COMBUSTION AND FUEL CHARACTERIZATION
OF COAL-WATER FUELS

VOLUME 5
PILOT-SCALE ASH DEPOSITION AND PERFORMANCE TESTING OF
COAL-WATER FUELS

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SUMMARY

The ash deposition and performance behavior of a cross-section of coal-water fuels (CWFs) were investigated during comprehensive pilot-scale testing under Task 5 of the Department of Energy's Combustion and Fuel Characterization of Coal-Water Fuels project. The key results from this effort including combustion, furnace slagging, convective pass fouling, fly ash erosion and electrostatic precipitator collection characteristics of the test fuels, are summarized in this report.

Data were obtained on twelve different CWFs as well as three baseline pulverized coals. Three coal types were fired at different levels of coal beneficiation to assess the effects of coal cleaning on performance. Five CWFs prepared from the same feed coal by different manufacturers were tested to assess the effects of slurry processing. CWFs prepared from both standard grind and microfine grind coals were evaluated. In addition a microfine CWF was fired at fuel temperatures up to 220°F to evaluate the effect of thermal atomization on performance.

Test results indicated that for selected high quality coals, CWFs can be fired at the high temperatures associated with tightly designed oil units with controllable ash deposits. Coal type and furnace temperature were the most dominant factors dictating deposit characteristics. Slurry processing did not have a strong direct impact on ash deposition. Coal beneficiation reduced the ash deposition rate and also significantly reduced the convection tube erosion rate. Atomizer spray quality was the most influential factor on combustion and fly ash size. Preheating to 220°F fuel temperature improved atomization quality and overall combustion and boiler performance characteristics of the microfine CWF.

Section 1

INTRODUCTION

Coal-water fuel (CWF) offers a means of shifting dependence from imported oil to domestic coals. However, there are many unanswered questions concerning the impact which these coal-based, higher ash containing fuels will have on furnaces originally designed for very low ash fuels. In order to assess the commercial viability of coal-water fuels, both combustion and fireside performance characteristics must be established to enable the prediction of potential unit derating, equipment modification and associated retrofit costs.

A four year research project sponsored by the Department of Energy was awarded to Combustion Engineering, Inc. (C-E) to develop the performance and cost data needed to evaluate the commercial application of CWF. Gulf Research and Development, Energy International and Adelphi Center for Energy Studies were subcontracted to support in the assessment of fuel properties of a cross-section of CWFs. Areas of investigation under this research program were divided into six tasks that began with coal resource evaluation and culminated in the assessment of the technical and economic consequences of switching representative commercial units from oil to state-of-the-art CWF firing.

This report (Volume 5) summarizes the results obtained during comprehensive pilot-scale testing on the ash deposition and performance behaviors of a cross-section of CWFs conducted under Task 5. Primary objectives were to assess waterwall slagging, convective pass fouling, fly ash erosion and electrostatic precipitator performance during CWF firing. Data were obtained from twelve different CWFs prepared from five different coal seams. Three of the coal seams beneficiated at different levels were evaluated to determine the effects of coal cleaning on CWF performance. Five CWFs prepared from the same feed coal by different manufacturers were evaluated to assess the effects of slurry processing. A CWF prepared from microfine ground coal (MCWF) was evaluated to assess the effect of thermal atomization. Additionally, baseline tests were conducted with both fine grind and typical boiler grind pulverized

coal to provide direct comparative data. Information obtained from this task provided inputs for predictions of commercial furnace performance under Task 6 Commercial Application and Economics of CWF.

A summary report (Volume 1) provides a general overview of the project and a summary of principal results and conclusions. Information on other project tasks regarding technical approaches, test equipment, test procedures, test data and analyses relating to specific aspects of the work, are provided in the following volumes.

Volume 1	-	Task 1 to Task 6	Final Summary Report
Volume 2	-	Task 1 & Task 3	Selection and Procurement of Candidate Coal-Water Fuels with Commercial Potential
Volume 3	-	Task 2	Bench-Scale Characterization of Chemical, Physical and Combustion Properties of Coal-Water Fuels
Volume 4	-	Task 4	Commercial-Scale Atomizer and Burner Evaluation
Volume 6	-	Task 6	Commercial Application and Economics of Coal-Water Fuels

Section 2

TEST METHODOLOGY

The test program developed for this task was designed to utilize comprehensive bench and pilot-scale testing techniques to provide detailed combustion and ash deposition data on coal-water fuels required to predict their performance in full size commercial units. Evaluation included the following key areas:

BENCH-SCALE FUEL CHARACTERIZATION

Bench-scale characterization of the CWFs was coordinated with Task 2 testing to provide data on the as-fired test fuels. Standard ASTM tests for solids content, proximate, ultimate, higher heating value, ash composition and ash fusibility temperatures were conducted to assess the general fuel characteristics and the relative combustion behavior of the CWF feed coals. Specialty in-house tests were used to provide more detailed information on specific coal characteristics. These included gravity fractionation analysis to assess furnace slagging potential by determining the segregated iron content of the coal, and weak acid leaching to assess fouling potential by determining the amount of active alkali content in the coal.

Each CWF was characterized for its rheological properties. The objective was to obtain information on CWF viscosity and flow behavior in order to predict atomization quality. Low and high shear viscosity measurements (100 sec^{-1} to 4000 sec^{-1} shear rates) were made to assess the flow behavior. Additionally, the effects of heating on MCWF's viscosities were measured at several solids concentrations (68%, 67% and 64% solids) to assess changes in fluid properties as a function of temperatures (80°F to 220°F). A more in-depth discussion of the bench-scale fuel characterization results is provided in Task 2 of this project.

COLD FLOW ATOMIZATION CHARACTERIZATION

The cold flow atomization characteristics of the CWFs were evaluated in the Atomization Test Facility (ATF) using a laser diffraction droplet sizing technique. A description of this facility is presented in Appendix A. The objective of the ATF testing was to establish atomizer operating conditions versus spray quality prior to combustion testing in the Fireside Performance Test Facility (FPTF). The goal was to maintain equivalent atomization quality (within realistic atomizer operating parameters) during the combustion testing of each CWF.

Each CWF was tested using a twin-fluid Y-jet atomizer covering a range of atomizing air-to-fuel ratios (0.05 to 0.20). Additionally, the MCWF was evaluated over a range of solids concentrations (67% to 64%) and fuel temperatures (70°F to 220°F) to assess their effects on atomization quality.

PILOT-SCALE COMBUSTION PERFORMANCE TESTING

The combustion performance of the CWFs and pulverized coals was evaluated in the Fireside Performance Test Facility (FPTF). A detailed description of the facility is in Appendix B. The FPTF is a 4×10^6 Btu/hr pilot-scale combustion facility used primarily to evaluate the fuel properties which influence fireside boiler performance. A schematic of the test furnace is shown in Figure 2-1. Three waterwall test panels are located in the radiant section of the furnace to study lower furnace ash deposition. In the upper section of the furnace, a test section simulating process heater surface is used to assess process heater deposition. In the convective section, four banks of air-cooled probes are used to simulate boiler superheater tubes to evaluate convective section ash deposition. Furnace gas temperature profiles and residence times in the FPTF are similar to typical utility boilers. Flame temperature is controlled by varying combustion air preheating from ambient to 1000°F. Test firing in the FPTF allowed a direct comparison of the performance characteristics of different test fuels and also provided inputs to C-E's computer models to predict boiler and auxiliary equipment performance under Task 6, Commercial Application and Economics of CWFs.

FIGURE 2-1 FIRESIDE PERFORMANCE TEST FURNACE

COMBUSTION PERFORMANCE TEST MATRIX

The combustion and performance characteristics of the CWFs were evaluated during comprehensive testing conducted in the FPTF at conditions similar to those anticipated for commercial CWF firing. Furnace flame temperatures, residence times, convection pass temperatures and velocities were controlled over a range representative of oil-designed boilers.

The performance test matrix is summarized in Table 2-1. Each test fuel is identified by coal type, ash level and producer code letter. For example, LK6.0C is made with Lower Kittanning coal at 6% ash by producer C. More than twenty-one 80-hour test runs were conducted to evaluate the performance of twelve different CWFs.

Tests 1 to 4 represent the Lower Kittanning test series. The beneficiated feed coal was tested as pulverized fuel at "standard" ($\sim 75\%$ -200 mesh) and "fine" ($\geq 90\%$ -200 mesh) grinds to provide comparative combustion performance and ash deposition data prior to the LK6.0C CWF test. Testing was performed at low and high firing rates, representing 3.1×10^6 Btu/hr and 4.1×10^6 Btu/hr, respectively, to simulate a range of boiler conditions and to evaluate the effects of gas temperature, gas velocity, heat release rate, etc., upon both radiant and convective pass ash deposition characteristics. In addition, a blend of 45% #6 and 55% #2 oil was test fired in the FPTF to provide baseline information. The oil blending ratio was determined based on bench-scale tests with the objective to obtain satisfactory viscosity for atomization at ambient temperature while still providing higher flame emissivities typical to those of #6 fuel oil.

