZE $43 \mu\text{m}$, AND IMPACTION ANGLE 30° .

Figure 3-17. ESTIMATE OF THE EROSION RATE OF CARBON STEEL BY FLY ASH AND UNBURNED CHAR FROM MICRONIZED COAL COMBUSTION UNDER THE FOLLOWING CONDITIONS: GAS TEMPERATURE 890 K, EXCESS OXYGEN 3.4 VOL%, METAL TEMPERATURE 550 K, TUBE DIAMETER 51 mm, PARTICLE LOADING 3.0 g/m^3 , PARTICLE DENSITY 835 kg/m^3 , PARTICLE SIZE $43 \mu\text{m}$, AND IMPACTION ANGLE 90° .

At low velocity the erosion rate is low, and erosion occurs only from oxide layer. Increasing the gas velocity increases the rate of oxide removal and decreases the steady thickness of the scale. At a critical velocity, the oxide layer becomes thin enough that erosion removes both oxide and metal, and the rate begins to increase markedly. The critical velocity is 25 m/s at an impaction angle of 30°, but this value decreases to 16 m/s for impaction at 90°.

In practical coal-fired utility units, a tube thickness loss of 0.05 $\mu\text{m}/\text{hour}$ is recommended as the maximum acceptable rate^[20], representing 5 mm wastage in 100,000 hours of operation. Erosion on the upstream stagnation line of the tube, at an impaction angle of 90°, is expected to be less than this rate at flue gas velocities below approximately 10 m/s, under the conditions of metal temperature, particle size, particle composition, and particle loading investigated. According to the model, erosion at collision angles near 30° is below 0.05 $\mu\text{m}/\text{h}$ for gas velocities up to 15 m/s. A source of uncertainty in these estimates is the role that ash deposition might play in placing a protective layer of particles on the surface at low gas velocities. The gas velocity dependence of deposition is being examined.

Determine Erosion Characteristics of Materials Subjected to Atomized Coal-water mixture

Background/Introduction

Successful utilization of CWM requires satisfactory atomization of the fuel. In the demonstration boiler's atomizer, a high pressure air blast (< 200 psig.) shears the slurry stream into droplets. Although small in size, the large velocities and erosive-corrosive properties of the CWM result in rapid metal wastage of atomizer components.

In an attempt to learn more about the mechanisms responsible for atomizer failure and evaluate candidate materials for future atomizer construction, experiments have been designed to characterize both the erosive and corrosive properties of atomized CWM.

Experimental Design

Experiments will be conducted in a small test facility (Figure 3-18) designed to investigate the effects of impact angle and atomization air pressure on erosion-corrosion characteristics of MCWM. The body of the testing chamber is constructed of 1/2" thick 6061-T6 aluminum plate and measures 2' x 2' x 2'. Candidate materials will be machined to 1.5" x 0.75" x 0.125", fastened to a rotating stage, and fixed 0.75" from a small Delevan atomizer (Figure 3-19) located at the center of the spray chamber. A Delevan atomizer was selected because of its small size and low flow rates. MCWM will be stored in a 5 gallon tank, continuously agitated, and pumped to the atomizer using a 3/4 horsepower progressive cavity pump. House air (<100 psig) will be used as the atomizing medium.

While testing, MCWM will collect at the bottom of the testing facility and stray droplets will translate throughout the chamber in the form of mist. Mist collection will be accomplished using a

Figure 3-18. ATOMIZATION / EROSION TEST FACILITY WITH INSITEC'S PARTICLE COUNTER-SIZER-VELOCIMETER PROBE

Figure 3-19. SCHEMATIC DIAGRAM OF THE DELAVAN NOZZLE

1.5" pneumatic eductor. MCWM droplets will be transported out of the chamber via Tygon tubing and deposited in a collecting tank. MCWM collected at the bottom of the testing facility will be removed, periodically tested for coal particle comminution, and either discarded (if there is a change in mean particle size) or reused (no change).

Tests will be conducted on 416 stainless steel (presently used in the construction of the boiler's atomizer) and plain carbon steel. Results will be reported in the form of weight loss measurements and scanning electron micrographs.

Summary of Activities

Design and Construction of Erosion-Corrosion Testing Facility

The erosion-corrosion testing facility has been completed and is fully operational.

Coal Selection and Procurement

Cleaned and uncleaned coal from the Brookville Seam in Lawrence County, Pennsylvania will be the constituent coal in the MCWM used for erosion-corrosion testing. Five 30 gallon barrels of the uncleaned and three 55 gallon drums of the cleaned coal have been received and stored. Representative samples to be used in chemical analysis were obtained for both the cleaned and uncleaned coal in accordance with ASTM standards.

Complete chemical characterization of the coal is to be conducted and consists of the following a) proximate analysis b) carbon, hydrogen, and nitrogen (CHN) analysis c) sulfur analysis d) calorific value determination and e) chlorine analysis. Presently a full proximate analysis has been performed on both coals and a CHN analysis of the uncleaned coal has been completed. The results are given in Table 3-6.

Coal Water Slurry Production and Analysis

The MCWM formulation for Brookville coal has been determined previously and is given in Table 3-7. Approximately 3 gallons of MCWM (60 % solids, pH = 9) was produced in a 14" ball mill to confirm the slurry formulation and analyze the particle size distribution. Analysis using a Malvern particle sizer was conducted showing a $D_{[v,0.5]} \approx 19.0 \mu\text{m}$, a $D_{[v,0.9]} \approx 58 \mu\text{m}$, and a $D_{[3,2]} \approx 7.0 \mu\text{m}$. Complete analysis of the fuel produced for erosion-corrosion testing will consist of particle size analysis, viscosity measurements, and chemical characterization.

Spray Characterization

Spray characterization is presently being conducted in the erosion-corrosion testing chamber using the Insitec Particle Counter-Sizer-Velocimeter (PCSV-P) laser light scattering probe.

Preliminary tests were conducted with atomized water and revealed some analytical difficulties due to the vicinity of the probe to the nozzle orifice (1.5"). The short distance the droplets traversed did not allow for spray dispersion which prevented adequate laser light from reaching the optical receiver. Without a sufficient number of signals reaching the receiver droplet size and velocity determination is not possible.

Table 3-6. Results of Proximate and CHN Analysis for Brookville Seam Coals

	Brookville Uncleaned	Brookville Cleaned
Wt. % (dry basis)		
Volatile Matter	31.43	36.03
Ash	14.15	3.03
Fixed Carbon	54.42	60.94
Carbon	71.10	NA
Hydrogen	4.57	NA
Nitrogen	1.27	NA

Table 3-7. CWSF Formulation for Brookville Seam Coal^a (as of 7/14/92)

Solids Loading (wt %)	66.8
Additives	
Dispersant, wt % (A-23M)	0.7
Stabilizer, wt % (4800C)	0.04
pH modifier (NH ₄ OH)	yes
pH range	9.0 - 9.3

^a All amounts are calculated on a dry coal basis.

The problem was partially solved by machining a small brass cylinder and fixing it to the laser beam housing on the transmitter side of the sample volume (Figure 3-20). The cylinder shielded the laser beams for half of the length of the sample volume effectively preventing premature obstruction of the laser. The number of scattered signals received was increased dramatically enabling the successful spray characterization of numerous operational parameters.

Spray analysis of water was completed for the range of attainable flow rates (< 10 lb/h - 70 lb/h) using 6 psig atomization air pressure (anything greater produced a mist that was too dense to measure accurately). The results indicate that as flow rate increases both the $D_{3,2}$ (Saunter mean diameter) and the percent oversize (percent droplets larger than the detection range) also increase. Droplet velocity remained almost independent of the range of flow rates tested at ≈ 10 m/s decreasing only slightly to ≈ 9 m/s as flow rate increased to a maximum of 70 lb/h.

Upon completion of water spray characterization an attempt was made to analyze atomized MCWM ($\approx 60\%$ solids, $D_{[v, 0.5]} \approx 11.0 \mu\text{m}$, constituent coal unknown). For the first test a flow rate of < 20 lb/hr was chosen together with an atomization air pressure of 12 psig (the minimum pressure achieved for the MCWM tested). Moments after the test was started, slurry collected on the brass shield and the optical housing fouling the laser optics and ending the test.

It is thought that the high viscosity of MCWM aided in the rapid collection of fuel on the probe optics. In an attempt to characterize the spray of a lower viscosity slurry, 500 ml. of MCWM was diluted with one gallon of water and atomized. A measurement was successfully made at a flow rate of < 20 lb/hr and 6 psig atomization air. Based on the success of the dilution test a number of slurries possessing different solids loading will be prepared using cleaned Brookville coal. Each fuel will then be pumped to the erosion-corrosion test facility and atomized. Spray characterization will be attempted at numerous flow rates and air pressures in an attempt to define the limits of MCWM characterization using the PCSV probe.

Test Material Procurement and Preparation

Two steels, plain carbon and 416 stainless, will be tested for erosion-corrosion resistance. Both were obtained during this reporting period in bulk form and are presently being machined to the design dimensions of $1.5'' \times 0.75'' \times 0.125''$. Chemical compositions of each and the distributor from which the steel was purchased are shown in Table 3-8.

Prior to erosion-corrosion testing the steel samples will be polished down to $0.3 \mu\text{m}$ and then chemically etched. At this time three of the carbon steel coupons have been polished and will be used for metallographic characterization (grain size and EDAX analysis).

Figure 3-20. SCHEMATIC DIAGRAM OF THE INSITEC PARTICLE COUNTER-SIZER-VELOCIMETER PROBE WITH LASER SHIELD

Table 3-8. Steel Chemical Composition (wt. %)

Type 416 Stainless Steel (ASTM A582-88 Type 416 Cond. A)^a

C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.10	0.36	0.58	0.016	0.30	13.17	0.21	0.03	0.03

ASTM A569 Carbon Steel^b

C	Mn	Si	P	S
0.11	0.33	0.23	0.028	0.044

^a Purchased from Carpenter Technology Corporation, Reading, Pa.

^b Purchased from Consolidated Steel Corporation, Cresson, Pa.

Computer Modeling of the Swirling Turbulent Diffusion Jet of Air and Coal in the Demonstration Boiler

Introduction

The objective of this aspect of the program is to model the combustion chamber of the demonstration boiler in order to fully understand the particle and gas behavior during coal combustion. The first step was to identify a code that could either be used in its present form or one that could be easily modified. A review of commercially available Computational Fluid Dynamics (CFD) codes was carried out based on a number of guidelines which the code had to satisfy. These were: 1) It must be convenient to define and change both the geometry and the simulated operating conditions; 2) The governing equations which are solved must correctly represent the physical and chemical processes which take place in the practical system; and 3) The results must be communicated in an easily assimilated form^[21].

A number of the commercially available CFD codes were investigated: PCGC-2 (Brigham Young University, U.T.), FLOW 3D (Flow Science, N.M.), FLUENT (FLUENT Inc., N.H.), NEKTON (FLUENT Inc., N.H.), SIMPLE (Imperial College, U.K.), and FLOTRAN (Swanson Analysis Systems Inc., P.A.). Based on the aforementioned guidelines, FLUENT was chosen for performing the CFD. FLUENT's capabilities to model solid fuel combustion are inadequate; however, it has excellent aerodynamic codes and offers strong capabilities to model different geometries compared to the other numerical modeling codes that were reviewed. Therefore, FLUENT should offer more flexibility in modeling coal combustion in the boiler.

The next step involved surveying the physical and mathematical models used in the codes. The objectives were to identify the appropriate turbulent-swirling, coal-based flame models to incorporate into FLUENT and to compare and contrast the models in FLUENT with the ones employed in the other codes.

A mathematical model for the combustion processes in an industrial boiler should consist of:

1. a turbulent model for gas-particle two phase swirling recirculating flow;
2. a turbulent combustion model for pulverized coal in a swirled burner;
3. a radiation model for a fuel oil-based boiler.

Each one of these models is subsequently discussed and some of their shortcomings addressed.

1) Gas-Phase Fluid Mechanics

It has been encountered by Rhode^[22] that inaccuracies in detail will occur in predicting recirculation zones with the standard k - ϵ turbulent model (isotropic effective viscosity μ_t hypothesis), especially under swirl flow conditions^[23]. The main reason is that turbulent effective viscosity μ_t is anisotropic in swirling flowfields, especially in concentric jets.

Correction Methods:

Method 1: Adjust the turbulence model constants for C_μ (which incorporates the effect of the annular swirling jets and controls the circulation zone pattern).

Method 2: Correct the turbulence model using the Ri (Richardson) Number^[24, 25].

Method 3: Use the Reynolds Stress Model instead of two-equation k- ϵ model.

In this work, the Reynolds Stress Model has been used to simulate the strong swirling in the boiler.

2) Particle-Phase Mechanics

(1) Turbulent Diffusion of Particle Dispersion

A shortcoming of the present particle models^[26] is the absence of the numerical diffusion of the particle cloud. That is, the particle dispersion due to turbulence is neglected. There is a significant effect of turbulence on particle dispersion in the swirling, recirculating flowfield.

Correction Methods:

Method 1: Effective Diffusion Velocity (or Diffusion "force") Correction:

To use an effective diffusion velocity (or diffusion "force")^[27, 28] in the particle motion equation, which is dependent on the particle concentration gradient, Fick's law is used to describe the turbulent diffusion of the particle. The effective diffusion coefficient, given in the following equation, is not well characterized:

$$(D_{pt} = \mu_{pt} / \sigma_{pt})$$

where μ_{pt} is the turbulent particle kinematic viscosity and σ_{pt} is the turbulent particle Schmidt number ($\sigma_{pt} = 0.34 - 0.7$)^[29, 30].

Method 2: Stochastic Models

Stochastic models are based on stochastic simulation of particle motion, which include the Stochastic Particle Tracking method (SPT;^[31] the Monte-Carlo Method^[32], the Fluctuation-Spectrum-Random-Trajectory model (FSRT;^[33] and the Statistical Transport model (ST).

The SPT method simulates the turbulent gas flowfield as a steady flow plus a random velocity fluctuation. The velocity fluctuations of the gas phase are assumed to be isotropic with a Gaussian probability density distribution. In the FSRT model, the velocity fluctuations of the gas phase are modeled as a random Fourier series based on the fluctuating frequency and spectrum of turbulence, which considers that the turbulent movement of gas flow is a random superposition of three fluctuation elements (i.e. different frequency, amplitudes and directions). The ST model is based on coupling a stochastic direct-modeling approach for particle/eddy interaction with continuous probability density functions (pdf). This improves the computational efficiency and robustness of spray combustion CFD analyses.

In this work, the stochastic model is used to simulate the particle trajectory in the demonstration boiler.

(2) Particle Momentum Equation

Generally the drag coefficient (spherical particles in steady flow) is only a function of Re_p . In the boiler (non-spherical particle motion in the combination swirling jets):

$$C_D = f(Re, \phi, f_b, B_m) \quad [34-36]$$

where ϕ is a shape factor (for pulverized coal, $\phi=0.62-0.39$);
 f_b is the average frequency of fluctuating turbulence (for the swirling gas an average frequency of turbulent fluctuation is 400Hz and a relative amplitude is 20-30%); and
 B_m is the particle blowing parameter for mass transfer.

(3) Particle Velocity and Concentration Field

Because the PSI-CELL technique is based on calculating the particle trajectories in a Lagrangian fashion, the particle velocity is only one of the trajectories or paths of the particles. The real particle velocity and the concentration field must be calculated, which can be obtained by a volume-average method. The particle concentration, C_v , in a cell is

$$C_v = \sum_i \sum_j (n_{ij} \Delta \tau V_{pij}) / \Delta V$$

and the particle velocity in the cell can be obtained by the average of the momentum:

$$\vec{v}_p = \sum_i \sum_j (n_{ij} \Delta \tau \vec{v}_{pij}) / \sum_i \sum_j (n_{ij} \Delta \tau)$$

where n_{ij} is the number density of particle in each cell and V_{pij} is the volume of particles.

3) Transport of Preheated Secondary Air in the Burner

Differential equations were added to account for the transport of preheated secondary air in the burner. The mixture fraction, f , is defined as:

$$f = \frac{\dot{m}_p}{\dot{m}_p + \dot{m}_s}$$

where $\dot{m}_p$, and $\dot{m}_s$ are primary and secondary air mass rate, respectively.

4) Turbulent Diffusion and Fluctuation of Coal Off-Gas

In addition to the species equation, differential equations were added to account for the fuel mixture fraction, η , for the turbulent diffusion and fluctuation of coal off-gas. The definition of the fuel mixture fraction is similar to the mixture fraction.

5) Turbulence Combustion Model

The eddy-break-up (EBU) model is used for turbulent combustion of the coal off-gas, but the mixing constant in the EBU model will be adjusted based on experimental data.

6) Simplification of the Basic Conservation Equations

The simplification of the basic conservation equations is based on:

- Flame symmetry;
- Special zone characteristics in the furnace;
- PC flame types.

7) Correction of the Effect of Turbulent Fluctuations on Scalar Variables

Time-mean gas properties (i.e. species composition, density, and temperature) can be obtained for any values of f and η by convolution over a joint probability density function (PDF).

Having reviewed the available models in the literature, the next step was to evaluate how well the mathematical models that are incorporated in FLUENT can be utilized. The aerodynamic characteristics of strongly swirled coaxial jets was modeled to test the capabilities of the code. Both Internal Recirculation Zones and External Recirculation Zones were simulated in the region close to the exit of the burner nozzles, and the effects of varying the operating conditions were examined. The numerical convergence, stability and rationality of the code modifications were examined by calculation examples.

The Reynolds Stress Model was used to simulate the swirling flow from the burner near the quarl of the boiler, with the corrections including all of the inlet boundary conditions (tangential velocities, turbulent intensities and characteristic lengths etc.). These conditions are further discussed in the later stages of this report.

It was found that the main characteristics of the swirling flowfield near the burner region of the boiler can be simulated under different operating conditions. Having established the capabilities of the code in predicting the conditions in the near burner region it was decided to model the entire boiler.

The bulk of the numerical modeling studies carried out on the boiler were using 2-dimensional geometries. The purpose of modeling a 3-dimensional geometry in 2-dimensions was to save on the computational Central Processing Unit (CPU) time. In order to achieve 2-dimensional modeling of a 3-dimensional geometry, the following simplifying assumptions had to be made: 1) The swirling turbulent diffusion jets issued by the primary, secondary and tertiary air streams of the burner were approximated by turbulent diffusion jets (in other words, the tangential

velocities of these jets were neglected); and 2) A single plane located at the center of the boiler was chosen for the 2-dimensional geometry and it was assumed that the mean values of velocity and temperature were representative of the entire furnace.

A 3-dimensional model, by definition, eliminates the above assumptions. Therefore it has the potential to provide more accurate information and more realistic predicting capabilities. The only drawback of a 3-dimensional model, however, is the substantial increase in the CPU usage. This increase in the CPU time can be justified in terms of the benefits of a 3-dimensional geometry. The numerical modeling work discussed below includes analyzing swirl in a 3- dimensional geometry and a dispersed phase of coal particles.

Theory

In this analysis, the fundamental equations governing the fluid flow (the mass continuity equation, the energy equation and the Navier-Stokes equations) are solved employing FLUENT which uses a finite difference numerical procedure. The success of any CFD simulation depends upon the correct use of the code and acknowledgment of the code's capabilities and limitations. 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. The conservation equations used include:

Conservation of mass

$$\frac{\partial}{\partial x_i} (\rho u_i) = 0$$

Conservation of momentum

$$\frac{\partial}{\partial x_i} (\rho u_i u_j) + (\rho u_i)' = -\frac{\partial \delta_{ij}}{\partial x_i}$$

$$\delta_{ij} = p\gamma_{ij} - \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{2}{3}\mu\left(\frac{\partial u_i}{\partial x_j}\right)\gamma_{ij}$$

The process of Reynolds decomposition and time averaging results in unknown correlations of the fluctuating velocity components. Therefore, a turbulence model is also required. Employing the $k - \varepsilon$ model requires the solution of two additional transport equations, one for the kinetic energy of turbulence, k , and another for the dissipation rate of this energy, ε .

$k - \varepsilon$ Turbulence model

$$\frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu + \mu_t}{\delta_k} \right) \left(\frac{\partial k}{\partial x_i} \right) \right) + P - \rho \varepsilon$$

$$\frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu + \mu_t}{\delta_\varepsilon} \right) \left(\frac{\partial \varepsilon}{\partial x_i} \right) \right) + C_1 \frac{\varepsilon}{k} P - C_2 \rho \frac{\varepsilon^2}{k}$$

$$\mu_t = 0.09 \times \frac{\rho k^2}{\varepsilon}$$

Modeling coefficients take the values $C_1=1.44$, $C_2=1.92$, $\delta_k=1.0$, $\delta_\varepsilon=1.3$. The prediction of single phase reacting flows requires further transport equations for the time averaged species concentration and enthalpy. Turbulent diffusion is modeled by analogy with Fick's law. That is, the gradient diffusion assumption is used. This method is adopted by most research groups dealing with large 3-dimensional calculations^[37]. Heat capacity data and the gas law are also required in order to relate gas density, temperature, and enthalpy. The equation set is summarized below:

Conservation of Enthalpy

$$\frac{\partial}{\partial x_i} (\rho u_i h) = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu + \mu_t}{\delta_h} \right) \left(\frac{\partial h}{\partial x_i} \right) \right) + S_h$$

Conservation of Chemical Species

$$\frac{\partial}{\partial x_i} (\rho u_i m_s) = \frac{\partial}{\partial x_i} \left(\left(\frac{\mu + \mu_t}{\delta_s} \right) \left(\frac{\partial m_s}{\partial x_i} \right) \right) + S_s$$

Equation of State

$$\rho = \frac{P}{RT \sum m_j / M_j}$$

In this analysis, the Reynolds Decomposition is retained and the density fluctuations are neglected. This procedure is consistent with the frequently used density weighted averaging method.

Coal Combustion Model

The trajectory of a coal-particle in the gas is predicted by integrating the force balance on the particle which is written in the Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written (for the z-direction in Cartesian coordinates) as:

$$\frac{du_p}{dt} = F_D (u_\infty - u_p) + \frac{(g_x (\rho_p - \rho_\infty))}{\rho_p} + F_x$$

The coal-particle combustion model includes four heat/mass transfer processes which are:

1. The initial heating of the coal-particles to the temperature at which the volatiles in the coal are released

A simple heat balance is used to relate the particle temperature $T_p(t)$, to the heat transfer at the particle surface:

$$m_p c_p \frac{dT_p}{dt} = h SA (T_\infty - T_p)$$

In the above heat balance it is assumed that there is negligible internal resistance to heat transfer, i.e., the particle is at uniform temperature throughout. The heat transfer coefficient, h , is evaluated using the correlation of Ranz and Marshall^[38, 39].

$$Nu = \frac{hD_p}{k_\infty} = 2.0 + 0.6 Re_d^{0.5} Pr^{0.3}$$

2. The devolatilization of the coal-particles

The kinetic devolatilization rate expressions of the form proposed by Kobayashi^[41] are employed to model the process of devolatilization:

$$R_1 = A_1 \exp \left(\frac{-E_1}{R T_p} \right)$$

$$R_2 = A_2 \exp \left(\frac{-E_2}{R T_p} \right)$$

where R_1 and R_2 are competing rates that may control devolatilization over different temperature ranges, A_1 and A_2 are the pre-exponential factors, and E_1 and E_2 are the activation energies.

3. Combustion of the volatiles

In this study the volatiles are represented by a single species, propane. As the propane is evolved from the coal, it is assumed to react with oxygen in the gas phase according to the reaction:

4. Combustion of char

The char combustion rate may be determined via either kinetics or via a diffusion rate. The diffusion rate is:

$$R_1 = C_1 \frac{[(T_p + T_\infty) / 2]^{0.75}}{D_p}$$

and a kinetic rate:

$$R_2 = C_2 \exp \left(\frac{-E}{R T_p} \right)$$

are weighted to yield a char combustion rate of:

$$\frac{dm_p}{dt} = -\pi D_p^2 P_{\text{O}_2} \frac{R_1 R_2}{R_1 + R_2}$$

the above equation is further expressed in terms of the oxygen mass fraction as:

$$\frac{dm_p}{dt} = -\pi D_p^2 \frac{\rho R T m_{\text{O}_2}}{M_{\text{O}_2}} \frac{R_1 R_2}{R_1 + R_2}$$

The diffusion rate model was chosen in this study and the combustion of char was approximated by a surface reaction with a rate determined by the molecular diffusion of the gaseous oxygen to the surface of the char-particle, given by Fick's law of diffusion:

$$J_{\text{oxygen}} = \rho_g D_{AB} \frac{dm_{\text{oxygen}}}{dz}$$

Assumptions

The simplifying assumptions employed in this analysis can be divided into two categories:

1) the assumptions inherent in the structure of FLUENT, and 2) the assumptions made by the user. Both categories need to be accounted for if the theoretical results are to be compatible with the empirical data. The most predominant simplifying assumption inherent in the structure of the code arises from the fact that unsteady flows cannot normally be computed by the code. Therefore,

special boundary cells called 'outlet' cells are provided to allow the user to treat all flows as steady. Consequently, in order to satisfy the overall mass continuity equation, enough mass is allowed to escape from these cells. Unlike the wall and input cells, the output cells are not subdivided into zones. FLUENT assumes that by the time the reacting flow has reached the outlet cells, all of its properties have reached steady values, there are no destabilizing effects acting on the fluid to change its properties drastically, and combustion reactions are complete and the only species present in the flow are the products of combustion by the time the reacting flow reaches the outlet cells. The second type of simplifying assumptions are made by the user while specifying the boundary conditions. For example, the flow velocity is put to zero at the boundary layers next to the walls.

Sources of Error

1. The solution may not be fully converged.
2. Numerical errors can be generated. These errors usually arise from the finite difference approximations. They can be overcome by using a finer grid and concentrating the grid lines in regions where gradients are steepest and also by interpolation by curve fitting values at several nodes.
3. Unrealistic boundary conditions such as inlet velocity profiles and turbulence levels.
4. Turbulence behavior can be far from isotropic. To overcome this, more sophisticated turbulence models can be used instead of the $k - \epsilon$ model.
5. Turbulence may not be fully developed locally, especially in the initial regions of the free shear layers.
6. Current turbulence models do not always accurately describe mixing of species at the molecular level.
7. Over simplistic treatment of the flame chemistry.
8. Over simplistic treatment of the coal-particles ignition and combustion.

Due to these shortcomings of numerical modeling, it is imperative for the predictions to be checked against experimental data where possible. This is currently being done.

Boundary Conditions

The choice of the boundary conditions in any computational modeling work is of paramount importance. The conditions at the boundaries of the geometrical domain were therefore carefully chosen. Furthermore, it was necessary to make certain simplifications to the modeled geometries of the burner and the boiler, since the actual geometries are rather complicated. For the sake of thoroughness, computational modeling of the burner was carried out separately. It should be noted that the original modeling work that was conducted was performed prior to the installation of the EER burner. New boundary conditions will be developed and modeling will be conducted for the EER burner. The resulting values of velocity and temperature obtained for the burner were used as input boundary conditions into the boiler. The values of gas velocity were further checked

against experimental values obtained through hot-wire anemometry and good agreement was found between the two.

The inlet boundary conditions for the 3-dimensional model:

Inlet Stream	w(m/s)	u (m/s)	v (m/s)	T (K)	S	mO	L(m)	T.I.
Primary Air	26.0	26.0	26.0	358	1.0	0.23	0.025	30%
Secondary Air	26.0	26.0	26.0	466	1.0	0.23	0.050	30%
Tertiary Air	26.0	26.0	26.0	466	1.0	0.23	0.060	30%

where,

w = the component of velocity in the x-direction

v = the component of velocity in the y-direction

u = the component of velocity in the z-direction

m_O = the mass fraction of oxygen

T = temperature

L = characteristic length

T.I. = turbulence intensity

S = the modified swirl number

In this study, the swirl number of the flow is defined as the ratio of the tangential component of axial momentum to the linear component of axial momentum. Furthermore, the pressure distribution component of axial momentum term is neglected. Therefore, the swirl number is defined as:

$$S = \frac{G_{\phi}}{G_x R}$$

where the tangential component is:

$$G_{\phi} = \int_0^R \rho u.(wr).2\pi r \, dr$$

and the linear component is:

$$G_x = \int_0^R \rho u.u.2\pi r \, dr$$

Based on the above definition of the swirl number, values of tangential velocity were calculated and expressed as mathematical functions of the u and v components of velocity in the inlet boundary conditions.

The boundary conditions for the particulate phase (micronized-coal particles) were set using the particle distribution of the micronized-coal fit to a Rosin-Rammler distribution function. Initial conditions of the micronized-coal particle were defined using the analysis of the coal, with the simplifying assumption of neglecting the moisture in the coal.

Discussion

The governing partial equations are solved in a Cartesian coordinate system. This is suited to the box-like geometry of the demonstration boiler, but, of course not to the axisymmetrical character of the near-burner flowfield. The focus of this numerical modeling effort is not on the near-burner flowfield, the prediction of this region being a matter for a separate study. The emphasis in this study is on the prediction of conditions within the larger scale volume of the boiler.

Generally, in the analysis of industrial boilers, the concept of a mean residence time is used. This mean residence time is defined as the ratio of the boiler volume to the volumetric flow rate of the hot combustion gases. In this analysis however, the concept of residence time distribution is employed. The reason for using the residence time distribution is the swirling nature of the flowfield. In general, the existence of swirl in a flow-field gives rise to variations in the degree of swirl due to decay of the kinetic energy in the swirling flow as a function of time or distance. As a result of the decay in the degree and intensity of swirl, there is a distribution of residence times for the different fluid-particles in the flowfield. In a turbulent swirling flowfield, the path of travel for the fluid is no longer a linear path. The fluid as a whole follows a spiral path. As a result of this spiral path, different particles of the fluid sweep through unequal distances. The direct result of this behavior is a distribution of residence times for the various fluid-particles. It is important to note that the term fluid-particles refers to the infinitesimal parcels of fluid and not physical particles. When referring to particles in the true sense of the word, they are referred to as coal-particles char-particles and ash-particles. In further reference to the distribution of residence times in turbulent swirling flows, it is due to this phenomenon that swirl affects the performance and the efficiency of a combustion chamber.

The experimental measurements and the theoretical predictions from numerical modeling have provided ample evidence for the existence of a highly asymmetrical flowfield in the boiler. The predictions of the temperature and velocity fields in the boiler obtained from numerical modeling are depicted in Figures 3-21 and 3-22. After examination of Figures 3-21 and 3-22, it becomes clear that the flowfield in the Demonstration Boiler is highly asymmetrical in the x - z plane. The reason for the asymmetrical nature of the flowfield is the physical location of the boiler

Figure 3-21. FILLED CONTOURS OF TEMPERATURE FOR A SLICE ALONG THE CENTER LINE OF THE DEMONSTRATION BOILER FIRING MICRONIZED-COAL

Figure 3-22. FILLED CONTOURS OF VELOCITY FOR A SLICE ALONG THE CENTER LINE OF THE DEMONSTRATION BOILER FIRING MICRONIZED-COAL

outlet. As a result of the location of the boiler outlet, the turbulent swirling jet issued by the burner does not fill the entire volume of the furnace. Rather, this jet travels in a skewed fashion toward the outlet of boiler. As a direct result of this asymmetry in the flow-field, coupled with the distributions of the residence times for the fluid-particles, the rates of convective and radiative heat transfer from the gas to the boiler walls vary throughout the volume of the boiler. In an industrial boiler designed for firing natural gas, this asymmetrical nature of the flow is not problematic because of the relatively short burn-out times associated with the combustion of natural gas. However, in a retrofit application to burn coal in such a boiler it is essential to analyze the path of travel of coal particles in the boiler. It is very likely that a percentage of the coal-particles follow the asymmetrical path of the flow and exit the boiler, resulting in residence times too short for all size fractions of coal to burn out with an acceptable combustion efficiency. Figure 3-23 shows the path of travel of coal-particles in the gas-field. Clearly, the asymmetrical flow-field affects the path of travel of coal-particles and a percentage of the coal particles do indeed exit the boiler before achieving satisfactory burnout. The 3-dimensional modeling discussed here is still at its initial stages of development, and for the sake of simplicity, the number of coal particles injected into the gas phase was kept to a minimum as was the mass flow rate of coal. As this work progresses, the over-simplistic treatment of the particulate phase will cease and a more realistic treatment of the coal-particles will ensue. In addition, gas temperatures, particle velocity and concentration, and heat flux in the boiler will be verified by measurement.