Tests 5 to 11 cover the Splash Dam fuel test series. The major objective of this test series was to evaluate the effect of slurry processing technique and coal cleaning level upon CWF performance characteristics. Fuels prepared by five CWF processors, A, C, D, E and F, were evaluated. One fuel, SD2.6C was prepared from the feed coal beneficiated at a deeper level (2.6% ash). SD5.7D was tested at the low and high firing rates. The rest of the CWFs were tested only at the high firing rate, which provided conditions typical to those for

TABLE 2-1

COAL-WATER FUEL PERFORMANCE TEST MATRIX

TEST NO.	FUEL DESC.	FUEL TYPE	% ASH	% SOLID	FUEL TEMP (°F)	FIRING RATE	
						TESTED	
						HIGH ⁽³⁾	LOW ⁽⁴⁾
1	P.C.-Standard ⁽¹⁾	L. Kittanning	6.0	--	--	X	X
2	P.C.-Fine ⁽²⁾	L. Kittanning	6.0	--	--	X	
3	Baseline Oil	Oil	--	--	Ambient	X	X
4	LK6.0C	L. Kittanning	6.0	66.0	Ambient	X	X
5	SD5.7D	Splash Dam	5.7	69.4	Ambient	X	X
6	SD5.7E	Splash Dam	5.7	66.0	Ambient	X	
7	SD5.7C	Splash Dam	5.7	70.0	Ambient	X	
8	SD4.5A	Splash Dam	4.5	69.5	Ambient	X	
9	P.C.-Standard ⁽¹⁾	Splash Dam	6.0	--	--	X	
10	SD2.6C	Splash Dam	2.6	69.7	Ambient	X	
11	SD6.7F	Splash Dam	6.7	73.2	Ambient	X	
12	UF13.7A	U. Freeport	13.7	69.3	Ambient	X	X
13	UF6.8A	U. Freeport	6.8	70.0	Ambient	X	
14	CG7.1A	Cedar Grove	7.1	69.0	Ambient	X	X
15	CG4.8A	Cedar Grove	4.8	68.0	Ambient	X	
16	AL5.8C	Alma	5.9	67.0	Ambient	X	
17	AL5.8C	Alma	5.9	64.0	Ambient	X	
18	AL5.8C	Alma	5.9	64.0	150	X	
19	AL5.8C	Alma	5.9	64.0	220	X	
20	P.C.- Standard ⁽¹⁾	Alma	5.9	--	--	X	
21	P.C.- Fine ⁽²⁾	Alma	5.9	--	--	X	

(1) Standard grind (~75% -200 mesh)

(2) Fine grind (~90% -200 mesh)

(3) 4.1×10^6 Btu/hr

(4) 3.1×10^6 Btu/hr

oil-designed units. This test series also included baseline pulverized coal at "standard" grind testing at the high firing rate.

Tests 12 to 15 include the Upper Freeport and Cedar Grove CWF test series. These fuels were prepared by the same processor (A) from each of the two feed coals beneficiated at two levels. The primary objectives were to provide data on additional coal types and to evaluate the effect of coal cleaning depth on CWF performance characteristics.

Tests 16 to 21 were the Alma Seam CWF test series. The Alma CWF was initially tested at 67% solids at ambient temperature. The CWF was subsequently diluted to 64% to improve atomization and combustion. It was then tested at 150°F and 220°F fuel temperatures to evaluate the effects of thermal atomization upon performance. Pulverized coal testing was also conducted at "standard" and "fine" grinds to provide baseline data in assessing the performance characteristics of the Alma fuels.

FURNACE SLAGGING CHARACTERIZATION

The furnace slagging characteristics of each fuel were assessed by determining deposit coverage, the effect on waterwall panel heat flux, deposit cleanability, and deposit physical and chemical characteristics. The key criteria used to classify the slagging potential of a fuel in the FPTF is based on the maximum fuel loading and critical flame temperature at which waterwall deposits are still cleanable by soot blowing. The generic ranges established based on this criteria are as follows:

Heat Input From Fuel (10 ⁶ Btu/hr.)	Flame Temperature (°F)	Furnace Slagging Potential
>4.0	>3050	Low
3.6 to 4.0	2900 to 3050	Moderate
3.2 to 3.6	2750 to 2900	High
<3.2	<2750	Severe

Deposit Coverage and Waterwall Panel Heat Flux

Deposit coverage on the waterwall panel is monitored and documented throughout the duration of each test run. The rate of deposit accumulation on the waterwall panel is reflected by panel heat absorption. When deposit buildup slows and begins to approach long term or steady state characteristics, the waterwall heat absorption rate also begins to level off.

Deposit Cleanability

The cleanability of deposits on two panels, located at the middle and bottom of the furnace waterwall, was evaluated on-line using a special soot blowing technique designed to simulate the removal forces associated with commercial soot blowing. The heat flux recovery after soot blowing and the observed deposit characteristics (physical state, thickness, percent coverage) before and after blowing were used to determine deposit cleanability.

Deposit Physical and Chemical Characterization

The physical characteristics of the waterwall deposits were continuously monitored during testing. Dry, lightly sintered deposits are typically most amenable to soot blowing. Highly sintered and molten deposits usually have a detrimental effect on cleanability and hence on long term unit operation. Other physical parameters examined are deposit coverage and thickness. Desirable conditions are low panel coverage and thin friable deposits. Molten deposits are generally considered difficult to remove from waterwall surfaces when using conventional soot blowers. However, depending on the tenacity of the bond between the deposit and the tube surface, thin molten deposits may be cleanable by soot blowing due to the thermal quenching effect of the blowing medium and subsequent differential contraction between deposits and tube metal. Waterwall deposits at the end of each test run were separated by layer and analyzed for chemical compositions to provide insights on specific reasons for the ash slagging behavior of a particular fuel.

CONVECTION PASS FOULING CHARACTERIZATION

The fouling characteristics of the coals were assessed by measuring deposit buildup rate, deposit cleanability, and deposit physical and chemical properties.

Deposit Buildup Rate

Deposit buildup rate is determined by the soot blowing frequency requirement and by documentation with on-line time sequence photographs. Deposit buildup rate influences boiler tube spacing and soot blowing requirements. Generally, there is a temperature below which deposit accumulation is minimal. Below this temperature, tubes can be relatively close together. Above this temperature, tubes would have to be spaced progressively further apart to accommodate the effect of increases in deposit accumulation.

Deposit Cleanability

Deposit cleanability is assessed by on-line measurements of deposit-to-tube bonding strength using a digital penetrometer. This device provides a quantitative measurement which can be related to the ease of deposit removal by soot blowing. Standard values shown below were established by C-E to classify relative deposit bonding strengths:

<u>Measurement</u>	<u>Deposit Bonding Strength</u>
<8	Low
8 to 15	Moderate
15 to 25	High
>25	Severe

These values were calibrated based on visual observations of deposit removal effectiveness during soot blowing and deposit-to-tube bonding strength field measurements with identical equipment in commercial boilers. Normally, deposits yielding bonding strength measurements up to 15 are considered controllable through conventional soot blowing techniques.

Deposit Physical and Chemical Properties

The deposit physical state, internal strength, and thickness can affect cleaning effectiveness. Friable deposits, which are easy to remove, will break into smaller pieces and not cause pluggage downstream where tube spacing is closer. However, deposits which have high internal strength can become lodged downstream in the more tightly spaced tubes. This can cause pluggage which results in draft loss, high local gas velocities and possible forced outages.

As with the waterwall panel deposits, convective pass deposits were collected and separated into layers and analyzed for ash fusibility temperatures and chemical compositions. This information was used to aid in the interpretation of the overall fouling behavior of each test fuel.

FLY ASH EROSION

Fly ash erosion characteristics of each fuel were evaluated on-line in the FPTF in a high velocity (~200 ft/sec) convection section using special test probes controlled at 800°F metal temperature. The high gas velocity is required to accelerate wear in order to provide measurable erosion over an 80-hour test period. A surface activation technique is used to measure the tube specimen's wear (1). The tube specimen is first made radioactive by impinging a particle beam on the surface. As the surface is eroded during exposure in the particulate laden flue gas, the level of gamma radiation emitted decreases. The change in radiation intensity is related to the depth of material loss. This data is then normalized to typical commercial operating conditions based upon an established in-house velocity correlation (2). These results, along with the information obtained from fly ash loading, fly ash size distribution and chemical composition analyses, were used to assess the overall relative erosion characteristics.

ELECTROSTATIC PRECIPITATOR PERFORMANCE

Fly ash collection efficiency during selected CWF tests was evaluated in a pilot-scale electrostatic precipitator (ESP) downstream of the FPTF. The

design specifications for the pilot-scale ESP are identical to the full-scale equipment except for the height of the electrodes (Appendix C). Flue gas enters the ESP at approximately 350°F to 400°F. Fly ash was collected in four modules consisting of a total of 358.5 ft² collecting plate area. Each module contains an independent transformer-rectifier set and automatic voltage controller to provide and control the high D.C. voltage necessary for electrostatic precipitation. Each automatic voltage controller (AVC) measures primary and secondary current and voltage, controls the operating power levels and provides diagnostic information in the event of equipment malfunction.