In order to correct the problem of an asymmetrical flow-field a range of operating conditions were attempted employing the control parameters of the burner. These parameters included the change in the percentage staging of secondary and tertiary air streams, swirl numbers, and the mass flow rate of primary air. However, under all of these conditions, the asymmetrical nature of the flow remained its most predominant feature. After careful analysis and numerical modeling of a range of operating conditions, it was decided to investigate the influence of actual modifications to the boiler geometry. Various modifications to the boiler geometry were analyzed employing numerical modeling and it was determined that the most feasible change was the installation of a wall (or ceramic tunnel) close to the boiler outlet. The impact of this wall as predicted by numerical modeling was to beneficially modify the flowfield.

Figures 3-24 and 3-25 depict the temperature and velocity fields in the boiler after the installation of the wall with the most noticeable change being the impact of the wall on the flow-field of the gas. The flowfield became more symmetrical as a result of the impact of the wall on the aerodynamics of the boiler. The modified path of the particles is shown in Figure 3-26. From the predictions made by the numerical modeling it can be concluded that the wall installed in the boiler has indeed made a beneficial impact on the flow-field.

Figure 3-23. TRAJECTORIES OF A SELECTED NUMBER OF MICRONIZED-COAL PARTICLES IN THE DEMONSTRATION BOILER

Figure 3-24. FILLED CONTOURS OF TEMPERATURE FOR A SLICE ALONG THE CENTER LINE OF THE DEMONSTRATION BOILER FIRING MICRONIZED-COAL (after installation of the Ceramic Tunnel)

Figure 3-25. FILLED CONTOURS OF VELOCITY FOR A SLICE ALONG THE CENTER LINE OF THE DEMONSTRATION BOILER FIRING MICRONIZED-COAL (after installation of the Ceramic Tunnel)

Figure 3-26. TRAJECTORIES OF A SELECTED NUMBER OF MICRONIZED-COAL PARTICLES IN THE DEMONSTRATION BOILER (after installation of the Ceramic Tunnel)

It is important to further discuss some of the short-comings of the present modeling work. The flowfield in the boiler is highly swirling with swirl numbers that approach or exceed unity. Generally, the use of the Reynolds Stress Model is recommended for modeling turbulence in highly swirling flows. The turbulence model used in this modeling work, however was the κ - ϵ model, as the use of the Reynolds Stress Model would increase the computational time significantly.

When modeling highly swirling flows, it is essential to have sufficient resolution in the grid. Typically, rotating boundary layers must be very thin and the grid must be very fine near the region where the flow has its maximum swirl intensity. While a non-uniform grid was used in this analysis and the grid near the furnace inlet was kept as fine as possible, the resulting computations could not predict the existence of the Internal Recirculation Zone of the flame which is one of the most striking features of highly swirling flows.

The modeling of the particulate-phase is another area of uncertainty. The heterogeneous reactions of coal combustion are often slow enough to be unaffected by the turbulent fluctuations, but many of the important reactions in the overall combustion process occur in the gas phase. The effect of turbulence on the mean chemical properties of coal combustion is often neglected in the numerical modeling due to the complexity of the physical models involved. However, two approximate methods have been suggested which attempt to address the impact of turbulent fluctuations on the mean properties of coal combustion. The first method^[40], the volatile reactivity model, is an extension of an approach for premixed gaseous combustion suggested by Magnussen and Hjertager^[41]. The second approach the statistical, coal-gas mixture-fraction model, is an extension of gaseous diffusion flame approaches. In the current analysis the impact of turbulent fluctuations on the mean properties of coal combustion was neglected which is bound to introduce error into the analysis.

Based on the above discussion, the future modeling work will employ the Reynolds Stress Model, modify some of the boundary conditions to reflect the current configuration (EER burner), and make an attempt at including the impact of turbulent fluctuations on the mean properties of coal combustion.

3.4 Subtask 2.4 Evaluate Emissions Reductions Strategies

No work was conducted in Subtask 2.4.

4.0 PHASE I, TASK 3: ENGINEERING DESIGN

Work continued on the retrofit designs of the boiler located at the Naval Surface Warfare Center at Crane, Indiana. The designs (except for the MCWM preparation facility) have been completed and are in the final review stage. The items that have been completed include DMC preparation, fuel handling, burner, ash removal, handling, and disposal, and air pollution control systems. A summary of the design activities of the subsystems is given in the following sections.

4.1 Subtask 3.1 MCWM/DMC Preparation Facilities

No work was conducted on the MCWM preparation facility. The DMC preparation facility is incorporated into Subtask 3.2 (see below).

4.2 Subtask 3.2 Fuel Handling

Work consisted of reviewing equipment performance specifications for compatibility with the system design and verifying equipment list parameters. A Z-conveyor has replaced the bucket elevator and unloading hopper screw conveyor. This revision will provide for better feed rate stability, fewer transitions, reduced amount of required equipment, and improved distribution in the coal storage silo.

4.3 Subtask 3.3 Burner System

Work consisted of reviewing equipment performance specifications for compatibility with the system design and incorporating the equipment into the planned arrangement.

EER continued its design effort on the MCWM injection system arrangement. A second MCWM injection pump was added to the design to increase the system stability.

A weigh-belt feeder was incorporated into the design per the DMC system requirements. Metal detection/capture in the coal system was added to the design.

EER received an interpretation of the National Fire Protection Agency (NFPA) codes regarding the weigh-belt feeder and inerting system for the mill. The NFPA interpretation regarding the rotary airlock states that a rotary airlock located on the inlet to the mill will act as a feeder and the NFPA requirement of 50 psig burst strength terminates two feet above the inlet to the rotary air lock.

Regarding the issue of inerting, NFPA addresses the mill and places the responsibility on the mill designer. TCS, Inc., the mill manufacturer, states that the mill will not require an inerting system since it has a low exit temperature, small quantity of coal in the mill, and when turned off, the mill will empty itself of coal as it slows down and stops.

4.4 Subtask 3.4 Ash Removal, Handling, and Disposal

Work consisted of reviewing equipment performance specifications for compatibility with the system design, verifying equipment list parameters, and incorporating the equipment into the planned arrangement. The preliminary design of a floor blast system has been completed. Per the recommendation of the air heater manufacturer, the number of required sootblowers has been reduced from four to one.

The installation of a second sootblower into the convective pass was explored (the retrofitted boiler already contains one sootblower). It was found that the addition of a second sootblower is technically possible, but it is not economically feasible at this time. To install a second sootblower, the boiler will require extensive modifications to the exterior and interior

casings and the tubewall which will result in an exorbitant cost. Therefore, it has been decided not to add the second sootblower unless the boiler would experience excessive ash deposition.

4.5 Subtask 3.5 Air Pollution Control

Work consisted of reviewing equipment performance specifications for compatibility with the system design and verifying equipment list parameters.

4.6 Subtask 3.6 Integrate Engineering Design

The preliminary instrument and motor location drawings have been completed. The preliminary design drawings have been completed.

5.0 PHASE I, TASK 4: ENGINEERING AND COST ANALYSIS

Task 4 is nearly completed. No work was conducted in Task 4 this reporting period.

5.1 Subtask 4.1 Survey Boiler Population/Identify Boilers for Conversion

No work was conducted this reporting period.

5.2 Subtask 4.2 Identify Appropriate Cost Estimating Methodologies

This task was completed and reported in the previous semiannual technical progress report (Miller et al., 1994a).

5.3 Subtask 4.3 Estimate Basic Costs of New Technologies

No work was conducted this reporting period.

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

No work was conducted this reporting period.

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 this reporting period.

5.6 Subtask 4.6 Community Spillovers

No work was conducted this reporting period.

5.7 Subtask 4.7 Regional Market Considerations and Impacts

No work was conducted this reporting period.

5.8 Subtask 4.8 Integrate the Analysis

No work was scheduled or conducted this reporting period.

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

No work was conducted on Task 5.

7.0 PHASE II, TASK 1: EMISSIONS REDUCTION

The objectives of this task are to develop strategies to provide for ultra-low emissions when firing coal-based fuels in industrial-scale boilers. Emissions to be addressed include SO₂, NO_x, fine particulate matter (<10 µm), and air toxics (volatile organic compounds and trace metals).

7.1 Subtask 1.1 Evaluation of Emissions Reduction Strategies

Proposals were received from potential suppliers of flue gas treatment systems during the last reporting period and were reviewed with DOE. A preliminary selection was made and Penn State worked with the supplier of the flue gas treatment system to ensure compatibility with the boiler system and applicability to industrial boilers in general. As a result of working with the vendor, and meetings that were conducted between the vendor and DOE, DOE has recommended that the type of pollution control system that will be installed on the demonstration boiler be a commercially-available system rather than one that will require a major research and development effort. Consequently, the effort in this subtask has been directed towards compiling information on SO₂ and NO_x control techniques. This includes conducting literature searches and compiling vendor information.

7.2 Subtask 1.2 Conduct Fundamental Emissions Reduction Studies

No work was conducted on this subtask.

7.3 Subtask 1.3 Install System on the Demonstration Boiler

No work was conducted on this subtask.

7.4 Subtask 1.4 Evaluate Emissions Reduction System

No work was conducted on this subtask.

8.0 PHASE II, TASK 2: COAL PREPARATION/UTILIZATION

The long-term objectives of this task are:

- to establish more precise criteria for the formulation of MCWM.
- to develop improved cleaning procedures in order to increase the yield of usable coal from any given source and to expand the reserve base of candidate coals for retrofitted boilers.
- to develop optimized procedures for low-cost production of MCWM.

8.1 Subtask 2.1 Optimization of Particle Size Consist for MCWM Formulation

The use of bimodal size distributions to produce slurries with acceptable solids content, stability and rheological character has been discussed at length in previous reports. It is common practice, on the other hand, to use broad, continuous size distributions, thereby eliminating the need for multi-stage grinding. An "optimum" size distribution based on work by Farris^[42] and Henderson and Scheffe^[43] is often advocated for coal-water slurry formulation. It should be

recognized, however, that there are important constraints which must be satisfied for this to represent an optimum size distribution.

The Farris treatment was based on multimodal distributions in which the ratio of sizes corresponding to successively finer modes was small (e.g. less than 0.1).^[43] extended Farris' analysis and presented an optimum size distribution of the form:

$$F_i \frac{D_i^n - D_s^n}{D_L^n - D_s^n} \quad (8 - 1)$$

where F_i is the fraction finer than or equal to size class i , D_i is the particle size of the i^{th} component, D_L and D_s are the respective sizes of the largest and smallest particles present and n is related to the range of sizes and the number of intermediate classes.

In fact, the Henderson-Scheffee analysis included an error which has recently been noted by Klima and Cho^[44] who have presented a corrected form of the expression:

$$F_i = \frac{D_i^n \theta - D_s^n}{D_L^n \theta - D_s^n} \quad (8 - 2)$$

where the quantity θ is defined by

$$\theta = (1 - \phi_T)^{-1/N} \quad (8 - 3)$$

in which ϕ_T is the overall solids concentration (volume fraction) and N is the number of size classes (i.e. discrete modes).

The important constraint on the use of Equation 8-2 is that the size classes i should

- (a) represent discrete modes (or at least reasonable approximations)
- (b) differ significantly in size (preferably by a ratio of 10:1 or more)

Such constraints cannot be satisfied by the use of a size distribution with the form of Equation 8-2 but with more closely-spaced size classes, which follow a $\sqrt{2}$ progression, for example.

8.2 Subtask 2.2 Fine Grinding/Classification/Liberation

Grinding Kinetics

Mathematical modeling of the size reduction process has been developed by defining two functions: the breakage rate function and the breakage distribution function^[45]. The breakage rate function, S_j , is the specific breakage rate of material in the j^{th} size interval. The breakage distribution function, b_{ij} , is the fraction of material broken out of the larger j^{th} size interval and into the i^{th} size interval.

For batch grinding, the above definitions of S and b lead to the size-mass balance equation^[45].

$$\frac{dw_i(t)}{dt} = -S_i w_i(t) + \sum_{j=i-1}^{i-1} b_{ij} S_j w_j(t) \quad (8 - 4)$$

where $w_i(t)$ is the weight fraction of material in the i^{th} size interval at time t . The specific rates of breakage vary with the particle size in a typical power function relationship given by

$$S_i = a(x_i / x_o)^\alpha \quad (8 - 5)$$

where S_i is the specific rate of breakage for particle size x_i , x_o is a standard (reference) particle size, and a and α are constants for a given material and set of grinding conditions. The b values can be represented in cumulative form as $B_{ij} = \sum_{k=n}^i b_{kj}$, which fits the empirical function^[45]

$$B_{ij} = \phi \left(\frac{x_{i-1}}{x_j} \right)^\gamma + (1 - \phi) \left(\frac{x_{i-1}}{x_j} \right)^\beta \quad (8 - 6)$$

where β , γ , and ϕ are constants that depend on the material being ground.

To provide the best estimate of the experimental parameters for the S and B functions, the one-size-fraction technique should be used^[45]. However, reasonable estimates can be obtained by back calculation using a non-linear optimization scheme^[46]. Figure 8-1 compares the simulated and experimental size distributions when grinding the Taggart seam coal at 40% solids. It can be seen that there is good agreement between the experimental and computed results. The back-calculated parameters are given in Table 8-1.

As reported previously^[47], the shape of product size distribution depends on the solids concentration. To compare the shape of the product size distributions at various solids concentrations for the Taggart seam coal, simulations were conducted using the back-calculated breakage parameters. Grinding times were selected that gave a product size of 80% passing 200 mesh and results are plotted in Figure 8-2. It can be seen that the size distributions fall into three distinct groups, one for slurry densities of 50% and less, one for high slurry densities of 60-65%, and one for the slurry density of 70%, with the higher density slurries producing comparatively more fines. The change in the shape of the size distribution indicates that

Figure 8-1. EXPERIMENTAL (symbols) AND SIMULATED (lines) PRODUCT SIZE DISTRIBUTIONS AFTER GRINDING THE -10 MESH SAMPLE OF THE TAGGART SEAM COAL IN A TUMBLING BALL MILL AT 40% SOLIDS (by weight) FOR VARIOUS TIMES

Table 8-1. Breakage parameters for the Taggart seam coal at various solids concentrations.

	a	α	ϕ	γ	β
40 wt. %	3.37	1.37	0.43	0.67	5.0
50 wt. %	3.40	1.37	0.32	0.58	5.0
60 wt. %	1.88	1.37	0.39	0.51	5.0
65 wt. % ^a	1.54	1.37	0.47	0.50	5.0
70 wt. % ^a	0.85	1.37	0.52	0.44	5.0

^a with 0.5 wt. % dispersant

Table 8-2. Breakage parameters and estimated false times for stirred ball mill ground Taggart seam coal at 40% solids.

Breakage Parameter	a	α	ϕ	γ	β
Values	3.37	1.37	0.43	0.67	5.0
Grinding Times	1 min.	2 min.	4 min.	8 min.	16 min.
False Times	1 min.	2 min.	3 min.	5 min.	8 min.

Figure 8-2. SIMULATED SIZE DISTRIBUTIONS FOR THE TAGGART SEAM COAL TO GIVE 80% PASSING 200 MESH (74 μm)

the mechanism of fracture changes when going from low to high pulp densities. This is more evident in Figure 8-3 where the back-calculated breakage distribution (B values) are shown. It can be seen that the breakage distribution is flatter for higher density slurries, producing more fines at higher solids concentrations. However, the breakage rate decreased at a higher solids concentration (Table 8-1). Hence, there is an operating range that will maximize fines production. This will be considered when developing grinding strategies for coal-water slurry production.