Isokinetic ash samples collected at the inlet and outlet of the ESP along with the information on flue gas moisture, fly ash particle size, chemical composition and fly ash resistivity were used to determine the overall ESP collecting efficiency and performance. Results were compared to those obtained from pulverized coal tests to determine the effect of CWF firing on ESP performance.

Section 3

TEST RESULTS

BENCH-SCALE FUEL CHARACTERIZATION

Beneficiated CWF Feed Coal Characteristics

Five feed coals were selected to provide a cross-section of commercially significant fuel properties which could be acceptable for CWF applications. Selection of these coals was conducted under Task 1 based upon coal washability, slurryability, combustion characteristics, ash slagging, fouling, erosion and emission criteria (Volume 2). Three of these coals were tested at two levels of beneficiation ("high ash" and "low ash") to assess the performance benefits associated with coal cleaning depth.

Typical analyses of the beneficiated feed coals on a moisture free basis are shown in Table 3-1. High volatile and low sulfur bituminous coals from the Eastern United States were selected. Although it is recognized that high volatile matter content in coal is not a definite indicator to predict good combustion performance, it would have strong impact during CWF firing. Unlike pulverized coal firing where a high concentration of very fine particles are present to assist in flame stabilization, the CWF firing has a lower fine particle concentration due to the tendency of particle agglomeration within atomizer spray droplets. CWFs prepared from high volatile matter feed coals would enhance the chances for good combustion characteristics. Thus, based on the volatile matter ($\geq 28\%$) and the fuel ratio (< 2.4 fixed carbon to volatile matter), the feed coals should exhibit relatively good combustion characteristics. Additional bench-scale evaluation conducted under Task 2 which included flammability index and coal char reactivity confirmed the good combustion characteristics of these coals (Volume 3).

The ash quality of the beneficiated feed coals was evaluated for slagging and fouling potentials. Ash slagging is associated with deposit formation in high temperature furnace radiant sections, and fouling is associated with deposit formation in convection sections at somewhat lower gas temperatures.

TABLE 3-1

ANALYSES OF THE BENEFICIATED CWF FEED COALS

	Lower Kittanning (LK6.0)	Splash Dam High Ash (SD5.7)	Splash Dam Low Ash (SD2.6)	Upper Freeport High Ash (UF13.7)	Upper Freeport Low Ash (UF6.8)	Cedar Grove High Ash (CG7.1)	Cedar Grove Low Ash (CG4.8)	Alma Seam (AL5.9)
Proximate, (Wt.%)								
Volatile Matter	33.9	28.0	30.5	33.0	33.1	33.1	33.0	37.3
Fixed Carbon	60.1	66.3	66.9	53.3	60.1	59.8	61.3	56.8
Ash	<u>6.0</u>	<u>5.7</u>	<u>2.6</u>	<u>13.7</u>	<u>6.8</u>	<u>7.1</u>	<u>4.8</u>	<u>5.9</u>
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
HHV (Btu/lb)	13650	14530	14950	12840	14060	13590	14260	13760
Fuel Ratio (FC/VM)	1.8	2.4	2.2	1.6	1.8	1.8	1.8	1.5
Flammability Index (°F)	1050	1050	980	980	1030	1070	1040	-
Ultimate, (Wt.%)								
Hydrogen	4.7	4.9	5.0	4.8	5.0	5.1	4.8	4.6
Carbon	78.7	81.6	85.7	72.3	79.1	78.7	80.0	78.7
Sulfur	1.0	0.9	0.7	2.6	1.7	0.8	0.8	1.7
Nitrogen	1.5	1.6	1.9	1.5	1.5	1.4	1.5	1.6
Oxygen	10.1	5.3	4.1	5.1	5.9	8.9	8.1	7.5
Ash	<u>6.0</u>	<u>5.7</u>	<u>2.6</u>	<u>13.7</u>	<u>6.8</u>	<u>7.1</u>	<u>4.8</u>	<u>5.9</u>
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
SO ₂ (lb/10 ⁶ Btu)	1.5	1.2	0.9	4.0	2.4	1.2	1.1	2.5
Ash Fusibility (°F)								
I.T.	2320	2440	2270	1990	1980	2510	2290	1920
S.T.	>2700	2610	>2700	2260	2270	2600	2650	2240
H.T.	>2700	>2700	>2700	2420	2390	>2700	>2700	2390
F.T.	>2700	>2700	>2700	2480	2460	>2700	>2700	2510
Ash Composition (Wt.%)								
SiO ₂	61.8	54.5	47.1	42.2	45.3	55.5	52.6	48.9
Al ₂ O ₃	24.1	27.0	30.8	24.9	24.7	28.9	28.2	22.8
Fe ₂ O ₃	7.8	10.2	11.7	21.0	21.5	8.7	8.8	18.0
CaO	1.3	0.9	2.2	2.0	1.6	1.7	2.1	3.9
MgO	0.6	0.7	0.6	0.6	0.7	0.8	0.8	0.7
Na ₂ O	0.7	1.1	1.9	0.3	0.4	0.4	0.5	0.7
K ₂ O	1.3	1.7	1.1	2.8	2.5	2.2	1.8	1.3
TiO ₂	1.8	1.5	1.6	0.9	2.1	1.0	2.0	1.8
SO ₃	<u>0.6</u>	<u>0.5</u>	<u>1.4</u>	<u>1.7</u>	<u>0.6</u>	<u>1.9</u>	<u>2.1</u>	<u>1.0</u>
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Quartz in Ash (Wt.%)	28.7	19.9	7.0	13.6	11.7	18.5	15.1	18.5

Coal ash slagging potentials of the beneficiated feed coals were assessed utilizing ash fusibility temperatures, ash content, ash composition and conventional slagging indices such as base-to-acid ratio, iron to calcium ratio, etc. In addition, gravity fractionation analyses was conducted on the coals to determine the amount of large, discrete iron compound particles which have marked impact on furnace slagging (3).

The slagging characteristics of each test fuel are summarized in Table 3-2. Ashes from the Lower Kittanning (LK 6.0), Splash Dam (SD 5.7 and SD 2.6) and Cedar Grove fuels can be characterized by their high fusibility temperatures (softening temperatures $\geq 2600^{\circ}\text{F}$); and the Upper Freeport (UF 13.6 and UF 6.8) and Alma Seam (AL 5.9) ashes by their moderate to low ash fusibility temperatures (softening temperatures $\geq 2240^{\circ}\text{F}$). Gravity fractionation analyses indicate all these fuels contained a high percentage of Fe_2O_3 (76.1% to 96.0%) in the ash of the 2.9 sink fuel fraction. These values would normally be associated with moderate to high slagging potential fuels. However, the total quantity of material recovered from the 2.9 sink fraction is very low for each fuel, ranging from $<0.1\%$ to 1.6% of total coal. This would indicate that the influence of segregated iron on slagging would be minimized for these fuels.

Overall, based on these bench-scale analyses, the Upper Freeport fuels exhibited moderate slagging potential, the Cedar Grove and Alma fuels low to moderate slagging potentials, and the Lower Kittanning and Splash Dam fuels low slagging potentials. The higher slagging characteristics of Upper Freeport fuels are mostly attributed to the lower ash fusibility temperatures.

Coal ash fouling potentials of the beneficiated feed coals were assessed by considering ash deformation and softening temperatures, and alkali content in the coal ash. In addition, the weak acid leaching analysis was conducted on each coal to provide information on the forms in which alkalis are present. Alkalies extracted during leaching (solubles) are considered to be present in forms which are released during combustion and are reactive in deposit formation, whereas the insolubles are considered present in stable forms and less active (4).

The fouling potentials of the Lower Kittanning, Splash Dam and Cedar Grove fuels were all low, whereas the Upper Freeport and Alma Seam fuels exhibited low to moderate fouling potentials (Table 3-3). The higher fouling characteristics of the Upper Freeport and Alma Seam fuels are attributed to the lower ash fusibility temperatures. All these fuels contained low sodium and potassium contents. The weak acid leaching results indicate that the potassium is primarily in an inactive form. The percentage of total sodium which existed in active form varied between coal types and with level of beneficiation. However, the low total concentration of active alkalis and the low ratio of active alkali to total alkali indicated fouling induced by alkali would be low for all these fuels. The weak acid leaching results were consistent with observed pilot-scale fouling performance as well as results typically obtained for low fouling Eastern U.S. bituminous coals.

Convection tube erosion resulting from fly ash can be the load limiting factor associated with CWF utilization. Units designed for oil or gas typically have considerably higher convection pass gas velocities and tighter tube spacings than coal-designed units. The high gas velocities accelerate erosion rates and reduce tube life. Fly ash erosion rates are believed to be exponentially related to ash impact velocity and linearly proportional to ash loading. Other significant factors include the size distribution of the ash and the relative erosiveness of the ash. The erosiveness of fly ash is primarily attributed to its quartz content and size due to the high hardness factor (6.5 mohs) of this constituent.

The concentrations of quartz in the laboratory prepared beneficiated coal ash samples determined by quantitative x-ray diffraction are shown in Table 3-1. In general, the more highly beneficiated fuel of each coal type exhibited lower erosiveness.