For the stirred ball milling, the estimation of the breakage rate (S values) was not sufficient, since the grinding data showed the slowing-down of breakage rate due to the viscosity increase as the mill content progressively became finer. Therefore, the simulation was performed using the false time concept^[45]. The false time, θ , is the equivalent first-order grinding time. In other words, if the breakage rate remains first-order, the size distribution at time t would be equivalent to the size distribution at time θ . Here, the slowing down of the breakage rate is assumed to be uniform for all sizes. Then, the breakage rate at time t can be represented by

$$S_i(t) = KS_i(0) \quad (8 - 7)$$

where $S_i(0)$ is the initial breakage rate and K is a reduction factor. The slowing-down factor K is related to θ and t by

$$K = \frac{\theta}{t} \quad (8 - 8)$$

As the grinding proceeds, K decreases as more fines build up in the charge. Table 8-2 lists the θ values at various grinding times along with the back-calculated breakage parameters. Simulations were performed using the back-calculated breakage parameters and false times. The results are shown in Figure 8-4. It can be seen that the simulated results are in reasonable agreement with the experimental results. Work in this area is continuing.

8.3 Subtask 2.3 Fine Gravity Concentration

The use of the batch hindered-settling model to investigate dense-medium separations continued. In particular, process variable interactions were examined, including the number of "g's", volumetric flow rate, and pulp split (mixture of coal and liquid).

Cyclone Separations

The interaction of process variables will impact dense-medium separations. A study was carried out using the batch hindered-settling model to examine the effect of variable interactions during the dense-medium cycloning of 28x100 mesh coal at a low medium density of 1.29^[44]. The model parameters were calculated for various pulp splits and cyclone

Figure 8-3. BACK-CALCULATED CUMULATIVE B-VALUES FOR VARIOUS SOLIDS CONCENTRATIONS OF THE TAGGART SEAM COAL

Figure 8-4. EXPERIMENTAL (symbols) AND SIMULATED (lines) PRODUCT SIZE DISTRIBUTIONS AFTER GRINDING THE -200 MESH SAMPLE OF THE TAGGART SEAM COAL IN A STIRRED BALL MILL AT 40% SOLIDS (by weight) FOR VARIOUS TIMES WITHOUT A DISPERSANT

diameters. The parameters were based on the operating conditions given by Chedgy et al.^[48]. These values are summarized in Table 8-3.

The model was used to generate the fractional recovery curves at each condition. The $E_p(x)$ and $r_{50}(x)$ values for each curve were determined by nonlinear optimization. These values were then plotted against the number of "g's" corresponding to a given flow rate (and pressure drop) for each cyclone diameter. The results are shown in Figure 8-5. As expected, for a given cyclone diameter, the separation improved ($E_p(x)$ and $r_{50}(x)$ decreased) with an increasing number of "g's" for pulp splits of 0.6 and 0.7. However, for a pulp split of 0.8, the $E_p(x)$ values became less sensitive to N_g , and the $r_{50}(x)$ values even increased slightly with increasing N_g . Therefore, depending on the operating pulp split, increasing the flow rate will not always result in a better separation. Also, it can be seen that for a given N_g , a smaller cyclone always produced a better separation, provided the same pulp split was maintained. And, changing the cyclone diameter had a greater effect on the parameters as opposed to varying the flow rate.

Additional simulations were run over the range of flow rates and corresponding pulp splits indicated by Figure 8-6. The pulp splits corresponded to a 350 mm diameter dense-medium cyclone operating at two different medium densities^[48]. In both cases, the pulp split increased as the flow rate increased. The results from the simulations are presented in Figures 8-7. The solid lines represent simulations at constant pulp splits, which bound the range of values used in the cyclone testing. It can be seen that $E_p(x)$ decreased slightly as the number of "g's" increased for both pulp splits. However, if the pulp split varied according to the relationship given in Figure 8-6, the data represented by the dashed line would result. Under these conditions, $E_p(x)$ increased with N_g , and the increase was the most significant at the lower values of N_g . In this range, the separation efficiency was more sensitive to the classification of the magnetite. Similar results were also obtained for the relative density of separation.

Centrifugal Separations

The solid-bowl centrifuge has been delivered. Construction of the test circuit (Figure 8-8) is currently in progress. This circuit will be used for both continuous dense-medium separation and coal classification. The circuit will be equipped with a variable-speed, progressive-cavity pump, which will allow the volumetric flow rate through the centrifuge and in turn, the mean retention time to be changed. The centrifuge is outfitted with a variable frequency drive to allow the bowl speed and hence, number of "g's" to be varied, independent of the retention time. The unit is also equipped with a variable-speed backdrive, which can also be used to change the retention time of the solids. This change may also affect the overall pulp split between the solids and concentrate streams. The height of the overflow weir can be varied, allowing the pulp split to be changed independent of the other variables.

Table 8-3. Summary of the input parameters used for the batch hindered-settling model (Klima and Cho [31]).

D_c^a , mm	P^b , kPa	Q_i^c , l/s	t^d , s	N_g^e	d_m^f , cm ² /s
150	41.3	3.53	1.74	100.	4.43
	62.0	4.81	1.28	186.	6.04
200	20.7	4.47	3.26	38.3	4.21
	41.3	6.25	2.33	74.7	5.89
	62.0	7.58	1.92	110.	7.14
250	20.7	6.44	4.42	26.0	4.86
	41.3	8.83	3.22	48.9	6.66
	62.0	11.0	2.60	75.5	8.27
360	20.7	15.1	5.43	24.7	8.04
	41.3	21.5	3.83	49.6	11.4
	62.0	25.8	3.18	71.8	13.7
500	62.0	51.8	4.40	52.5	19.5
	82.7	57.4	3.97	64.6	21.6
	103.4	63.1	3.61	78.1	23.8

a Cyclone diameter.

b Pressure drop.

c Volumetric flow rate.

d Retention time.

e Number of "g's".

f Diffusion coefficient.

Figure 8-5a. PROBABLE ERRORS FOR THE 28 x 100 MESH COAL OBTAINED FROM SIMULATIONS OF VARIOUS CYCLONE DIAMETERS AT DIFFERENT FLOW RATES AND PULP SPLITS:
 (Cyclone diameters: — 500 mm, - - 350 mm, --- 250 mm, - · - 200mm, · · · 150 mm)

Figure 8-5b. RELATIVE DENSITIES OF SEPARATION FOR THE 28 x 100 MESH COAL OBTAINED FROM SIMULATIONS OF VARIOUS CYCLONE DIAMETERS AT DIFFERENT FLOW RATES AND PULP SPLITS:
 (Cyclone diameters: — 500 mm, - - 350 mm, - · - 250 mm, · · · 200mm, · · · · 150 mm)

Figure 8-6. VOLUMETRIC FRACTION OF THE FEED SLURRY REPORTING TO THE OVERFLOW OF A 360 mm DIAMETER CYCLONE FOR TWO MEDIUM DENSITIES (Chedgy et al., [7])

Figure 8-7. CHARACTERISTIC PARAMETERS FOR THE 28 x 100 MESH COAL OBTAINED FROM SIMULATIONS OF A 360 mm DIAMETER CYCLONE AT DIFFERENT FLOW RATES AND PULP SPLITS: (a) probable errors, (b) relative densities of separation

Figure 8-8. SCHEMATIC DIAGRAM OF THE CONTINUOUS, SOLID-BOWL CENTRIFUGE TEST CIRCUIT

Magnetic Fluid Separation

Because of electrical problems with the existing Magstream separator, another unit was received on loan from the manufacturer. This unit has been installed and preliminary testing is now underway. The Magstream separator will be used to determine some of the baseline parameters for the test program.

As shown in the previous semiannual technical progress report^[3], a magnet geometry was selected that would provide an isodynamic magnetic field to ensure effective separations of the particles. The magnet pole pieces are being machined out of magnetic iron according to the specifications given previously. This material is uniquely suited for providing a high magnetic field in the gap between the poles because of its low impurity content. Several magnetic iron spacers are also being machined to allow the gap to be varied.

The pole pieces will be attached to an existing Franz isodynamic magnetic separator. This unit is equipped variable strength electromagnet. Also, the magnet orientation can be changed to any angle.

The preliminary separations will be made in a continuous separator, which was fabricated out of Plexiglas. The unit was designed to fit between the pole pieces of the magnet (Figure 8-9). The feed slurry will be pumped through the separator, and the float and sink products will be split at the discharge end. The pulp split can be changed by changing the height of the splitter. A water-based magnetic fluid composed of iron lignosulfonate will be used as the separating medium. This suspension has a high magnetization, which is necessary to achieve the desired in-fluid pressure at an acceptable fluid viscosity.

In conjunction with the test program, a theoretical study involving the mapping of the magnetic field in the air gap has been initiated. This modeling effort will provide a better understanding of the interaction between the pole shape and the resulting magnetic field. As such, different magnet geometries can be investigated, reducing the amount of time required for determining the optimum geometry.

8.4 Subtask 2.4 Agglomeration/Flotation Studies

Evaluation of Flotation Kinetics

Studies were continued to further develop methods to estimate flotation kinetics parameters for various coals. The parameters obtained by Method I, which was described in a previous semiannual report ^[3], are given in Table 8-4 for Sample #2 of the Upper Freeport seam. The results of Sample #1 of the Upper Freeport and the Pittsburgh seam coals are included for comparison. The size consist of the feed for the three coals was kept similar to those reported previously. The model with normal distribution of flotation rates gave the best results when Method I was used. This model was developed as a part of this project and details were given previously^[3]. While the quality of fit with various models changed from one material to another, the model FND-3 gave the

Figure 8-9. SCHEMATIC DIAGRAM OF THE SEPARATOR AND POLE PIECES FOR MAGNETIC FLUID SEPARATION

Table 8-4. Model Parameters and the fitting errors calculated using Method I for the Upper Freeport and Pittsburgh samples.

		KCFO	KFRD	KFSD	$\mu_{\text{FND-2}}$	$\mu_{\text{FND-3}}$	$\sigma_{\text{FND-3}}$
Predicted Parameter Value	UF1	3.12	7.81	5.42	3.34	3.41	1.31
	UF2	5.20	8.22	6.25	5.78	5.75	1.87
	PC	4.80	14.59	8.80	5.31	4.93	0.84
Fitting Error	UFR	2.92	1.55	0.46	0.28	0.29	
	UFC	0.42	2.87	0.21	0.06	0.07	
	PC	0.11	5.64	1.01	0.35	0.12	

UF1 Upper Freeport Sample No. 1
 UF2 Upper Freeport Sample No. 2
 PC Pittsburgh Sample

best fit in most cases. The flotation model parameters for various size intervals were calculated by Method II and are given in Table 8-5a for Sample #2 of the Upper Freeport seam. The corresponding curve fitting errors are given in Table 8-5b. In most cases the model FND-3 gave the best results.

8.5 Subtask 2.5 Fundamental Studies of Surface-Based Processes

The objective of this task is to relate adsorption of various reagents, and other surface properties such as wettability, to coal cleanability and slurry properties. To determine adsorption of surfactants on coal, various methods to analyze polyethelene oxide-polypropylene oxide concentration in solution were reviewed. This group of surfactants was chosen because of its effectiveness in enhancing coal flotation. A preliminary investigation with UV/Visible spectroscopic methods showed that the available methods do not have the desired sensitivity of detection. After a thorough literature review and several preliminary tests it was concluded that a 'pyroprobe' is required to analyze the reagent solutions. Since the investigations conducted so far show that the choice of the reagent type and concentration is specific to the coal to be cleaned, we propose that the adsorption work be continued during Phase 3 of the project. In another part of this investigation, the zeta potential of Pittsburgh seam coal was measured in the presence of dispersant used in formulation of the slurry, Coalmaster A-23M. The results, presented in Figure 8-10, show that the reagent acts through a charge stabilization mechanism. The reagent is especially effective in the acidic pH range where 1.0 ppm of the reagent changed the zeta potential of coal from positive to negative values. In the alkaline pH range, the zeta potential became more negative but the amount of reagent needed was relatively large. These results imply that the reagent requirements could change with pH of the slurry. Tests with other coals are planned.

8.6 Subtask 2.6 Column Flotation

Test work on Type III-1 coal (Upper Freeport) commenced. The characteristics of the Upper Freeport coal is given in Table 8-6. The washability of the coal was presented in a previous report [1]. The flotation experiments were carried out in a 0.063 m diameter flotation column equipped with the Mott Metallurgical bubble generator. The column was operated in a semi-batch mode with tailing recirculation^[49]. The column has an overall height of 1.5 m. However, provision was made for the recycle stream to be introduced at 0.33 m, 0.64 m, 0.89 m and 1.14 m from the base of the column. For the experiments reported here, the recycle stream was introduced at a height of 0.89 m from the base of the column.

A 5 wt. % coal slurry was prepared and transferred into the column using a peristaltic pump. The required dosage of methyl iso-butyl carbinol (MIBC) frother was added. The tailings were recirculated to the column at a fixed rate of 0.072 m³/h. After allowing for the frother to be properly mixed with the slurry, the air was turned on to the desired value and the froth overflowing

Table 8-5a. Model parameters calculated using Method II for the Upper Freeport Sample No. 2.

Size, μm	KCFO	KFRD	KFSD	$\mu\text{FND-2}$	$\mu\text{FND-3}$	$\sigma\text{FND-3}$
+600	5.41	17.36	9.79	6.02	6.02	2.01
600x300	6.74	27.48	12.99	7.77	7.47	2.14
300x150	6.80	28.48	13.19	7.86	7.02	1.16
150x75	5.39	18.12	9.89	6.05	5.39	0.01
75x38	3.96	10.90	6.90	4.32	3.96	0.01
-38	2.92	7.26	4.93	3.12	3.12	1.04

Table 8-5b. Fitting errors calculated using Method II for the Upper Freeport Sample No. 2.

Error	CFO	FRD	FSD	FND-2	FND-3
E ₊₆₀₀	0.85	1.46	0.27	0.35	0.44
E _{600x300}	0.11	1.78	0.25	0.08	0.06
E _{300x150}	0.02	2.35	0.44	0.15	0.02
E _{150x75}	0.62	8.29	2.87	1.74	0.78
E _{75x38}	1.11	12.99	4.45	2.84	1.34
E ₋₃₈	1.99	2.71	0.26	0.51	0.64
E _{II}	0.33	4.37	1.25	0.73	0.34
E _{II} [*]	0.64	4.06	1.07	0.68	0.29

* Excluding the -38 mm fraction.

Figure 8-10. ZETA POTENTIAL OF PITTSBURGH SEAM COAL AS A FUNCTION OF pH AT SEVERAL CONCENTRATIONS OF COALMASTER A-23 M.

Coalmaster A-23 M concentration:

Table 8-6. Effect of gas velocity on the column flotation of Upper Freeport coal at a frother concentration of 50 ppm.

Gas velocity (cm/s)	Coal Yield (%)	Sulfur	
		wt. %	Rejection (%)
0.59	54	1.16	75
1.74	64	1.26	68
2.90	81	1.48	52

Table 8-7. Effect of frother concentration on the column flotation of Upper Freeport coal at a gas velocity of 2.9 cm/s.

MIBC concentration (ppm)	Coal Yield (%)	Sulfur	
		wt. %	Rejection (%)
17	48	1.16	78
33	63	1.21	75
50	81	1.48	52

the cell lip was collected as a function of time. In these experiments, no collector or wash water addition were used. The preliminary results obtained are shown in Tables 8-6 and 8-7.

These results show that the product grade decreases as the yield increases. In addition, they also show that without wash water addition and/or collector, Type III-1 coal (e.g. Upper Freeport) cannot be cleaned in a single stage to meet the project objectives. The single stage yield-grade curve obtained in the present study is comparable to the three-stage (rougher, scavenger, cleaner) microbubble flotation test work reported by Huttenhain et al^[50]. For example, with a 1.56% sulfur Upper Freeport coal, their three stage circuit produced 1.10% sulfur clean coal product at 67% yield (i.e. 53% sulfur rejection). Ash analysis is continuing and will be reported in the next progress report. Studies are continuing to identify promising process conditions for the treatment of Type II and III coals to meet the project objectives.

8.7 Subtask 2.7 Dry Cleaning of Fine Coal

A continuous electrostatic separator has been designed and fabricated (Figure 8-11). The separator was constructed from a Plexiglass cylinder, 12.5 cm in diameter by 91 cm long. A copper sheet, 61 cm in length, was attached to the inside of the tube. A 0.6 cm diameter copper rod extends along the center of the tube.

During the operation, the coal is fed through an in-line static mixer and then distributed across the cross sectional area of cylinder. A voltage drop is applied across the plate and the rod to induce separation. Compressed sweep air is injected through small jets located around the periphery of the cylinder and the rod. The jets dislodge the products off the plate and the rod. This sweeping action also assists in carrying the material to the end of the separator. The two products pass through a splitter and are then directed into collection cyclones where the solids are recovered from the air streams. Testing of the continuous separator has been initiated.

As noted previously, the argon laser has been received. A light sheet beam generator utilizing the argon ion laser and a cylindrical lens system was designed and will be used to illuminate the particle stream within the separator. This will allow visualization of flow patterns and particle trajectories, while providing light for photographic recording. The optical system used to generate the laser sheet is shown in Figure 8-12. It is an adaptation of the system described by Deimunsch and Prenal^[51]. A single long focal length spherical lens, L_1 , is used to focus the sheet. A set of two cylindrical lens, LC_2 and LC_3 is used to expand the sheet. The sheet width, an expansion ratio of an entering collimated beam, is expressed as

$$L = \phi \frac{f_2}{f_1} \quad (8 - 9)$$

where f_1 and f_2 are the focal lengths of LC_2 and LC_3 , and ϕ is the laser beam diameter.

Figure 8-11. SCHEMATIC DIAGRAM OF THE CONTINUOUS TRIBOELECTROSTATIC SEPARATOR

Figure 8-12. SCHEMATIC DIAGRAM OF THE LASER SHEET GENERATOR SETUP

In our system, LC_2 is 19 mm and LC_3 is 300 mm. This gives a sheet width that is approximately 16 times larger than the laser beam. With a 6 mm laser beam, the sheet width is 96 mm at LC_3 . When the finite dimensions of the optics are taken into account, the actual sheet width is around 50 mm. The effect of the spherical lens on the spreading operation can typically be neglected if the distance between L_1 and LC_2 is small compared to the focal length of L_1 . A high energy laser mirror (M) with a special coating is employed to deviate visible light in the laser beam. Most near-infrared energy generated by the argon ion laser is absorbed by a beam dump (D). A right-angle prism (P) is utilized to deflect the laser beam. All the optical components are mounted on a solid work table, along with the argon ion laser.

This setup will be used to determine the magnitude of the charge on the particles. The laser sheet can be rotated at any angle to examine the particle behavior with and without the application of an electric field. Thereby, the charge on the particles can be estimated. The effect of contact materials (e.g., steel, copper, plastic, and etc.), environmental factors (humidity, temperature, and applied gaseous stream), and the nature of contact on the magnitude and polarity of the charge on the particles will be studied. The fabrication of a device for charging the particles is in progress.

8.8 Subtask 2.8 MCWM Density Control

The grinding kinetics studies reported under Subtask 2.2 reveal that product size distributions vary substantially with slurry density in the mill (Figure 8-2). The finer product obtained at 70% solids may be desirable for slurry production. However, pre-cleaning steps may be more appropriately carried out at lower concentrations: 30% solids for example. Obviously this would necessitate a slurry-thickening step between cleaning and final grinding.

In order to evaluate the slurry thickening process, stabilization, destabilization and sedimentation, tests are to be performed using procedures similar to those described under Subtask 1.3 of the Phase I research. Since the fine sizes represent the greatest challenge in the slurry-thickening process, this test work will be carried out on a specially-prepared fine coal-slurry. A substantial quantity of nominally -10 mm Taggart coal has been prepared for this purpose. The size distribution of this material is shown in Figure 8-13. A study of the effects of pH, agitation, slurry density and surfactant addition on the stability and sedimentation behavior of suspensions on this coal has been initiated. The results will be supplemented by electrokinetics measurements.

8.9 Subtask 2.9 Stabilization of MCWM

Overview

The purpose of this part of the project is to obtain an understanding of the hydrodynamic properties of coal/water mixtures with the ultimate goal of obtaining stable coal/water suspensions where the detrimental effects of coal particle aggregation and sedimentation are eliminated or at least minimized. More specifically it is necessary to understand how MCWM viscosity,

Figure 8-13. REPLICATE MEASUREMENTS OF THE PARTICLE SIZE DISTRIBUTION OF MICRONIZED TAGGART SEAM COAL TO BE USED IN SLURRY THICKENING STUDIES

sedimentation, and particle aggregation is affected by coal particle size distribution and concentration, additives (dispersants and polymer stabilizers), and coal oxidation.

In Phase 1, models were developed that describe the viscosity, sedimentation and aggregation of coal in coal-water mixtures. All of this work assumed a log normal distribution of particles sizes, so in the last year (Phase 2) the focus was on developing a model to describe the optimal size distribution. It was originally thought that a model due to Furnas could be used, but upon close examination found that this approach had some serious problems. These are discussed below.

A second, related, thrust that was initiated during the past year concerns coal oxidation. Work in Phase 1 indicated that the presence of charged species on the surface of coal particles could lead to problems. As oxidation produces carboxylic acid groups which form COO^- groups at the usual pH of slurries, this could be a problem. Progress in this area will also be described below.

Introduction

In previous reports, a relationship between the viscosity of a coal-water mixture and the "maximal packing ratio" (defined as the volume fraction occupied by the coal particles when maximum packing has been achieved) was described. As might be intuitively expected, the mixture's viscosity varies inversely with this ratio at a given volume fraction. In this initial work only a log normal distribution of particle sizes was used, however. In other words, for a *given distribution* the maximal packing ratio and viscosity was calculated.

During the last year, attention was directed to a related but more difficult problem; which distribution yields the best packing? The importance of this question is obvious, in that this size distribution will yield the lowest effective viscosity at any given volume fraction. This distribution is called the *optimal size distribution*.

The problem of the optimal size distribution was discussed in the classical work of Furnas^[52] as early as 1931. During the last 55 years Furnas' theory, in its original form or with some modifications ^[53], has been a major tool in particle packing theory. However, the Furnas theory has some drawbacks. First, there are some discrepancies with experimental data ^[54]. Second, it is necessary to calculate an integer constant n , which is a root of a rather complicated equation. Third, in this model the transition to a smooth size distribution is neither clear nor self-consistent. Fourth, it is not clear how the limiting cases of infinitely broad and infinitely narrow distributions may be derived from the Furnas' theory. Fifth, there are some intuitively clear qualitative aspects of the behavior of a slurry, such as the obvious fact that when more sieves are used, better control can be ensured in terms of matching the actual size distribution to the optimal size distribution. These considerations are not easily handled in the Furnas theory.

Accordingly, it was necessary to reassess the Furnas' theory and the new analysis is presented first. Then a new model is considered.

The Furnas' Theory

Furnas commenced his analysis by considering a binary mixture of two spheres that have very different sizes; i.e. $D_S/D_L \ll 1$, where D_L and D_S are the diameters of the large and small spheres, respectively. If the large spheres are randomly packed in a container, their maximum volume fraction is $\phi_m \sim 0.637$. The small spheres can subsequently be accommodated in the voids between the large ones, as illustrated in Figure 8-14. If $D_S \ll D_L$, there is no so-called screening effect and all the space not occupied by the large spheres is accessible to the smaller ones. The volume fraction of the space accessible to the small spheres is therefore $(1 - \phi_m)$, so the maximal volume fraction occupied by the small spheres is $(1 - \phi_m) \phi_m$. It follows immediately that in a binary mixture with a large difference in particle diameters the optimal volume ratio of large spheres to small spheres is $\phi_m : \phi_m (1 - \phi_m) = 1 : (1 - \phi_m)$. [Note that Furnas defined this ratio in terms of the fraction of voids. It is easy to show that the two definitions are entirely equivalent].

Any deviation from this ratio will lead to a larger voids volume fraction. If, for example, the content of smaller balls is less than $(1 - \phi_m)$, there would be unfilled space between the large spheres. If this content is more than $(1 - \phi_m)$ then not all of the small spheres will fit into the space between large ones and some must be accommodated "outside" this region (e.g. on the surface). The volume fraction of solids in this "outside" region will be ϕ_m and the overall content of solids would be less than the maximal.

To summarize, the ratio $1 : (1 - \phi_m)$ is optimal for a binary mixture of spheres which differ greatly in size. The voids content is $(1 - \phi_m)^2$, and the volume fraction of balls is therefore $1 - (1 - \phi_m)^2$.

The extension of these arguments to a ternary system containing three kinds of balls with diameters D_1, D_2, D_3 , such that

$$D_1 \gg D_2 \gg D_3 \quad (8-10)$$

uses an analogy to a set of telescope tubes, each of which fits inside the other, to obtain the optimal distribution. First, the largest spheres are placed in the container. Then the voids are filled by the spheres of intermediate diameter. Finally, the remaining voids are filled using the smallest spheres. It is clear from the arguments given above that the optimal ratio of large: intermediate: small spheres must be $1 : (1 - \phi_m) : (1 - \phi_m)^2$, and the voids volume fraction is $(1 - \phi_m)^3$.

Furnas treats an n-component system with diameters:

$$D_1 \gg D_2 \gg \dots D_i \gg D_{i+1} \dots \gg D_n \quad (8-11)$$

in an analogous fashion. The optimal ratio of spheres, in order of descending radii, is:

$$1 : (1 - \phi_m) : (1 - \phi_m)^2 : \dots : (1 - \phi_m)^{n-1} \quad (8-12)$$

Figure 8-14. RANDOM CLOSE PACKING OF SPHERES

and the voids volume fraction is

$$V_n = (1 - \phi_m)^n \quad (8-13)$$

where n is the number of sizes.

These results, describing an ideal system of spheres where the first component is large, but the others are infinitely smaller, are exact, but must obviously be modified in order to describe a real system such as a coal slurry. Furnas considered a system of spheres where the maximal diameter $D_L = D_1$ and minimal diameter $D_S = D_n$ are known and essentially asked the question, what distribution of sizes between these limits gives the optimal distribution? If spheres of various diameters are introduced such that:

$$D_L = D_1 > D_2 > D_3 \dots > D_n = D_S \quad (8-14)$$

then Furnas argued that the best choice for the spacing between the D_i 's is an equal spacing in a log scale, so that

$$\frac{D_{i+1}}{D_i} = \text{const} = \left(\frac{D_S}{D_L} \right)^{1/n-1} \quad (8-15)$$

From Equation 8-13, which describes the relationship between the volume fractions of spheres of diameter D_i $\left(1 : (\phi_m) : (1 - \phi_m)^2 \dots \right)$ for optimal packing, the volume fraction of spheres of radius D_i is given by

$$f_i = \frac{1}{A} (1 - \phi_m)^{i-1} \quad \text{where} \quad D_i = D_S \left(\frac{D_L}{D_S} \right)^{\frac{i-1}{n-1}} \quad (8-16)$$

and the normalizing constant is

$$A = 1 + (1 - \phi_m) + (1 - \phi_m)^2 + \dots = \frac{1 - (1 - \phi_m)^n}{\phi_m} \quad (8-17)$$

A crucial question concerns the number of "divisions" or fractions that should be between the smallest and largest particles. The naive approach is based on the following argument; the fraction of voids is $(1 - \phi_m)^n$, so that n should be as large as possible. Unfortunately, in the Furnas model this will not give the optimal distribution, as a sketch of the distribution function (Equation 8-16) as a function of the parameter n quickly reveals, as shown in Figure 8-15. It can be seen that as $n \rightarrow \infty$, the distribution becomes narrower and narrower. At the limit of large values of n only spheres of diameter D_L are present in the mixture, i.e., there is only one component!

The reason for this discrepancy is simple: if n is large, the consecutive diameters D_i, D_{i+1} are close, and the main assumption of the Furnas theory, that the difference in diameters between each type of sphere is large, is no longer valid.

Figure 8-15. FURNAS' DISTRIBUTIONS FOR DIFFERENT n

To account for this discrepancy Furnas introduces an empirical factor y , defined as the ratio of actual gain in volume upon mixing to the ideal gain (i.e., when assumption (2) is valid). It is then assumed that the factor y depends only on the ratio of subsequent diameters. Using new nomenclature (which is different to that used by Furnas), let this ratio be x

$$x = \frac{D_{i+1}}{D_i} = \left(\frac{D_s}{D_L} \right)^{1/n-1} \quad (8-18)$$

and impose the conditions $y(x=0)=1$ (ideal case) and $y(x=1) = 0$ (no gain upon mixing of spheres of equal diameter), then the empirical expression for y can be expressed, which was obtained by Furnas from a fit to experimental data, as;

$$y = 1.0 - 2.62 x + 3.62 x^2 \quad (8-19)$$

Now, if n grows, the volume gain is affected by two factors:

- 1) The 'ideal' gain in volume increases,
- 2) The ratio y decreases.

Therefore, there is an optimal number n such that these two opposite tendencies are balanced. Differentiating the gain with respect to n , Furnas proposes an equation for n which is rather complicated:

$$\frac{(1-\phi_m)^{n+1} \ln(1-\phi_m) \phi_m}{(1-(1-\phi_m)^{n+2})(1-(1-\phi_m)^{n+1})} = \frac{(2.62 K^{1/(n+1)} - 3.24 K^{2/(n+2)}) \ln K}{(1.0 - 2.62 K^{1/n+1} + 1.62 K^{2/n+2})(n+1)^3} \quad (8-20)$$

where in the new nomenclature

$$K = \frac{D_s}{D_L} \quad (8-21)$$

This equation can be solved numerically for any given K and it gives the optimal number of sizes, n . Unfortunately, in most cases its solution is not an integer, so additional adjustments are necessary.

Suppose now that there are m sizes such that $m > n$. Furnas suggested that a power law distribution

$$f_i = D_i^{K-1} \quad (8-22)$$

should be used, where K is chosen as to ensure that if we take n sizes, the ratio successive values of f_i would be $(1-\phi_m)$. In other words,

$$K = \frac{1-n}{m} \ln(1-\phi_m) \quad (8-23)$$

This gives an expression for the cumulative weight percent (the fraction of balls with diameters less or equal to D_i)

$$F_i = \frac{D_i^K - D_s^K}{D_L^K - D_s^K} \quad (8-24)$$

(Note that in order to make the new notation consistent with the following section, some changes have been made to that used by Furnas.)

After this lengthy sketch of the Furnas theory, it can be seen where it is valid and where it is not. It is valid when the consecutive diameters of the particles are far apart, but it becomes very complicated if the diameters are close. The corrections are not introduced in a self-consistent manner. Corrections are made when the number of sizes are calculated, but not when the volume ratios of the balls of these sizes are calculated. This is neither elegant nor convincing. This theory does not allow the calculation of the volume fraction of voids in the continuous case, nor how this volume fraction depends on D_L/D_S .

In an attempt to improve this situation a new theory has been constructed. Unlike the Furnas model, as the starting point a distribution of particles where the successive size difference is small is chosen. The transition to a continuous distribution then follows naturally.

A Modified Theory

Suppose that there is a mixture of m kinds of balls with sizes

$$D_L = D_1 > D_2 > \dots > D_m = D_S \quad (8-25)$$

Assume that the ratio

$$t = \frac{D_{i+1}}{D_i} = \text{const} \quad (8-26)$$

for all i , so

$$t = \left(\frac{D_S}{D_L} \right)^{1/(m-1)} \quad (8-27)$$

The size distribution of balls that ensures optimal packing is to be determined.

Following the Furnas' idea of "telescopic tubes," a volume V is first filled with large spheres. Their volume fraction is:

$$f_1 = \phi_m \quad (8-28)$$

and the volume fraction of voids is

$$V_1 = 1 - \phi_m \quad (8-29)$$

Now some spheres of diameter D_2 are added and first assume that the packing can be changed in such a way that the total volume is unchanged (this assumption will be modified below). Suppose this is accomplished and the maximal volume of spheres of diameter D_2 is $f_2 V$. The resulting fraction of voids is $V_2 < V_1$. Then add spheres of diameter D_3 , and so on.