Coal-Water Fuel Characteristics

A total of twelve CWFs were prepared by established producers using their own technical approach (coal particle size distribution and loading, chemical additive package, etc.). Primary specifications requested of the CWF producers

TABLE 3-2

BENCH-SCALE ASH SLAGGING CHARACTERISTICS

COAL TYPE	ST (°F)	FT (°F)	B/A RATIO	Fe ₂ O ₃ /CaO RATIO	Fe ₂ O ₃ 2.9 SINK	2.9 SINK IN COAL (%)	SLAGGING POTENTIAL
LK8.0	>2700	>2700	0.1	6.0	76.1	0.1	Low
SD5.7	2610	>2700	0.2	11.3	36.2	0.1	Low
SD2.6	>2700	>2700	0.2	5.3	86.1	<0.1	Low
UF13.7	2280	2480	0.4	10.5	94.9	1.6	Moderate
UF6.8	2270	2480	0.4	13.4	96.0	0.8	Moderate
CG7.1	2600	>2700	0.2	5.1	82.0	0.1	Low/Moderate
CG4.8	2650	>2700	0.2	4.2	80.6	0.8	Low/Moderate
AL5.9	2240	2510	0.3	4.6	89.0	0.2	Low/Moderate

TABLE 3-3

BENCH-SCALE FOULING CHARACTERISTICS

COAL TYPE	IDT (°F)	ST (°F)	TOTAL ALKALI (%)	SOL. Na ₂ O (%)	SOL. K ₂ O (%)	SOL. TOTAL FRACTION	FOULING POTENTIAL
LK8.0	2320	>2700	2.0	0.4	<0.1	0.2	Low
SD5.7	2440	2610	2.8	0.2	0.1	0.1	Low
SD2.6	2270	>2700	3.0	0.7	0.1	0.3	Low
UF13.7	1990	2260	3.1	0.1	<0.1	<0.1	Moderate
UF6.8	1980	2270	2.9	0.4	<0.1	0.1	Low/Moderate
CG7.1	2510	2600	2.6	0.4	0.1	0.2	Low
CG4.8	2290	2650	2.3	0.7	0.1	0.3	Low
AL5.9	1920	2240	2.0	0.5	<0.1	0.3	Low/Moderate

were to 1) provide test CWFs representative of high solids loading, stabilized commercial fuels; 2) limit particle top size to control atomizer plugging; and 3) insure the fuels could be pumped and handled. Typical properties of these fuels tested are summarized in Table 3-4.

Overall, the test CWFs varied considerably in stability, handling and atomization characteristics. The solid loading of these fuels varied between 64% and 71%. The Mass Mean Diameter (MMD) ranged between 11 and 50 microns. Low shear viscosity (100 sec^{-1} @ 20°C) measured with a Haake rotational viscometer varied between 215 cps and 1830 cps. The power law function exponent, which reflects the viscosity versus shear rate relationships, ranged from 0.7 to 1.5, indicated some of the CWFs exhibited pseudoplastic behavior ($n < 1$, viscosity decreased with shear rate) while others showed dilatant characteristics ($n > 1$, viscosity increased with shear rate).

The low shear viscosity data was useful for estimating pumping characteristics of the CWFs. Atomization performance should ideally be predicted as a function of fuel rheology and atomization quality generally improved with decreasing viscosities. However, accurate predictions of atomization quality could not be made from the bench-scale data. The power law exponent, which reflects the fuel's change in viscosity with shear rate, did not reliably predict the CWF atomization quality. Neither pseudoplastic nor dilatant behavior over narrow shear ranges could be correlated to atomizer performance (Volume 3).

COLD FLOW ATOMIZATION CHARACTERISTICS

Atomization quality is extremely important during the CWF firing since smaller droplets produce better combustion in the furnace. Ignition, flame stability, and carbon burnout are all improved as atomization quality improves. In order to determine and control atomizer droplet spray quality during the pilot-scale combustion and ash deposition performance tests, each CWF was first cold-flow tested on C-E's Atomizer Test Facility (ATF). Compressed air was used as the atomizing media. Mass mean droplet diameters were determined as a function of air-to-fuel ratio for each CWF fuel to be fired in the FPTF. The ATF test data is shown in Appendix A.

TABLE 3-4

COAL-WATER FUEL PROPERTIES

Fuel Code	LK6.0C	SD5.7D	SD5.7E	SD5.7C	SD4.5A	SD2.6C	SD6.7F	UF13.7A	UF6.8A	CG7.1A	CG4.8A	AL5.9C
% Solids	68	69	68	70	69	70	71	69	70	69	68	67
pH	8	8	8	9	9	9	8	8	8	9	9	8
CWF Screen Analysis												
#80 mesh (250 μ)	0.1	0.2	0.1	0.1	0.0	0.1	0.2	0.3	0.1	0.2	0.1	0.0
80x100 mesh (250x150 μ)	0.7	3.5	0.2	0.9	2.1	1.1	3.8	5.2	4.4	5.9	2.2	0.0
100x200 mesh (150x75 μ)	0.5	15.5	0.4	3.8	17.4	2.7	12.6	17.5	15.6	19.1	12.5	0.5
200x325 mesh (75x45 μ)	7.6	18.5	11.2	8.9	12.4	8.1	10.8	11.1	12.0	12.3	10.0	0.5
-325 mesh (5 μ)	91.1	62.5	88.1	86.3	88.1	88.0	72.6	65.9	67.9	62.5	75.2	99.0
Coal Particle MMD (μ)	15	50	25	15	33	15	35	30	29	32	25	9
Viscosity @ 100 sec ⁻¹ (1)	1500	840	860	840	1400	610	1610	1700	1600	1830	1080	617
Power Law Exp. (1)	0.96	1.5	1.2	1.4	1.1	1.4	0.95	0.98	0.89	1.1	1.2	0.70
Viscosity @ 1100 sec ⁻¹ (2)				983			2074			1953	1152	2010
Viscosity @ 2000 sec ⁻¹ (2)				1700			2600			2337	1300	2240
Viscosity @ 4000 sec ⁻¹ (2)				2850			2785			2400	1492	2390
Viscosity @ 1100 sec ⁻¹ (3)				1250			2395			1655	2717	1860
Viscosity @ 1500 sec ⁻¹ (3)				2137			2740			2187	3250	2590
CWF Temp @ Atomizer (°F)		80	88	84	71	82	69	78	98	93	90	80
A/F	0.16	0.18	0.16	0.17	0.16	0.17	0.18	0.17	0.17	0.17	0.17	0.17
Droplet MMD (μ)	93	86	79	72	100	83	93	119	98	75	85	72
Droplet SMD (μ)	72	63	62	56	75	65	70	82	66	56	63	-
% droplets >320 μ	.01	.01	0.00	0.00	0.37	0.02	0.22	3.43	2.19	0.02	.04	0.0
% droplets >225 μ	1.18	0.98	0.40	0.22	5.07	1.28	3.83	14.61	9.64	1.00	1.64	0.2

(1) Rotational Viscometer @ 20°C.

(2) Extrusion Rheometer @ Room Temp.

(3) Variable High Shear Viscometer @ 20°C

Table 3-5 shows the ATF cold flow atomization results at equivalent firing rate of 4.1×10^6 Btu/hr. for each of the CWFs tested using the FPTF Y-jet atomizer. Overall, the cold flow atomization characteristics of the CWFs were good. Most of the fuels were atomized to the desired mass mean droplet diameter (MMD) between 70 and 80 μ . However, some CWFs could not be atomized to MMD of 80 μ with the maximum available atomizing air pressure of 200 psig.

The effects of fuel temperature and solids loading on atomization performance were evaluated for the CWFs prepared from the microfine Alma coal. Fuel temperatures were varied from 80°F to 220°F for these fuels at solids loadings of approximately 67% and 64%. Contrary to the bench-scale viscosity data shown in Figure 3-1, no significant improvement in spray quality was indicated due to heating when the fuel was cold-flow tested in the ATF. However, the reduction in solids loading had a beneficial effect on spray quality. Although the MMD was similar with and without water dilution (58 μ and 61 μ , 67% and 64% solids, respectively), the percentage of large droplets (greater than 170 μ) was reduced with reduction in solids content for a given atomizing air-to-fuel ratio as shown in Figure 3-2.

CWF COMBUSTION PERFORMANCE CHARACTERISTICS

The combustion behavior of each CWF was evaluated in the pilot-scale FPTF after establishing the appropriate atomizer settings. All tests were conducted at 25% excess air. Peak furnace temperatures ranged between 2800°F and 3100°F, and furnace residence times ranged between 0.9 and 1.3 sec. Typical FPTF operating temperature profiles for low and high firing rates during the CWF testing are shown in Figure 3-3. A summary of the combustion results is shown in Table 3-6. In general, the combustion behavior of each CWF was very good during nearly all of the FPTF tests. Good flame stability and carbon conversions in excess of 99% were obtained from these tests. Atomizer droplet size and furnace residence time were the most important parameters influencing combustion efficiency during these tests.