After the i -th step, the fraction of voids is V_i . How many spheres of diameter D_{i+1} can be added at the $(i+1)$ th step? If $t = \frac{D_{i+1}}{D_i}$ is small, spheres can be added whose total volume, $f_{i+1} = \phi_m V_i$, (because maximal packing is maintained) and the fraction of voids after $(i+1)$ th step is $V_{i+1} = V_i (1 - \phi_m)$. If, however, $t = \frac{D_{i+1}}{D_i} = 1$, no more spheres can be added because there is close packing at each step! (So, in this case, $f_{i+1} = 0$, $V_{i+1} = V_i$.) In the intermediate case

$$\begin{aligned}
f_{i+1} &= s \phi_m V_i \\
V_{i+1} &= V_i (1 - s \phi_m) \\
f_1 &= \phi_m; \quad V_1 = (1 - \phi_m)
\end{aligned}
\tag{8-30}$$

where s is a "correction factor" that allows for volume change, analogous to the factor y in the Furnas theory.

In analogy to Furnas' treatment, the assumption has been made that the factor s depends only on t , and does not depend on m . Then for the function s :

$$s(t) = \begin{cases} 1, & t = 0 \\ 0, & t = 1 \end{cases} \tag{8-31}$$

For t close to 1

$$s(t) = \alpha(1-t) \tag{8-32}$$

where it is assumed that α is a universal constant which does not depend on the size distribution.

The total volume fraction of voids is then;

$$V_m = (1 - \phi_m) [1 - \phi_m s(t)]^{m-1} \tag{8-33}$$

and the volume fraction occupied by the balls of diameter D_i is

$$f_i = s(t) \phi_m (1 - \phi_m) [1 - \phi_m s(t)]^{i-1} \tag{8-34}$$

The total volume fraction of spheres is given by

$$1 - V_m = 1 - (1 - \phi_m) [1 - \phi_m s(t)]^{m-1} \tag{8-35}$$

and it is possible to determine the cumulative distribution function, F_i , given by

$$dF_i = \frac{P_i}{\sum_{i=1}^m P_i} \tag{8-36}$$

This gives

$$dF_i = \frac{s(t) \phi_m (1 - \phi_m) [1 - \phi_m s(t)]^{i-1}}{1 - (1 - \phi_m) [1 - \phi_m s(t)]^{m-1}} \tag{8-37}$$

The formula for the radii must be added:

$$D_i = D_L t^{i-1} = D_L K^{-(i-1)/(m-1)} \tag{8-38}$$

where $K = \frac{D_L}{D_S}$ is the width of the distribution.

Suppose now that $m \gg 1$. Assume that $m \gg 5 \sim 10$ for most broad distributions. Then

$$t = K^{-\frac{1}{m-1}} = \exp\left(-\frac{\ln K}{m-1}\right) \approx 1 - \frac{\ln K}{m-1} \quad (8-39)$$

and

$$s(t) \approx \frac{d}{m-1} \ln K \quad (8-40)$$

Using the limit $\lim_{m \rightarrow \infty} \left(1 + \frac{1}{m}\right)^m = e$, the volume fraction of voids is given by

$$V_m = \frac{1 - \phi_m}{K^{\alpha \phi_m}} \quad (8-41)$$

and the cumulative distribution function is determined by the equation

$$\frac{dF}{dD} = \frac{1}{D_L} \frac{\alpha \phi_m (1 - \phi_m)}{(1 - (1 - \phi_m) K^{-\alpha \phi_m})} \left(\frac{D}{D_L}\right)^{K \phi_m - 1} \quad (8-42)$$

Integrating this equation and using the boundary conditions

$$\lim_{D \rightarrow D_S - 0} F(D) = 0$$

$$\lim_{D \rightarrow D_L + 0} F(D) = 1 \quad (8-43)$$

gives:

$$F_D = \begin{cases} 0, D < D_S \\ \frac{1 - \phi_m}{K^r - 1 + \phi_m} \left[\left(\frac{D}{D_S}\right)^r - 1 \right], D_S < D < D_L \\ 1, D > D_L \end{cases} \quad (8-44)$$

Analysis and Extension

The first step is to evaluate the constant r in Equation 8-44. A more thorough analysis reveals that the function $s(t)$ coincides with the Furnas' function $y(K^{1/n})$. Unfortunately, Furnas was interested only in the limit $t \rightarrow 0$ while the limit $t \rightarrow 1$ is of interest. (To reiterate, Furnas started with particles that have a large difference in radii, the new analysis starts from small differences). Accordingly, his data considers only regions of small t . Strangely enough, during the 60 years since Furnas proposed his model, nobody appears to have reported comprehensive experiments in this area. A rough estimate gives

$$\alpha \sim 0.3, \text{ so that } r \approx 0.18 \sim 0.19 \quad (8-45)$$

The most interesting feature of the distribution described by Equation 8-44 is that it has a discontinuity at $D \rightarrow D_L$.

We have:

$$\lim_{D \rightarrow D_L - 0} F(D) = \frac{(1 - \phi_m)(K^r - 1)}{K^r - 1 + \phi_m} \quad (8-46)$$

$$\lim_{D \rightarrow D_L + 0} F(D) = 1 \quad (8-47)$$

There is a difference between these two limits, equal to

$$1 - \frac{(1 - \phi_m)(K^r - 1)}{K^r - 1 + \phi_m} = \frac{K^r \phi_m}{K^r - 1 + \phi_m} \quad (8-48)$$

Therefore, the cumulative distribution function has the structure shown in Figure 8-16.

To understand what this means, consider the differential size distribution,

$$f = \frac{dF}{dD} \quad (8-49)$$

This has a simple meaning; the volume fraction of balls with diameters between D and $D + dD$ is $f(D) dD$.

Substituting from Equation 8-49, gives

$$f(D) = \frac{r(1 - \phi_m)}{(K^r - 1 + \phi_m)D_L} \left(\frac{D}{D_s} \right)^{r-1} + \frac{K^r(1 - \phi_m)}{K^r - 1 + \phi_m} \delta(D - D_L) \quad (8-50)$$

The distribution has two terms: a continuous distribution and a step function or δ -like peak. (Figure 8-17)

The meaning of this peak is simple. The starting point was the volume filled by the balls of diameter D_L . This gives the δ -like initial distribution. By adding other balls a continuous

Figure 8-16. CUMULATIVE DISTRIBUTION FUNCTION FROM EQUATION 8-44,
 $K = 10$

Figure 8-17. DIFFERENTIAL DISTRIBUTION FUNCTION FROM EQUATION 8-50,
 $K = 10$

spectrum is introduced in the distribution, but the initially placed big balls remain, hence the calculated peak remains.

This result can also be obtained starting from the "other end". The space can first be filled with small balls (of diameter D_S) and then gradually balls of greater and greater radius added. The final differential distribution will have the form shown on Figure 8-18 .

$$f(D) = \frac{\phi_m K^r}{K^r - 1 + \phi_m} \delta(D - D_S) + \frac{r(1 - \phi_m)}{(K^r - 1 + \phi_m) D_S} \left(\frac{D}{D_S} \right)^{r-1} \quad (8-51)$$

with a peak at D_S . The cumulative distribution in this case will be:

$$F_D = \begin{cases} 0, D < D_S \\ \frac{1 - \phi_m}{K^r - 1 + \phi_m} \left[\left(\frac{D}{D_S} \right)^r - 1 \right] + \frac{\phi_m K^r}{K^r - 1 + \phi_m}, D_S < D < D_L \\ 1, D > D_L \end{cases} \quad (8-52)$$

So the optimal packing can be approached in the following way: first the space is filled by either the smallest or biggest balls. Then the voids are filled with the continuously distributed balls. In both cases the continuous distribution and final fraction of voids are the same.

Assume some balls that obey the distribution described by Equation 8-44 and some balls that obey the distribution described by Equation 8-51 are mixed. The fraction of voids in both distributions is the same: $(1 - \phi_m) K^{-r}$, so the fraction of voids in the mix cannot be larger than this. It will probably not be less, although this is more difficult to prove. This gives the following distribution:

$$F = \begin{cases} 0, D < D_S \\ \frac{1 - \phi_m}{K^r - 1 + \phi_m} \left[\left(\frac{D}{D_S} \right)^r - 1 \right] + \frac{\alpha \phi_m K^r}{K^r - 1 + \phi_m}, D_S < D < D_L \\ 1, D > D_L \end{cases} \quad (8-53)$$

where

$$0 \leq \alpha \leq 1 \quad (8-54)$$

Here α is an arbitrary constant. Its meaning is simple: first there are big and small balls only, and the ratio of their volume fractions is $(1 - \alpha) : \alpha$. Then intermediate balls are added up to the value determined by Equation 8-53. The differential size distribution is (Figure 8-19)

Figure 8-18. DIFFERENTIAL DISTRIBUTION FUNCTION FROM EQUATION 8-51,
 $K = 10$

Figure 8-19. DIFFERENTIAL DISTRIBUTION FUNCTION FROM EQUATION 8-45,
 $K = 10, \alpha = 0.5$

$$f(D) = \frac{\alpha\phi_m K^r}{K^r - 1 + \phi_m} \delta(D - D_S) + \frac{(1-\alpha)K^r(\phi_m)}{K^r - 1 + \phi_m} \delta(D - D_L) + \frac{r(1-\phi_m)}{(K^r - 1 + \phi_m)D_S} \left(\frac{D}{D_S}\right)^{r-1} \quad (8-55)$$

This distribution has two peaks, at D_S and D_L , with a peak height ratio $\alpha:(1-\alpha)$ and an intermediate power-law curve linking them.

Limiting Cases

Consider some limiting cases of the distribution. The distribution depends only on the parameter $K = D_L/D_S$, so the limiting cases $K \rightarrow \infty$ and $K \rightarrow 1$ must be discussed.

a) $K \rightarrow 1$. In this case there is only one size of balls $D_S = D_L$.

Therefore Equation 8-52 gives:

$$F(D) = \begin{cases} 0, D < D_L \\ 1, D > D_L \end{cases} \quad (8-56)$$

The fraction of voids is:

$$\frac{(1-\phi_m)}{K^r} = 1 - \phi_m \quad (8-57)$$

This is reasonable; this is the mono-disperse close-packing limit.

b) $K \rightarrow \infty$. In this case

$$F = \begin{cases} 0, D < D_S \\ \alpha\phi_m + (1-\phi_m) \left(\frac{D}{D_L}\right)^r, D_S < D < D_L \\ 1, D > D_L \end{cases} \quad (8-58)$$

The fraction of voids is

$$\frac{1 - \phi_m}{K^r} = 0 \quad (8-59)$$

This means there is a sufficiently broad particle size distribution, all available space can be filled with balls. The power-law continuous distribution does not depend on D_s only on D_L .

Accordingly, this theory predicts that if the particles are made sufficiently small, all the space can be filled and the distribution is not sensitive to the cut-off size (size of the smallest particle). This too seems to be intuitively reasonable.

Comparison with Furnas' Distribution

In this report the disadvantages of Furnas' theory have been considered and a new model proposed that appears more attractive from a fundamental point of view; because it is more self-consistent, does not involve complex computations and has a proper limiting behavior. However, is it better from a practical point of view?

In Figure 8-20, the fraction of voids in the Furnas' theory is compared with the new theory.

The results of the comparison are:

(1) In the most interesting region $K \sim 10$ ($1/K \sim 0.1$) the new theory predicts that a much higher "loading" (i.e., coal density) should be obtained than that predicted by Furnas' theory. This can be experimentally tested. It can be seen that if nothing is done with the distribution, the fraction of voids will be about 35% (log-normal distribution with $\delta \sim 3$). If particles are recombined following Furnas' recommendations, this fraction will be 30%. If particles are recombined according to this new theory, 25% voids can be obtained. The gain is very large!

(2) In the region $K \rightarrow \infty$ the new theory makes more sense than the Furnas' model.

(3) There is a region of $10^2 < K < 10^3$, where Furnas' distribution gives similar results to this new model. The difference is slight (about 1%) and lies in a region where the application of the Furnas' theory is questionable. One should recall that Furnas' predictions are based on an approximation concerning ball size (note the unphysical hump in the Furnas curves at $K \sim 2$).

Coal Distribution

The size of coal particles in the mixtures ranged from $1.8 \mu\text{m}$ to $200 \mu\text{m}$, so $K \sim 100$. In this region, both Furnas' and the new distribution give comparable results for the fraction of voids: about 15%. In practice the fraction of voids is about 30%, so, in principle, this can be halved by recombining fractions.

The experimental (or actual) cumulative distribution function (Figure 8-21) shows that the actual distribution is far from the optimal one (as predicted by both the Furnas' Model and the new

Figure 8-20. EFFICIENCY OF PACKING

■ Experimental Data Set 1	□ Optimal distribution with $\alpha = 0.5$
● Experimental Data Set 2	◇ Optimal distribution with $\alpha = 1.0$
▲ Experimental Data Set 3	+ Furnas Distribution, $n = 2$
○ Optimal distribution with $\alpha = 0$	

Figure 8-21. PRELIMINARY DATA ON COAL PARTICLES SIZE DISTRIBUTION AND OPTIMAL DISTRIBUTIONS

theory). In fact the cumulative function may be misleading, because it describes integral characteristics of the distribution, while recombining is based on differential characteristics.

The Oxidation of Coal Particles

In the last year, work has focused largely on developing an appropriate methodology, and a systematic study of the effect of oxidation on coal-water mixture properties can now be started.

There are essentially three sampling methods that can be applied to the analysis of coal oxidation. The first of these is the standard KBr pellet method, where coal is ground with KBr and a transparent pellet is produced by compressing the resulting powder in a die. This method samples the coal as a whole and therefore averages both bulk and surface effects. The second method is diffuse reflectance, which essentially uses the scattered radiation from coal placed in a cup. The final method uses a photoacoustic cell. The last two methods measure some surface features, but there is a degrees of penetration into the bulk of the coal particles that remains poorly defined.

It was found that both the photoacoustic and diffuse reflectance procedures gave similar results. Figure 8-22, for example, shows the photoacoustic spectra of an "old" (i.e. weathered) and "new" sample. The spectra appear very similar, but by subtracting one from the other the carbonyl bands (near 1700 cm^{-1}) due to oxidation can be detected. Diffuse reflectance gave higher quality spectra (see Figure 8-23), so this technique will be used. Samples prepared using KBr pellets gave much less definitive results.

A number of samples were oxidized under laboratory conditions to validate these conclusions and produced spectra similar to those shown in Figures 8-22 and 8-23.

9.0 PHASE II, TASK 3 COAL PRECOMBUSTION

Two coal precombustion options will be investigated as retrofit technologies for industrial boilers. One is to utilize a slagging combustor to remove a majority of the ash as a liquid slag upstream of the boiler. The second option is a gasifier that produces a clean fuel for subsequent combustion in the boiler.

9.1 Subtask 3.1 Evaluate Coal Precombustion Options

Proposals that were received from three potential suppliers of slagging combustion systems were reviewed by Penn State and DOE. Because of concerns of the commercial status and applicability of these systems for retrofitting small, industrial boilers, the selection of a system for installation on Penn State's research boiler has been delayed.

9.2 Subtask 3.2 Fundamental and Pilot-Scale Precombustion Studies

No work was conducted on this task.

Figure 8-22. PHOTOACOUSTIC SPECTROSCOPY RESPONSES FOR A WEATHERED COAL SAMPLE (a), A FRESH COAL SAMPLE (b), AND THE DIFFERENCE BETWEEN THE WEATHERED AND FRESH COAL SAMPLES (a - b)

Figure 8-23. DIFFUSE REFLECTANCE SPECTROSCOPY RESPONSES FOR A WEATHERED COAL SAMPLE (a), A FRESH COAL SAMPLE (b), AND THE DIFFERENCE BETWEEN THE WEATHERED AND FRESH COAL SAMPLES (a - b)

10.0 PHASE II, TASK 4 ENGINEERING DESIGN AND COST; AND ECONOMIC ANALYSIS

10.1 Subtask 4.1 Basic Cost Estimation of Boiler Retrofits

Work on this task began with a literature review of slagging combustion and gasification retrofit technologies that supplemented what was already known about the MCWM and DMC technologies. A preliminary review of this literature suggests that the benefits and cost considerations are similar for all four conversion technologies since each is intended to retrofit a fuel oil-designed water tube boiler to fire coal or coal-derived products.