The effect of atomization quality on CWF combustion performance is illustrated by the SD 5.7 C test series (Table 3-6). Carbon conversion dropped sharply as

TABLE 3-5

CWF COLD FLOW ATOMIZATION TEST RESULTS

AT FUEL FLOW RATE OF 4.1×10^6 BTU/HR.

FUEL TYPE	SOLID CONTENT (%)	FUEL TEMP (*F)	ATOMIZING AIR TO FUEL RATIO (LB AIR/LB FUEL)	SPRAY DROPLET SIZE (μ)
LK6.0C	66.0	80	0.15	88
SD5.7D	69.4	80	0.22	76
SD5.7E	66.0	80	0.19	69
SD5.7C	70.0	80	0.19	72
SD4.5A	69.5	80	0.12 ⁽¹⁾	98
SD2.6C	69.7	80	0.22	81
SD6.7F	73.2	80	0.20	72
UF13.7A	69.3	80	0.17 ⁽¹⁾	115
UF6.8A	70.0	80	0.17 ⁽¹⁾	100
CG7.1A	69.0	80	0.17	75
CG4.8A	68.0	80	0.18	85
AL5.8C	67.0	80	0.17	72
AL5.8C	64.0	80	0.17	61
AL5.8C	64.0	150	0.17	79
AL5.8C	64.0	220	0.16	78

(1) Maximum Atomizing Air Flow/Pressure Available

FIGURE 3-1 EFFECT OF FUEL TEMPERATURE ON ALMA MCWF VISCOSITY DURING BENCH-SCALE TESTS

FIGURE 3-2 EFFECT OF SOLIDS LOADING ON ALMA MCWF ATOMIZATION SPRAY QUALITY DURING COLD FLOW TESTS IN THE ATOMIZER TEST FACILITY

FIGURE 3-3 TYPICAL FTFF TEMPERATURE PROFILES DURING CWF FIRING AT 3.1×10^6 AND 4.1×10^6 Btu/hr FIRING RATES

TABLE 3-8

CWF COMBUSTION TEST RESULTS IN THE FPTF
AT 25% EXCESS AIR

FUEL TYPE	SOLIDS CONTENT (%)	FIRING RATE (10 ⁶ Btu/hr)	FURNACE TEMP (°F)	FURNACE RES. TIME (SEC)	COAL MMD (μ)	DROPLET MMD (μ)	FLY ASH MMD (μ)	CARBON CONV. (%)
LK p.c. Std.	--	3.1	2870	1.28	45	--	8	99.9
LK p.c. Std.	--	4.1	2960	1.10	40	--	13	99.9
LK p.c. Fine	--	4.1	2960	1.10	27	--	14	99.9
LK6.0C	66.0	3.1	2770	1.38	18	86	9	99.9
LK6.0C	66.0	4.1	2940	0.99	15	88	14	99.6
SD p.c. Std.	--	4.1	3070	1.02	52	--	13	99.8
SD p.c. Fine	--	4.1	3000	1.02	11	--	16	99.5
SD 5.7D	69.4	3.1	2770	1.36	50	63	19	99.3
SD 5.7D	69.4	4.1	2950	1.00	50	76	15	99.6
SD 5.7E	66.0	4.1	2930	1.03	25	69	16	99.5
SD 5.7C	70.0	4.1	2800	1.04	15	106	44	98.2
	70.0	4.1	2850	1.04	15	72	27	98.9
	70.0	4.1	2750	1.04	15	61	13	99.9
	70.0	4.1	3020	0.99	15	72	12	99.7
SD 4.4A	69.5	4.1	3050	0.97	24	98	34	98.7
SD 2.6C	69.7	4.1	2970	1.04	15	81	51	97.0
SD 6.7F	73.2	4.1	3080	0.97	35	72	13	99.5
UF13.7A	69.3	4.1	3050	1.05	30	115	20	99.4
UF6.8A	70.0	4.1	3060	0.90	29	100	18	99.7
CG7.1A	69.0	3.1	2920	1.29	32	75	23	99.5
CG7.1A	69.0	4.1	3020	0.94	32	75	34	99.1
CG4.8A	68.0	4.1	2080	0.97	25	85	19	99.5
AL p.c. Std.	--	4.1	2990	1.00	39	--	6	99.8
AL p.c. Fine	--	4.1	2980	1.01	28	--	4	99.9
AL 5.9C ⁽¹⁾	67.0	3.8	2830	1.06	9	72	36	97.7
AL 5.9C ⁽¹⁾	64.0	4.1	2980	0.95	7	61	9	99.6
AL 5.9C ⁽²⁾	64.0	4.1	2990	0.96	7	73	7	99.9
AL 5.9C ⁽³⁾	64.0	4.1	3000	0.95	7	78	4	99.9

- (1) At 80°F Fuel Temperature
(2) At 150°F Fuel Temperature
(3) At 220°F Fuel Temperature

atomizer droplet MMD's increased from 61 microns to 106 microns. Fly ash size also increased sharply as droplet size was increased. This increase in fly ash size is attributed to the incomplete combustion of larger char particles generated by the coarser spray droplets. Results from this program and others have indicated that the coal particles within a CWF spray droplet agglomerate to form a single char particle upon heating (Volume 4, 6).

During the Alma AL 5.9 C microfine (MCWF) initial testing at high solids loading of 67%, a high population of large sparklers was present and carbon conversion was only 97.7%. The dilution of this fuel to lower solids loading significantly improved combustion. Combustion performance at the 64% solids was very good as all large sparklers leaving the furnace were eliminated and carbon conversion increased to 99.6%. This improvement in combustion was attributed to the improved atomization in the combustion environment visually observed.

Analysis of the in-flame solid samples collected axially along the FPTF furnace during the AL 5.9 C test series also indicate the rate of carbon conversion improved and approached those of the pulverized coals when CWF was heated to approximately 220°F fuel temperature (Figure 3-4). This was probably due to the secondary atomization effect, as a portion of the water from the CWF exiting the atomizer may be flashed to steam, generating the necessary forces to effect further breakup of the CWF droplets. No significant improvement was observed when the CWF was heated to only 150°F fuel temperature.

FURNACE SLAGGING CHARACTERISTICS

The ash slagging characteristics of each fuel were assessed as a function of firing conditions. Waterwall slagging behavior was characterized by determining radiant deposit buildup rates, coverage, thickness, physical state (friable, sintered or molten deposits) and susceptibility to sootblowing, as well as measuring chemical and thermal properties of radiant deposits. The effects of deposits on waterwall heat transfer and the cleanability of waterwall deposits were the primary data used in assessing slagging potential.

FIGURE 3-4 CARBON CONVERSION OF ALMA SEAM PULVERIZED-COAL AND COAL-WATER FUEL AT VARIOUS FUEL TEMPERATURES

CWF feed coal properties played a dominant role on ash deposit behavior of the CWF. The relative slagging characteristics of each CWF corresponded to the behavior of the feed coals. In general, waterwall deposit characteristics indicated low slagging during the Lower Kittanning and Splash Dam tests, moderate slagging during the Cedar Grove and Alma tests, and high slagging during the Upper Freeport tests. The Alma MCWF exhibited relatively low slagging potential in relation to its predicted performance based on the bench-scale analyses. A summary of the furnace deposit physical characteristics from the FPTF waterwall panel elevation C is presented in Table 3-7.

Comparison Between Pulverized Coal and CWF Firing

The beneficiated feed coals used to prepare the Lower Kittanning, Splash Dam and Alma CWFs were test fired in a dry, pulverized state to provide comparative ash slagging baseline data. Test results from the Lower Kittanning and Splash Dam fuels indicated that slagging behavior of CWF was better than pulverized coal at similar conditions. During the Lower Kittanning high firing rate pulverized coal runs, sintered deposits accumulated to approximately 1/4 inch thick and covered between 60% and 70% of the waterwall surface, compared to thinner (less than 1/8 inch thick) and drier (powdery) deposits with less surface coverage (10%) during the high firing rate CWF run. Photographs in Figure 3-5 compare the deposits present during these tests. Waterwall heat absorption rates measured during these tests further illustrate this difference in slagging behavior (Figure 3-6). Waterwall heat flux decreased more rapidly and reached much lower values during the p.c. tests. Similar results were obtained during the Splash Dam tests. Ash deposition was less and waterwall heat flux was higher during all of the Splash Dam CWF tests than during its baseline pulverized coal test. The Alma test series also showed similar results during the CWF test with 64% solids at 220°F fuel temperature. However, during the CWF test at 80°F fuel temperature, waterwall heat flux was lower than during the pulverized coal tests. The difference was probably due to the poorer atomization at 80°F fuel temperature.