In Phase I, the MCWM and DMC retrofit technologies utilized a premium coal fuel with low ash and low sulfur characteristics in order to mitigate handling and emissions concerns. If the planned Phase II slagging combustion and gasification technologies are implemented, they would extend the types of fuels that can be used to include the higher sulfur and ash coals. The major benefits of being able to utilize these types of coals are the likely lower cost of fuel production and wider availability of these types of coals. The potential disadvantages of using these technologies include: 1) higher costs to retrofit an industrial boiler; 2) increased costs in transporting additional mineral matter for a given quantity of coal; and 3) additional costs for SO₂ control and ash disposal.

It has been decided that the appropriate focus of further efforts should be directed toward development of the linear programming (LP) model as described in Subtask 4.5 "Technology Adoption." This model will be a decision-making tool for selecting new technologies.

10.2 Subtask 4.2 Process Analysis

No work was conducted during this reporting period.

10.3 Subtask 4.3 Environmental and Regulatory Impacts

Subtask 4.3 is focused mainly on the environmental impacts and regulatory burdens associated with the slagging combustor and coal gasification technologies. Although the two technologies are still in the experimental stages of development, several researchers have estimated the commercial potential and the degree to which these technologies can be integrated into current systems. In addition, DOE and EPA have encouraged and supported a number of groups to develop and commercialize the two clean coal technologies. Many interesting results came from these groups, but some of the results are still not publicly available. The technical reports concerning environmental and regulatory aspects of the two technologies have been collected and carefully reviewed over the past several months. The acquisition of reports that are not publicly available has been arranged, and the reports will be reviewed upon their arrival.

In addition to studying the technical reports, government documents have been continually monitored for any regulatory changes affecting coal mining, processing, waste disposal, transportation, combustion, and air emissions. Also, more complete emissions data from the

demonstration boiler at Penn State have been collected and reviewed. These emissions data concern the level of SO_x, NO_x, and particulates associated with various types of coal, and will be used as a basis for estimating the possible emissions discharge from small-scale industrial coal-fired boilers in Pennsylvania.

10.4 Subtask 4.4 Transportation Cost Analysis

No work was conducted this reporting period.

10.5 Subtask 4.5 Technology Adoption

Work on this task started with the receipt of a current census database of industrial and commercial boilers located in the state of Pennsylvania. The census was based upon data collected by the Pennsylvania Department of Labor & Industry (DL&I) and includes only those boilers that have been in active use within the past two years. The population of boilers is quite large, 66,262 boilers, resulting in a database that is about 13 MB in size.

The database was imported into a usable form and then classified as to the particular type of boiler, or boilers, in use at each location. This allowed for a 'first-pass' sifting of the database to isolate a subset of boilers for further analysis that includes only water tube boilers. A preliminary summary of the boiler census by boiler type is presented below. From the table it can be seen that 6,936 have been identified as being water tube boilers.

Summary of Pennsylvania Boilers by Type

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

The summary presented above should be treated as preliminary since the equipment type data field contained various, nonstandardized, designations to denote the equipment type. In addition, this count includes boilers of all sizes and using all types of fuels.

A spatial distribution of all the water tube boilers was also performed at a three-digit zip code region level. The resulting map of the distribution of boilers across the state has allowed for a preliminary assessment to be made of likely regions in the state where high concentrations of water tube boilers and coal supplies exist. A two county region which encompasses some four hundred boilers has been identified for further, more detailed, analysis. The next step in the analysis is to

refine the data for each boiler in the selected region to enable the construction of the linear programming model.

10.6 Subtask 4.6 Regional Economic Impacts

The Pennsylvania computable general equilibrium (CGE) model has been refined. This includes collection of data to update the model and to further delineate its energy sectors. Papers summarizing the construction of the model and illustrating its use have been completed for presentation at major professional conferences and for submission to refereed journals. These papers will be circulated to other project members and to work on ways to expedite the transfer of technical data, as it becomes available, into the model. This will improve the accuracy of the estimation of the regional economic impacts of the adoption of new technologies by DOD and the private sector.

10.7 Subtask 4.7 Public Perception of Benefits and Costs

Part of this subtask focuses on the environmental damages caused by coal fines and the costs associated with those damages. Technological advances in coal mining in recent years and the rising price of coal have led mining firms to attempt to recover and make use of coal fines. Although confirming statistical data has not been obtained, it is believed that increased use of longwall mining methods will be associated with increased coal fines production (see Figure 10-1). The relative increase in the production of coal fines means a relative increase in coal fines shipped by rail, and an increase in coal losses from trains. No Federal regulations exist governing the emission of particulates during coal loading, transport, and unloading, and only West Virginia has specific coal-handling regulations. Given the increasing quantity of coal fines transported without preventative measures, environmental impacts can also be expected to rise.

Following extensive evaluation of potential locations for observing and measuring the impacts of rail transport with coal fines emission, the Vancouver area of British Columbia (B.C.) in Canada was chosen as a primary site. Public complaints about nuisance coal dust from coal trains arose in the early 1970's in B.C. where significant coal train traffic existed as a result of moving coal for export from mines in Western Canada to tidewater terminals. Coal has been shipped over the main rail lines through the Fraser Valley to Vancouver for decades, the quantity transported increased markedly with the opening of the Roberts Bank coal terminal in Vancouver in 1970. In 1984 over 1,950 trains carried approximately 19.5 million tonnes of coal through southern B.C. to Vancouver coal terminals, Roberts Bank and Neptune Terminals.

Concern about the deposition of coal dust in the Cranbrook area and in the communities of Kamloops, Agassiz and Surrey was expressed by the public in numerous complaints to railway companies, municipalities, Members of Parliament and government agencies. Most of the complaints relating to nuisance coal dust prior to 1975 came from citizens and town councils in communities located from Kamloops to Vancouver. Since the advent of sealant sprays in 1975 the

Figure 10-1. LONGWALL COAL PRODUCTION AS PORTION OF TOTAL U.S. COAL PRODUCTION

number of complaints have declined, those received have come from Agassiz, Surrey and Kamloops, B.C., and are associated with the CNR and CPR rail corridors. Currently (according to sources at Environment Canada) any occurrence of severe dusting is reported to the mine or terminal and measures are taken (increased spraying) to correct the problem. With respect to government legislation, there is no federal or provincial standard which applies specifically to the short-duration nuisance pollution incidents associated with wind-blown coal dust from trains. Existing air quality objectives for particulate matter established by various government agencies apply to total suspended particulates or total dustfall without regard to its composition or source. There are no specific air quality objectives for coal particles.

In an effort to initiate a hedonic property value study, housing transactions information with the B.C. Assessment Authority is being pursued. The B.C. Assessment Authority has a central computerized database of all the pertinent information although housing characteristics data is confidential. Reports can be generated which provide the following information: owner, address, location, class and date of construction. The associate commissioner of the B.C. Assessment Authority informed Penn State that confidentiality could not be waived. The cost of obtaining a restricted data set and the feasibility of continuing with a hedonic price study is being determined. As a parallel, a contingent valuation survey instrument is being developed. This is a survey based method of asking people their value for environmental commodities. Since these commodities are not bought and sold in regular markets there is no data available on their value. The contingent valuation methods is well researched and considered a valid method of valuing environmental commodities. In essence, a survey will explain the commodity to individuals and then through a series of questions determine the individual's value for changes in the level of environmental quality. This could be used as a stand alone research tool or could include sections to illicit housing data characteristics which could increase the feasibility of a hedonic study.

In addition to the B.C. research effort, information is being collected on the Altavista, Virginia area as a potential test site or as a source of additional anecdotal evidence, especially with respect to averting cost expenditures. In Virginia, the test will be to determine if coal dust from rail transport has an economic impact. This suggest an extra-market side-effect from increased coal usage not captured in standard economic markets. The contingent valuation survey has been initiated in the Virginia area and preliminary results suggest that there is an impact from coal dust and coal transport but that it is not very large. Empirical analysis will begin once it appears no more surveys will be returned. Averting cost expenditures is another method for valuing environmental commodities. In this case, a value is put on avoiding environmental damage to suggest the value of having a clean environment. Reports from Virginia suggested that certain firms were having to undertake extra cleaning expenses in response to increased coal dusting. Calculating the increased costs of cleaning up after coal dusting provides a lower bound estimate of

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

No work was scheduled or conducted.

12.0 MISCELLANEOUS ACTIVITIES

Three papers were prepared and will be presented at the Tenth Coal Preparation, Utilization, and Environmental Control Contractors Conference which was held at Pittsburgh, Pennsylvania on July 18-21, 1994. The titles and authors of the papers are:

- "The Economic Prospects of Coal-Based Fuels for Non-utility Boilers," authored by Richard L. Gordon, Timothy J. Considine, Jeffrey Lazo, Katherine T. McClain, and Adam Rose;
- "Preparing Coal for Industrial Boiler Retrofit Applications," authored by Mark S. Klima, Richard Hogg, Subhash Chander, M. Thaddeus Ityokumbal, Peter T. Luckie, and Heechau Cho; and
- "Engineering Design Considerations of Industrial Boiler Retrofits," authored by Donald K. Morrison, Robert L. Frato, Todd A. Melick, Todd M. Sommer, Bruce G. Miller, and Alan W. Scaroni.

13.0 NEXT SEMIANNUAL ACTIVITIES

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

- Begin detailed test program using the continuous, high-speed solid-bowl centrifuge;
- Use the batch hindered-settling model to examine centrifugal separations;
- Evaluate the effect of collector and surfactant concentration during the advanced froth flotation studies;
- Continue investigations into grinding kinetics;
- Continue the formulation of the test coals and produce laboratory-scale quantities for atomization and combustion performance characterizations;
- Complete the installation of the MCWM circuit and begin shakedown;
- Conduct micronized coal testing in the demonstration boiler;
- Continue the fundamental studies into atomizer erosion, demonstration boiler modeling and model validation, and corrosion-erosion studies of the boiler convective pass;
- Begin the fundamental emissions studies;
- Identify and begin procuring pollution control systems for the demonstration boiler;
- Obtain estimates of the quantity of coal fines lost during transport. Coal companies are being contacted to obtain load size distribution samples to determine the quantity of coal

the value of not having coal dusting. Due to the extreme difficulty in collecting reliable averting cost expenditures and the fact that this only provides a lower bound estimate, this method has not been used very much to date.

10.8 Subtask 4.8 Social Benefits

No work was conducted this reporting period.

10.9 Subtask 4.9 Coal Market Analysis

Coal consumption and production in the United States declined after the end of World War II until the early 1960s, when an increasing trend commenced. Although coal has historically been the main fuel for electric utilities, the electricity generation sector only accounted for 17% of coal use in 1949. However, electricity has, by degrees, become the predominate market for coal, accounting for 85% of coal use in 1991. Not only has there been a shift in the shares of end-users as consumers of coal, but also, the amount of coal consumed by electric utilities between 1947 and 1992 increased sharply, while coal use in other sectors declined.

The location of the growth in consumption and supply has a bearing on the growth in electric utility coal use and the shift of coal from a multi-use fuel to a predominately single-use fuel. An analysis of principal coal consuming states revealed that the rate of increase of coal use by electric utilities was greater in the West than in the East. Furthermore, in the western principal coal consuming states, where coal is almost exclusively consumed by electric utilities, coal increased its share of an expanding electricity market. Coal lost share of the electricity market in all the main eastern coal using states; however, the growth of electricity offset these losses, more state energy in the West is in the form of electricity than in the East, and a greater proportion of state energy is generated by coal in the West than in the East.

The growth in coal output corresponded to the areas of increasing consumption. The majority of the growth in coal supply came from western states, particularly the Mountain region states, Texas in the West South Central region, and North Dakota in the West North Central region. The relatively low production costs and sulfur content of Wyoming and Montana coal have resulted in broad distribution of coal shipments from these states, enabling them to capture markets from Illinois Basin producers.

At least four factors explain the differential use of coal by electric utilities across states: 1) the shift of the New England states to oil, 2) the emergence of nuclear power, 3) rising natural gas prices, and 4) increasing incremental costs of expanding hydropower projects.

10.10 Subtask 4.10 Engineering Design

No work was scheduled or conducted.

10.11 Subtask 4.11 Integration of Analyses

No work was scheduled or conducted.

finest now being transported. Information is being compiled on the technical generation of coal dust and the coal processing and transport cycle to determine the magnitude of the fugitive coal dust problem.

- Estimate the economic losses associated with the fugitive coal fines. The primary focus is on the collection of hedonic property value information in the Vancouver, B.C. area to be supplemented by a contingent valuation survey implementation.
- Review mitigation measures and their estimate costs. This will be collected from published information and data supplied by various industry contacts.
- Estimate the economic costs to homeowners and businesses who suffer damages from fugitive coal fines. Averting expenditures information may be available in the Altavista area or from other previously published information. Additional averting expenditure information will be obtained in the C.V. survey instrument but will not conduct data collection primarily on such expenditures.

14.0 SELECTED NOMENCLATURE

c_p	Specific heat capacity at constant pressure for the gas
c_p	Heat capacity of the particle
D_p	Particle diameter
F_D	drag force per unit particle mass
h	Enthalpy
h	Convective heat transfer coefficient
k	Kinetic energy of turbulence
k_∞	Thermal conductivity of the continuous phase
M_i	Molecular weight of species i
m_i	Mass fraction of species i
m_p	Mass of the particle
P	Pressure
Pr	Prandtl number of the gas
R	Gas constant
Re_d	Reynolds number based on the particle diameter and the relative velocity
SA	Surface area of the particle
S_h	Enthalpy source term due to chemical reaction
S_s	Species source term due to chemical reaction
T	Temperature
T_∞	Local temperature of the continuous phase
t	Time

u	u -velocity vector
u_i	Time average velocity component
u'_i	Fluctuating component of u_i
Δt	The integration time step
γ_{ij}	Kronecker delta
ε	Dissipation rate of k
ρ	Gas density
ρ_p	Particle density
τ	Turbulence time scale
δ	Empirical constant
	Subscripts
C	Combustion products
F	Fuel
k	Kinetic energy of turbulence
O	Oxidant
p	Particle
s	Chemical species
ε	Dissipation rate of k
∞	Continuous phase

15.0 ACKNOWLEDGMENTS

Funding for the work was provided by the U.S. Department of Defense (via an interagency agreement with the U.S. Department of Energy) and the Commonwealth of Pennsylvania under Cooperative Agreement No. DE-FC22-92PC92162. The project is being managed by the U.S. Department of Energy, Pittsburgh Energy Technology Center (PETC). John Winslow of PETC is the project manager.

The following Penn State staff were actively involved in the program: Michael Anna, Paul Colose, William Cooke, Robert C. Gilbert, Howard R. Glunt, Ruth Krebs, Scott Lyons, Bradley Maben, Joseph Suefert, Christopher Snyder, Sarma V. Pisupati, and Ronald T. Wincek.

The following Penn State graduate students were actively involved in the program: Mitra Ahmadi, Girish Ahuja, Juan Benavides, Ben Eduardo, Mohamed Fofana, Oscar Frias, Brett Humphries, Gi Jung, John Kovalchick, Yuliang Li, Hurriyet Polat, Mehmet Polat, Robert Weiland, Timothy Wilkinson, Daode Xu, and Ronghua Zhou.

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Appendix A. Burner Stability Summary Test Sheets

The summary sheets contained in Appendix A are copies of the data sheets. It should be noted that the steam drum pressure was less than 200 psig (at high firing rate) when it normally is greater than 200 psig. This resulted in steam production rates greater than 15,000 lb/h which is atypical operation. Also, the last column which contains a stability ranking is a subjective ranking performed by the operating personnel.