TABLE 3-7

FURNACE WATERWALL DEPOSIT PHYSICAL CHARACTERISTICS
PANEL ELEVATION C

FUEL TYPE	FIRING RATE (10 ⁶ Btu/hr)	FURNACE TEMP. (°F)	DEPOSIT PHYSICAL STATE	PANEL COVERAGE (%)	DEPOSIT THICKNESS (in)	DEPOSIT CLEANABILITY	ESTIMATED ⁽⁴⁾ CRITICAL TEMP. (°F)
LK P.C. Std.	3.1	2870	Powdered	50	<1/2	Excellent	
LK P.C. Std.	4.1	2960	L. Sintered	60	<1/2	Very Good	
LK P.C. Fine	4.1	2960	L. Sintered	70	<1/2	Very Good	>3000
LK 6.0C	3.1	2770	Powdered	10	<1/8	Excellent	
LK 6.0C	4.1	2940	Powdered	10	<1/8	Excellent	
SD P.C. Std.	4.1	3070	Sintered	90	<3/4	Very Good	
SD P.C. Fine	4.1	3000	Sintered	90	<3/4	Very Good	
SD 5.7 D	3.1	2770	Powdered	10	<1/8	Excellent	
SD 5.7 D	4.1	2950	Powdered	15	<1/4	Excellent	>3000
SD 5.7 E	4.1	2930	Sintered	10	<1/4	Very Good	
SD 5.7 C	4.1	3020	Sintered	15	<1/2	Very Good	
SD 4.5 A	4.1	3050	L. Sintered	15	<1/4	Very Good	
SD 2.6 C	4.1	2970	L. Sintered	10	<1/8	Very Good	
SD 6.7 F	4.1	3080	L. Sintered	15	<1/4	Very Good	
UF 13.7 A	3.1	2830	L. Sintered	25	<1/4	Good	
UF 13.7 A	4.1	3050	Molten	100	<3	Poor	<3000
UF 6.8 A	4.1	3060	Molten	100	<1	Marginal	
CG 7.1 A	3.1	2920	Sintered	30	<1/2	Fair	>3000
CG 7.1 A	4.1	3020	Molten	100	<1/2	Marginal	<3000
CG 4.8 A	4.1	2980	Molten	50	<1/2	Good	
AL P.C. STd.	4.1	2990	Molten	40	<1/2	Good	
AL P.C. Fine ⁽¹⁾	4.1	2980	Molten	40	<1/2	Good	
AL 5.9 C ⁽¹⁾	3.8	2830	Molten	40	<1/2	Good	>3000
AL 5.9 C ⁽²⁾	4.1	2980	Molten	40	<1/2	Good	
AL 5.9 C ⁽²⁾	4.1	2990	Molten	40	<1/2	Good	
AL 5.9 C ⁽³⁾	4.1	3000	Molten	40	<1/2	Good	

(1) At 80°F Fuel Temperature

(2) At 150° Fuel Temperature

(3) At 220° Fuel Temperature

(4) Maximum Temperature At Which Deposits Are Still Cleanable by Soot Blowing.

STD GRIND
PULVERIZED COAL

FINE GRIND
PULVERIZED COAL

COAL-WATER
FUEL

Waterwall deposits during Lower Kittanning tests at high firing rate

PULVERIZED COAL
HIGH ASH

CWF
HIGH ASH

CWF
LOW ASH

Waterwall deposit during Splash Dam tests at high firing rate

STD GRIND
PULVERIZED COAL

FINE GRIND
PULVERIZED COAL

CWF AT 200°F
FUEL TEMPERATURE

Waterwall deposit during Alma Seam tests at high firing rate

FIGURE 3-5 COMPARISON OF WATERWALL DEPOSITION BETWEEN
PULVERIZED COAL AND CWF FIRINGS.

FPTF WATERWALL HEAT FLUX DURING LOWER KITTANNING TESTS AT HIGH FIRING RATE

FPTF WATERWALL HEAT FLUX DURING SPLASH DAM TESTS AT HIGH FIRING RATE

FPTF WATERWALL HEAT FLUX DURING ALMA SEAM TESTS AT HIGH FIRING RATE

FIGURE 3-6 COMPARISON OF WATERWALL HEAT FLUX BETWEEN PULVERIZED-COAL AND CWF FIRINGS

General conclusions on potential slagging benefits associated with CWF firing cannot be drawn based only on these tests, particularly since all of the above test fuels exhibited relatively low slagging behavior. Reasons for improved behavior with CWF are not clearly evident. One difference between CWF and p.c. combustion which could have a beneficial effect on ash deposition is the time delay associated with drying a CWF droplet prior to burning. The time-temperature history which the coal mineral matter undergoes during CWF firing may be sufficiently different than for p.c. firing, hence influencing ash deposition behavior.

Comparison Between CWF Processors

The effect of slurry type on CWF slagging behavior was assessed by comparing results from the five Splash Dam CWFs prepared from the same feed coal. Waterwall deposits developed from each fuel were thin ($<1/2$ inch) and were easily cleaned by soot blowing. The low ash deposition rate from each fuel is reflected by the waterwall heat flux as it varied little with time (Figure 3-7). Based upon the slight differences in waterwall deposit characteristics between the five different slurry types, it appears that the variations in CWF particle size distribution and additive package did not have a major influence on slagging performance. However, it should be noted that these tests were performed with uniform atomizer spray quality, and these results may not apply to different coal types or different additive packages.

Comparison Between Coal Beneficiation Levels

The effects of coal beneficiation were assessed for the Splash Dam, Upper Freeport, and Cedar Grove CWFs. Overall, a significant improvement in slagging characteristics was observed as the level of beneficiation was increased for each fuel. In general, the more highly beneficiated CWFs exhibited lower ash deposition rates and generated deposits which were less fused and more readily cleanable than the respective high ash CWF.

WATERWALL HEAT FLUX DURING SPLASH DAM
CWF TESTS AT HIGH FIRING RATE

FIGURE 3-7 COMPARISON OF FURNACE SLAGGING CHARACTERISTIC
BETWEEN CWF PROCESSERS

Deposits during high ash Cedar Grove (CG 7.1 A) tests were 1/2 to 1-1/2 inches thick compared to 1/4-1/2 inches thick during the low ash Cedar Grove (CG 4.8 A) test. The difference in physical state and the improvement in deposit cleanability was more pronounced during these tests than the Upper Freeport tests. At similar conditions, waterwall heat flux after sootblowing was approximately 93% of the clean value for the low ash compared to only about 80% for the high ash Cedar Grove CWF (Figure 3-8).

The slagging characteristics of both Upper Freeport and Cedar Grove CWFs were highly dependent on firing conditions. Significant slagging occurred with fuels from these two coal types at temperatures within the ranges predicted for some commercial oil designed units. Establishing their slagging characteristics as a function of temperature is therefore very important. During the Upper Freeport high ash test, ash deposition was minimal below furnace temperatures of 2850°F. However, at 3040°F thick molten deposits were generated which were not cleanable with sootblowers. If sootblowers are not effective in controlling waterwall deposition, normally furnace thermal loadings must be reduced to improve deposit cleanability. Critical furnace temperatures for cleanable deposits with high ash Upper Freeport CWF were estimated to be approximately 2900-2950°F. The critical temperature for the low ash Upper Freeport was estimated at approximately 3000°F. Critical temperatures for cleanable deposits for the high ash Cedar Grove CWF were estimated between 2950-3000°F, whereas that for the low ash fuel was estimated to be slightly above 3000°F.

CONVECTIVE PASS FOULING CHARACTERISTICS

Ash fouling characteristics are an extremely important consideration for CWF utilization in that they dictate the temperatures to which the gas must be cooled prior to entering tightly spaced convection tube sections. The ash fouling performance of the test fuels were assessed as a function of firing conditions by examining deposits generated on a series of convective pass probe banks. Convection tube deposits were characterized by measuring deposit buildup rate, deposit cleanability, impact on heat transfer, and deposit physical and chemical properties. Primary results used in establishing fouling potential are deposit buildup rate and deposit cleanability. In general, local gas

WATERWALL HEAT FLUX DURING THE UPPER FREEPORT CWF TESTS AT HIGH FIRING RATE

WATERWALL HEAT FLUX DURING THE CEDAR GROVE CWF TESTS AT HIGH FIRING RATE

FIGURE 3-8 COMPARISON OF WATERWALL HEAT FLUX BETWEEN CWF COAL BENEFICIATION LEVELS

temperature was the most important operating parameter influencing convection tube deposit characteristics during a specific test. Gas temperature had a significant effect on both the rate of deposit accumulation and the tenacity of deposits. The rate of deposition was also significantly affected by ash loading. For a given coal type, deposit accumulation rates decreased as the ash levels in the CWF coals decreased due to beneficiation.

Overall, the relative fouling characteristics of each CWF were influenced by the properties of its feed coal. Test results indicate that the fouling potential of the Lower Kittanning, Splash Dam, and Cedar Grove fuels were low. Upper Freeport CWFs ranged from low to moderate fouling. Alma MCWF had low fouling despite the fact that its ash analysis indicated somewhat higher potential. Table 3-8 summarizes fouling characteristics of the fuels.

The Lower Kittanning fuels had excellent ash fouling characteristics. Very little ash deposition occurred below gas temperatures of 2300°F. Convection tube deposits remained lightly sintered and reached a maximum thickness of approximately 1-1/2 inches at gas temperatures up to 2450°F. Sootblowing requirements were minimal due to the low deposit buildup rates. Deposit to tube bonding strength measurements (BSMs) were low (less than 2). Consequently, the cleanability of the convective pass deposits was very good.