MATRIX #1 MOVING SECONDARY DAMPER ONLY								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	162.00	1376.36	3516.80	max (7 3/8)	max (8.625")	532.00
2.00	2.75	15200000	165.00	1295.40	3538.04	6.375 "	max (8.625")	533.50
3.00	2.75	15200000	162.00	1374.46	3535.85	5.375	max (8.625")	532.80
4.00	2.75	15200000	164.00	795.19	3700.17	4.375	max (8.625")	532.40
5.00	2.75	15200000	163.00	459.60	3905.89	3.375	max (8.625")	532.20
6.00	2.75	15200000	160.00	0.00	3953.20	2.375	max (8.625")	531.40
7.00	2.75	15200000	158.00	0.00	3958.09	min (2.0)	max (8.625")	531.40

Test Point	SEC SWIRL	TERT SWIRL	%O2	LAND	LAND	STEAM PPH	GUN DIMEN.	STABILITY
				CO	CO2			
1.00	max	max	3.30	13.00	10.32	16900000	30 inches	10.00
2.00	max	max	3.06	18.00	10.33	17100000	30 inches	9.90
3.00	max	max	2.89	19.00	10.48	16800000	30 inches	9.90
4.00	max	max	2.53	20.00	10.68	16700000	30 inches	9.90
5.00	max	max	2.45	21.00	10.88	16900000	30 inches	9.90
6.00	max	max	2.12	20.00	11.06	16500000	30 inches	9.90
7.00	max	max	2.29	22.00	10.99	16200000	30 inches	9.90

NOTES: This configuration seemed to have very little effect on the stability of the burner
The throat of the burner remained black with some refractory becoming radiant at the very end of the tile
O2 was not adversely affected as the damper was completely closed

MATRIX #2 MOVING TERTIARY DAMPER ONLY								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	157.00	1374.83	3805.39	MAX (7 3/8)	7.625	534.00
2.00	2.75	15200000	160.00	1211.74	4100.00	MAX (7 3/8)	6.625	532.00
3.00	2.75	15200000	157.00	1447.78	3311.13	MAX (7 3/8)	5.625	529.60
4.00	2.75	15200000	161.00	1647.95	2587.54	MAX (7 3/8)	4.625	505.10
5.00	2.75	15200000						
6.00	2.75	15200000						
7.00	2.75	15200000						

Test Point	SEC SWIRL	TERT SWIRL	%O2	LAND	LAND	STEAM PPH	GUN DIMEN.	STABILITY
				CO	CO2			
1.00	max	max	3.35	21.00	10.24	16300000	30 inches	9.90
2.00	max	max	3.28	19.00	10.15	16300000	30 inches	9.90
3.00	max	max	2.48	18.00	10.62	16300000	30 inches	9.90
4.00	max	max	0.36	23000.00	12.05	15000000	30 inches	7.80
5.00								
6.00								
7.00								

NOTES: As expected the O2 concentration fell off drastically as the damper stroke reached the half way point

MATRIX #3 CHANGING SECONDARY SWIRL ONLY								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	157.00	1406.21	3406.78	Max (7 3/8")	Max (8 5/8")	533.50
2.00	2.75	15200000	154.00	1407.09	3386.91	Max (7 3/8")	Max (8 5/8")	532.40
3.00	2.75	15200000	156.00	1549.10	3389.01	Max (7 3/8")	Max (8 5/8")	532.70
4.00	2.75	15200000	151.00	1549.28	3502.01	Max (7 3/8")	Max (8 5/8")	532.20
5.00	2.75	15200000	155.00	1615.24	3530.12	Max (7 3/8")	Max (8 5/8")	532.40
6.00	2.75	15200000	154.00	1615.24	3557.16	Max (7 3/8")	Max (8 5/8")	532.30
7.00	2.75	15200000	154.00	1483.15	3508.96	Max (7 3/8")	Max (8 5/8")	534.70

Test Point	SEC SWIRL	TERT SWIRL	%O2	CO	CO2	STEAM PPH	GUN DIMEN.	STABILITY
1.00	max (O)	max (O)	3.08	4.00	10.36	15800.00	30 inches	10.00
2.00	5.250	max (O)	3.05	5.00	10.39	16000.00	30 inches	9.90
3.00	6.250	max (O)	3.15	6.00	10.26	16500.00	30 inches	9.90
4.00	7.250	max (O)	3.08	6.00	10.27	16100.00	30 inches	9.80
5.00	8.250	max (O)	3.10	7.00	10.29	16400.00	30 inches	9.80
6.00	9.250	max (O)	3.20	8.00	10.27	15300.00	30 inches	9.80
7.00	10.125	max (O)	3.08	8.00	10.31	16000.00	30 inches	9.80

NOTES: At test point #4 the dark zone in the burner tile moved outward even more while the flame narrowed
Some pulsing of the flame was noticed at the last 3 points of this set

MATRIX #4 MOVING TERTIARY SWIRL ONLY								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	150.00	1448.11	3539.27	Max (7 3/8")	Max (8 5/8")	537.40
2.00	2.75	15200000	157.00	1413.70	3734.23	Max (7 3/8")	Max (8 5/8")	538.40
3.00	2.75	15200000	156.00	1414.74	3841.28	Max (7 3/8")	Max (8 5/8")	537.00
4.00	2.75	15200000	159.00	1076.59	3867.27	Max (7 3/8")	Max (8 5/8")	535.50
5.00	2.75	15200000	157.00	1124.46	3918.30	Max (7 3/8")	Max (8 5/8")	537.60
6.00	2.75	15200000	149.00	1338.54	3868.68	Max (7 3/8")	Max (8 5/8")	539.70
7.00	2.75	15200000	153.00	1377.86	3920.25	Max (7 3/8")	Max (8 5/8")	540.20
8.00	2.75	15200000	156.00	1374.46	4009.58	Max (7 3/8")	Max (8 5/8")	541.50
9.00	2.75	15200000	151.00	1448.81	3860.11	Max (7 3/8")	Max (8 5/8")	537.70

Test Point	SEC SWIRL	TERT SWIRL	%O2	CO	CO2	STEAM PPH	GUN DIMEN.	STABILITY
1.00	MAX (0)	4.625	3.51	10.00	10.01	16100.00	30 inches	10.00
2.00	MAX (0)	5.625	3.90	11.00	9.80	15800.00	30 inches	9.80
3.00	MAX (0)	6.125	4.05	11.00	9.70	17300.00	30 inches	9.80
4.00	MAX (0)	6.625	4.19	4.00	9.55	17400.00	30 inches	9.80
5.00	MAX (0)	7.125	4.18	6.00	9.41	17300.00	30 inches	9.80
6.00	MAX (0)	7.625	4.27	9.00	9.58	17500.00	30 inches	9.80
7.00	MAX (0)	8.125	4.31	12.00	9.57	17300.00	30 inches	9.80
8.00	MAX (0)	8.625	4.23	13.00	9.41	17400.00	30 inches	9.70
9.00	MAX (0)	9.250	4.35	14.00	9.35	17400.00	30 inches	9.70

Notes: Flame started to approach the rear wall
Flame started to bounce out of the burner tile around points 8 and 9
Burner throat still dark

MATRIX #5 MOVING TERTIARY DMPR. W/MIN TERT SWIRL								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	158.00	1455.43	3876.81	MAX (7 3/8)	8.625	534.50
2.00	2.75	15200000	162.00	1387.00	3895.34	MAX (7 3/8)	7.625	535.50
3.00	2.75	15200000	166.00	1379.38	3922.66	MAX (7 3/8)	6.625	536.20
4.00	2.75	15200000	167.00	1381.83	3450.96	MAX (7 3/8)	5.625	533.80
5.00	2.75	15200000	163.00	1456.17	2444.07	MAX (7 3/8)	5.000	530.00
6.00	2.75	15200000						
7.00	2.75	15200000						

Test Point	SEC SWIRL	TERT SWIRL	%O2	CO	CO2	STEAM PPH	GUN DIMEN.	STABILITY
1.00	MAX	MIN (9.25)	3.13	19	10.10	17373.00	30	9.80
2.00	MAX	MIN (9.25)	3.67	21	9.73	17235.00	30	9.85
3.00	MAX	MIN (9.25)	3.60	21	9.73	17664.00	30	9.85
4.00	MAX	MIN (9.25)	2.68	17	10.23	17690.00	30	9.80
5.00	MAX	MIN (9.25)	1.27	23	11.20	17446.00	30	9.50
6.00								
7.00								

NOTE: Beyond point 5, CO rose sharply and the breaching started rumbling

MATRIX #6 CLOSING SECONDARY WITH MIN. TERT. SWIRL

Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	165.00	1456.67	3778.02	6.50	MAX (8 5/8)	536.40
2.00	2.75	15200000	161.00	1457.01	3721.54	5.50	MAX (8 5/8)	537.30
3.00	2.75	15200000	164.00	922.38	3875.84	4.50	MAX (8 5/8)	537.20
4.00	2.75	15200000	167.00	800.37	3981.42	3.50	MAX (8 5/8)	536.40
5.00	2.75	15200000	164.00	462.04	4007.23	2.50	MAX (8 5/8)	535.40
6.00	2.75	15200000	157.00	0.00	4083.23	CLOSED (2)	MAX (8 5/8)	536.00
7.00	2.75	15200000						

Test Point	SEC SWIRL	TERT SWIRL	%O2	CO	CO2	STEAM PPH	GUN DIMEN.	STABILITY
1.00	MAX	MIN (9.25)	3.67	24.00	9.79	17951.00	30	9.80
2.00	MAX	MIN (9.25)	3.49	24.00	9.93	17235.00	30	9.80
3.00	MAX	MIN (9.25)	3.14	24.00	10.17	16539.00	30	9.80
4.00	MAX	MIN (9.25)	2.84	25.00	10.34	16541.00	30	9.80
5.00	MAX	MIN (9.25)	2.88	25.00	10.38	17081.00	30	9.80
6.00	MAX	MIN (9.25)	2.79	25.00	10.43	16770.00	30	9.80
7.00								

MATRIX #7 CLOSING TERTIARY WITH MIN. SEC. SWIRL								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	155.00	1454.55	3608.39	MAX (7 3/8)	7.625	534.10
2.00	2.75	15200000	160.00	1453.65	3660.41	MAX (7 3/8)	6.625	532.40
3.00	2.75	15200000	163.00	1454.56	3144.53	MAX (7 3/8)	5.625	531.40
4.00	2.75	15200000						
5.00	2.75	15200000						
6.00	2.75	15200000						
7.00	2.75	15200000						

Test Point	SEC SWIRL	TERT SWIRL	%O2	CO	CO2	STEAM PPH	GUN DIMEN.	STABILITY
1.00	MIN	MAX	2.47	25.00	10.47	17044.00	30	9.90
2.00	MIN	MAX	2.43	25.00	10.49	16736.00	30	9.90
3.00	MIN	MAX	1.78	26.00	10.93	17462.00	30	9.50
4.00								
5.00								
6.00								
7.00								

MATRIX #8 CLOSING SECONDARY WITH MIN. SEC. SWIRL								
Test Point	GAS VOLTS	GAS RATE	PRIM. ACFM	SEC. ACFM	TERT. ACFM	SEC DAMPER	TERT DAMPER	BOILER OUTLET
1.00	2.75	15200000	152.00	1453.11	3436.24	6.50	MAX (8 5/8)	533.40
2.00	2.75	15200000	161.00	1454.36	3439.18	5.50	MAX (8 5/8)	533.30
3.00	2.75	15200000	163.00	1030.00	3438.35	4.50	MAX (8 5/8)	533.50
4.00	2.75	15200000	167.00	799.30	3441.30	3.50	MAX (8 5/8)	532.60
5.00	2.75	15200000	159.00	799.19	3551.11	2.50	MAX (8 5/8)	532.20
6.00	2.75	15200000	170.00	0.00	3495.19	CLOSED	MAX (8 5/8)	531.90
7.00	2.75	15200000						

Test Point	SEC SWIRL	TERT SWIRL	%O2	CO	CO2	STEAM PPH	GUN DIMEN.	STABILITY
1.00	MIN	MAX	2.60	38.00	10.54	17220.00	30	N/A
2.00	MIN	MAX	2.20	34.00	10.67	16835.00	30	N/A
3.00	MIN	MAX	1.58	31.00	11.06	16820.00	30	N/A
4.00	MIN	MAX	1.50	30.00	11.20	17189.00	30	N/A
5.00	MIN	MAX	1.50	29.00	11.14	16840.00	30	N/A
6.00	MIN	MAX	1.50	29.00	11.11	17052.00	30	N/A
7.00								

NOTE: SOME STEAM FLOWS ARE ARTIFICALLY HIGH DUE TO DROP IN STEAM PRESSURE

Appendix B. Test Summary Graphs

Number of Data Points - 30 second time interval
(T_0 at 06:05 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 7/13/94

Boiler Outlet Temp. vs Time for Test Conducted on 7/13/94

O₂ and CO Concentration vs Time for Testing Conducted on 7/14/94

Boiler Outlet Temp. vs Time for Test Conducted on 7/14/94

Number of Data Points - 30 second time interval
(T_O at 08:34 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 7/15/94

Boiler Outlet Temp. vs Time for Test Conducted on 7/15/94

Number of Data Points - 30 second time interval
 (T_o at 05:59 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 7/18/94

Boiler Outlet Temp. vs Time for Test Conducted on 7/18/94

Number of Data Points - 30 second time interval
(T_o at 06:00 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 7/19/94

Number of Data Points - 30 second time interval
(T_o at 06:00 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 7/19/94

O₂ and CO Concentration vs Time for Testing Conducted on 7/20/94

Boiler Outlet Temp. vs Time for Test Conducted on 7/20/94

O₂ and CO Concentration vs Time for Testing Conducted on 7/21/94

Number of Data Points - 30 second time interval
(T_O at 05:58 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 7/21/94

O₂ and CO Concentration vs Time for Testing Conducted on 7/27/94

Number of Data Points - 30 second time interval
(T_o at 11:03 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 7/27/94

Number of Data Points - 30 second time interval
(T₀ at 06:05 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 7/28/94

Number of Data Points - 30 second time interval
(T_o at 06:05 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 7/28/94

Number of Data Points - 30 second time interval
(T_o at 06:04 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 7/29/94

Boiler Outlet Temp. vs Time for Test Conducted on 7/29/94

Number of Data Points - 30 second time interval
(T_o at 06:00 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/01/94

Boiler Outlet Temp. vs Time for Test Conducted on 8/01/94

Number of Data Points - 30 second time interval
(T_o at 11:38 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/03/94

Number of Data Points - 30 second time interval
(T_o at 11:38 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 8/03/94

Number of Data Points - 30 second time interval
(T_0 at 06:10 a.m.)

O_2 and CO Concentration vs Time for Testing Conducted on 8/04/94

Boiler Outlet Temp. vs Time for Test Conducted on 8/04/94

Number of Data Points - 30 second time interval
(T_o at 06:26 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/05/94

Number of Data Points - 30 second time interval
(T_o at 06:26 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 8/05/94

Number of Data Points - 30 second time interval
(T_o at 09:44 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/10/94

O₂ and CO Concentration vs Time for Testing Conducted on 8/23/94

Number of Data Points - 30 second time interval
(T_o at 05:47 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 8/23/94

Number of Data Points - 30 second time interval
(T₀ at 06:04 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/25/94

Boiler Outlet Temp. vs Time for Test Conducted on 8/25/94

Number of Data Points - 30 second time interval
(T_o at 06:26 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/30/94

Number of Data Points - 30 second time interval
(T_o at 06:26 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 8/30/94

Number of Data Points - 30 second time interval
(T_o at 06:00 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 8/31/94

Boiler Outlet Temp. vs Time for Test Conducted on 8/31/94

Number of Data Points - 30 second time interval
(T_o at 06:02 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 9/01/94

Number of Data Points - 30 second time interval
(T_o at 06:02 a.m.)

Boiler Outlet Temp. vs Time for Test Conducted on 9/01/94

Number of Data Points - 30 second time interval
(T_o at 06:00 a.m.)

O₂ and CO Concentration vs Time for Testing Conducted on 9/02/94

Boiler Outlet Temp. vs Time for Test Conducted on 9/02/94