The overall fouling performance of the Splash Dam fuels was also very good. Vendor process did not appear to have a strong impact on fouling characteristics, as all of these CWFs exhibited low convection tube deposit buildup rates and weakly bonded, friable deposits. In general, at gas temperatures below 2250°F, ash deposition was minimal consisting of light powder. At gas temperatures in the range of 2250°F to 2355°F, deposits consisted of a thin inner layer of hard scale and a powdery or lightly sintered outer deposit layer. Deposits remained lightly sintered and reached a maximum thickness of approximately 2-1/2 inches at the maximum gas temperature (2355°F) tested. During all the Splash Dam tests, convection tube deposits were weakly bonded (BSM less than 1) and could be readily removed by soot blowing.

TABLE 3-8

CONVECTIVE PASS FOULING CHARACTERISTICS

FUEL TYPE	FIRING	GAS TEMP. PROBES (°F)	RELATIVE BUILDUP RATE (TIME BETWEEN SOOTBLOWING, hr)	DEPOSIT BONDING STRENGTH	DEPOSIT CLEANABILITY
	RATE 10 ⁶ Btu/hr)				
LK 6.0 P.C. Std. ¹	4.1	2350	>40	1.8	Good
LK 6.0 P.C. Fine ²	4.1	2450	>40	0.4	Excellent
LK 6.0 S	4.1	2280	>40	--	Excellent
SD 6.0 P.C. Std.	4.1	2300	>40	<1	Excellent
SD 5.7 C	4.1	2270	>40	<1	Excellent
SD 5.7 D	4.1	2270	>40	<1	Excellent
SD 5.7 E	4.1	2350	>40	<1	Excellent
SD 4.5 A	4.1	2390	>40	<1	Excellent
SD 2.6 F	4.1	2320	>40	<1	Excellent
SD 6.7 F	4.1	2240	>40	<1	Excellent
UF 13.7 A	3.1	2260	20-30	<1	Excellent
UF 13.7 A	4.1	2490	4-6	16	Marginal
UF 6.8 A	4.1	2350	8-10	2	Very Good
CG 7.1 A	3.1	2270	>40	<2	Very Good
CG 7.1 A	4.1	2320	25-30	<2	Very Good
CG 4.8 A	4.1	2350	8-10	<2	Very Good
AL 5.9 C ³	3.8	2220	>40	<2	Very Good
AL 5.9 C ⁴	4.1	2400	>40	<2	Very Good
AL 5.9 C ⁵	4.1	2240	>40	<2	Very Good
AL 5.9 C ⁶	4.1	2400	>40	<2	Very Good

1. Standard grind dry, pulverized coal (@ 75% less than 200 mesh)
2. Fine grind dry, pulverized coal (@ 90% less than 200 mesh)
3. MCWF At 67% solids and 80°F fuel temperature
4. MCWF At 64% solids and 80°F fuel temperature
5. MCWF At 64% solids and 150°F fuel temperature
6. MCWF At 64% solids and 220°F fuel temperature

The fouling characteristics of the Upper Freeport CWFs varied significantly between firing rates and between levels of beneficiation. The increase in ash deposition with firing rate illustrates the combined effect of increased gas temperatures and increased ash loading (Figure 3-9). For the high ash fuel, ash deposition was minimal at the low firing rate (2250°F gas temperature) compared to the accumulation of 6 inch thick deposits in approximately four to six hours at the high firing rate (2450°F gas temperature).

An improvement in fouling performance was observed with the more highly beneficiated Upper Freeport fuel. Sootblowing is performed when convection tube deposits reach 4 to 6 inches in thickness. Sootblowing was necessary every 4 to 6 hours for the high ash Upper Freeport CWF compared to every 8 to 10 hours for the low ash CWF. At similar firing conditions, ash buildup rates were about 50% lower for the more beneficiated fuel, which is roughly proportional to the reduction in ash loading between the high ash and low ash fuels. Beneficiation did not appear to have a strong effect on the physical characteristics of deposits. In general, during the Upper Freeport tests, convection tube deposits remained friable and weakly bonded up to gas temperatures of 2400°F.

Coal beneficiation also improved the fouling performance of the Cedar Grove CWFs. Sootblowing requirements were less for the lower ash fuel. Sootblowing was required after approximately 30 hours for the high ash CWF compared to about every 40 hours for the low ash fuel. The effect of beneficiation on the fouling characteristics of the Cedar Grove CWFs was not as pronounced as the Upper Freeport because of the lower deposition rates (Figure 3-10). Convection tube deposition during the Cedar Grove tests was minimal below gas temperatures of 2200°F, and only lightly sintered deposits less than 1 inch thick were generated at maximum temperatures tested (2350°F).

The fouling potential of the Alma MCWF fuels was low. Heating MCWF to fuel temperatures up to 220°F had little effect on the fouling characteristics of the Alma Seam CWF. The ash deposition rate was greater during the pulverized coal tests than observed during the MCWF tests (Figure 3-11). All deposits were readily cleanable as they had low deposit-to-tube bonding strength up to the maximum gas temperature tested (2400°F).

UF 13.7A

T = 2350°F

UF 6.8A

T = 2350°F

FIGURE 3-9 CONVECTION TUBE DEPOSITS DURING THE UPPER FREEPORT CWF TESTING.

CG 7.1A

T = 2270°F

4 HOURS

8 HOURS

12 HOURS

CG 7.1A

T = 2320°F

4 HOURS

6 HOURS

10 HOURS

CG 4.8A

T = 2350°F

4 HOURS

8 HOURS

12 HOURS

FIGURE 3-10 CONVECTION TUBE DEPOSITS DURING THE CEDAR GROVE CWF TESTING.

AL 5.7C @ 80°F

T = 2400°F

4 HOURS

6 HOURS

12 HOURS

AL 5.7C @ 220°F

T = 2400°F

4 HOURS

6 HOURS

12 HOURS

AL 5.7 STD P.C.

T = 2410°F

1 HOUR

4 HOURS

6 HOURS

FIGURE 3-11 CONVECTION TUBE DEPOSITS DURING THE ALMA FUEL TESTING.

Overall, the relatively low fouling characteristics for the four coal types evaluated is not unusual considering the low concentrations of alkali metals and alkaline earth constituents in the fuels. High volatile bituminous coals from these geographical regions are typically low fouling. Firing these coals as CWFs did not appear to cause a change in fouling.

FLY ASH EROSION CHARACTERISTICS

Relative fly ash erosion characteristics were studied in a high velocity test section downstream of the FPTF convection tube banks. Tube specimens of carbon steel controlled at 800°F metal temperatures were directly exposed to the particulate laden flue gas stream. Erosion measurements were obtained at 160 ft/sec to 275 ft/sec gas velocities and gas temperatures between 1000°F and 1400°F. These high gas velocities were required in order to accelerate wear and provide measurable erosion over the 80 hour testing period.

Results of the erosion testing along with relevant fly ash properties are summarized in Table 3-9. Since FPTF data were obtained at velocities two to three times higher than those found in typical oil-designed boiler convection passes, erosion rates were normalized by using an empirical correlation established in C-E's Ash Erosion Test Facility (AETF). The normalized wear rate allowed more direct comparisons between fuels and extrapolation to actual boiler conditions.

Coal beneficiation had a very significant impact on erosion characteristics (Figure 3-12). This effect is anticipated due to the combined influence of lower ash loading and reduced quartz content in the ash of the fuels beneficiated at deeper level. At similar gas velocities erosion for CWF prepared from the lower ash Upper Freeport and Cedar Grove decreased by 60% and 70% respectively.

The effect of slurry preparation did not appear to have a strong influence on fly ash erosion characteristics when firing under similar conditions. The three Splash Dam CWFs prepared from the same coal produced similar erosion, and all three CWFs yielded similar erosion results as the parent coal fired in a dry pulverized state.

TABLE 3-9

FLY ASH EROSION CHARACTERISTICS

FUEL TYPE	FIRING RATE (10 ⁶ Btu/hr)	ASH INPUT (LB/HR)	GAS VELOCITY (FT/SEC)	COAL MMD (μ)	FLY ASH MMD (μ)	CARBON FLY ASH (%)	NORMALIZED WEAR ⁽¹⁾ (MILS/10,000 F ₄)
SD 6.0 P.C. ⁽²⁾	4.1	17.1	245	52	13	99.8	0.6
SD 5.7 E	4.1	16.8	255	25	16	99.5	0.4
SD 4.5 A	4.1	12.8	260	24	34	98.7	0.4
SD 6.7 F	4.1	19.6	255	35	13	99.5	0.5
SD 2.6 C	4.1	7.1	285	15	53	97.0	<0.1
UF 13.7 A	4.1	42.5	265	30	20	99.4	2.9
UF 6.8 A	4.1	19.3	275	29	18	99.7	0.6
CG 7.1 A	3.1	24.0	180	32	23	99.5	1.4
CG 7.1 A	4.1	24.0	265	32	34	99.1	1.7
CG 4.8 A	4.1	14.0	260	25	19	99.5	0.4
AL 5.9 P.C. ⁽²⁾	4.1	17.8	220	39	6	97.7	1.2
AL 5.9 P.C. ⁽³⁾	4.1	17.8	220	28	4	99.9	0.4
AL 5.9 C ⁽⁴⁾	3.0	16.1	220	7	36	99.6	1.8
AL 5.9 C ⁽⁵⁾	4.1	17.8	240	7	9	99.9	1.0
AL 5.9 C ⁽⁶⁾	4.1	17.8	240	7	4	99.8	0.3

(1) Normalized to 60 ft/sec gas velocity

(2) Standard grind pulverized coal

(3) Fine grind pulverized coal

(4) MCWF at 67% solid and 80°F fuel temperature

(5) MCWF at 64% solid and 80°F fuel temperature

(6) MCWF at 64% solid and 220°F fuel temperature

*NORMALIZED TO 60 FT/SEC GAS VELOCITY

FIGURE 3-12 EFFECT OF BENEFICIATION ON FLY ASH EROSION

Although there were significant differences between the coal particle size distribution in the CWFs, results do not show a strong relationship between coal size, fly ash size and erosion. For pulverized coal firing, it is generally expected that as the fuel size decreases, the ash size and erosion rates will also decrease. This does not appear to be true for CWF firing due to the manner in which these fuels burn. As discussed earlier, when CWF is sprayed into a combustion chamber, the coal particles within a given atomized spray droplet tend to agglomerate during drying to form a single particle. Therefore, the CWF droplet size has a very strong effect upon the resulting fuel/char particle size which influences fly ash size.

Heated fuel tests were conducted on Alma MCWF to assess the effect on fly ash characteristics and its potential as a means of realizing full benefits of finer coal particles in the fuel. Changes in fly ash characteristics resulting from dilution or heating the Alma MCWF had a significant impact on erosion (Figure 3-13). Dilution of the MCWF from 67% to 64% solids decreased the carbon content of the fly ash (improved combustion) from approximately 28% to 6% and decreased the fly ash size from mass mean diameters (MMD) of about 36 to 9 microns. The reduction in relative erosion rates between these cases was approximately 45%. Heating the 64% solids MCWF also provided a significant change in performance. The fly ash produced during the 220°F fuel test had lower carbon content (1% versus 6%) and finer fly ash (4 versus 9 micron MMD) compared to that from the ambient test. The relative erosion rates during this heated fuel test were about 70% lower than those during the ambient tests at the same solids loading (64%).

ELECTROSTATIC PRECIPITATOR PERFORMANCE

The electrostatic precipitator (ESP) performance was evaluated during the Splash Dam and Cedar Grove CWF test series. The Splash Dam was additionally tested as pulverized coal to provide baseline data for comparison. The effects of coal type, beneficiation level, firing conditions and the inherent fly ash properties (particle size, resistivity and chemical composition) were assessed in determining the ESP performance.

*NORMALIZED TO A GAS VELOCITY OF 60 FT/SEC

FIGURE 3-13 ALMA MICROFINE CWF FLY ASH EROSION CHARACTERISTICS

Overall, results indicate the CWF tests showed slight improvement in fly ash collection efficiencies compared to those of the pulverized coal firing. The extent of this effect will be dependent on coal type, CWF properties, firing conditions, fly ash characteristics, and specific ESP design and operating conditions.

The ESP data measured during the Splash Dam and Cedar Grove tests are summarized in Tables 3-10 and 3-11. These results can be used in a general equation proposed by Deutch-Anderson and described by H.J. White (8). The collection efficiency of an ESP can be expressed as a function of the migration velocity of the ash particles toward the collector plate, the surface area of the collector plate, and the volumetric flow of the gas past the plates, by the equation:

$$\eta = 1 - \exp(-SCA w_e / 60)$$

Where:

- η - efficiency
- SCA - collector area/volumetric flow, $\text{ft}^2/1000 \text{ acfm}$
- w_e - migration velocity, cm/s

Migration velocities generally can be related to the resistivity of the ash particles. Fly ash samples collected from the hopper under each field of the ESP were analyzed for resistivity per the Institute of Electronic and Electrical Engineers (IEEE) Standard 548. The resulting measurements showed a significant variation in fly ash resistivity for each of the test fuels as many interrelated variables, including firing conditions, flue gas, temperature, moisture, fly ash chemical composition, and particle size distribution influence the results. A general trend cannot be established for the Cedar Grove test series. However, comparison between the Splash Dam pulverized-coal and CWF firings indicate that the fly ash resistivity was lower with CWF. This is most likely due to the flue gas humidification effect associated with CWF firing.

TABLE 3-10

ESP PERFORMANCE RESULTS FOR SPLASHDAM

COAL TYPE	SD P. C. HFR		SD2.6C HFR		SD6.7F HFR		
GAS TEMP., F							
INLET	383	382	453	451	534	498	551
OUTLET	283	253	334	308	378	341	408
GAS FLOW, acfm							
INLET	1791	1740	1982	2087	2350	2095	2455
OUTLET	2374	2255	1841	2014	2205	2038	2287
DUST LOADING, gr/acf							
INLET	5.5	5.0	11.5	9.5	9.0	10.0	8.7
OUTLET	1.8	2.1	10.4	9.8	7.8	9.0	7.8
MOISTURE, %							
INLET	5.5	5.0	11.5	9.5	9.0	10.0	8.7
OUTLET	1.8	2.1	10.4	9.8	7.8	8.0	7.8
ASH RESISTIVITY, 10^{10} ohm-cm							
INLET HOPPER	9.0	13.	.75	.73	.33	.60	.22
ASH MEAN DIAMETER, micron							
INLET HOPPER	23	23	16	16	40	40	22
TOTAL SCA, $ft^2/1000acfm$	200	208	183	173	115	171	146
MODULES OPERATING	1234	1234	1234	1234	234	1234	1234
EFFICIENCY, %	90.1	87.1	93.9	93.7	92.4	91.7	87.0
MIGRATION VEL, cm/s	5.87	5.08	7.79	8.09	11.5	7.37	7.09

TABLE 3-11

ESP PERFORMANCE RESULTS FOR CEDAR GROVE

COAL TYPE	CG7.1A LFR			CG7.1A HFR			CG4.8A HFR		
GAS TEMP., F									
INLET	322	333		417	422	419	429	465	475
OUTLET	224	241		308	316	313	314	338	347
GAS FLOW, acfm									
INLET	1421	1566		2098	2160	2184	1895	1994	2052
OUTLET	1610	2047		2122	2186	2168	1830	1862	1915
DUST LOADING, gr/acf									
INLET	817	1472		1197	1149	1501	822	864	750
OUTLET	88.3	83.6		32.8	68.8	33.9	74.5	43.3	86.0
MOISTURE, %									
INLET	10.5	10.5		14.1	10.1	10.2	10.9	11.0	10.8
OUTLET	7.6	8.2		8.0	8.4	8.6	9.6	9.4	9.2
ASH RESISTIVITY, 10^{10} ohm-cm									
INLET HOPPER	60.	58.		23.	21.	23.	6.5	3.3	2.8
ASH MEAN DIAMETER, micron									
INLET HOPPER	22	22		26	26	26	20	20	20
TOTAL SCA, $\text{ft}^2/1000\text{acfm}$	252	229		171	166	164	189	135	87
MODULES OPERATING	1234	1234		1234	1234	1234	1234	123	12
EFFICIENCY, %	89.2	94.3		97.3	94.0	97.7	90.9	95.0	88.5
MIGRATION VEL., cm/s	4.48	6.37		10.7	8.62	11.7	6.45	11.3	12.6

Figures 3-14 and 3-15 show the overall ESP efficiencies measured from the Splash Dam and Cedar Grove test series. The predicted performance of each fuel based on the Deutch-Anderson relationship between the collecting efficiency, specific collection areas (SCA), gas flow and average ash particle migration velocity, is also shown for comparison. Overall, the measured ESP efficiency during the pulverized coal firing was closely matched with the predicted performance. However, there were more variations between the measured and predicted data during CWF firing. The collection characteristics of CWF ashes appeared to have a higher potential to deviate from those predicted based on pulverized coal experience, since electrical resistivity (due to carbon content) and particle size distribution are highly dependent on slurry properties and firing conditions.

In summary, ESP performance during CWF firing did not appear to be substantially different than during pulverized coal combustion. Fly ash characteristics which are dictated by the coal type, slurry properties, and firing conditions have a strong impact on collection efficiencies.

FIGURE 3-14 ESP OVERALL EFFICIENCY FOR SPLASHDAM

FIGURE 3-15 ESP OVERALL EFFICIENCY FOR CEDAR GROVE

Section 4

CONCLUSIONS

Pilot-scale combustion tests on CWFs prepared by five different manufacturers and from five different coals indicate that these CWFs can be efficiently burned under conditions representative of oil-designed commercial furnaces without severe ash slagging and fouling behavior. Ash properties of the CWF feed coal appear to be the dominant factor influencing deposit characteristics. For the feed coals from Lower Kittanning and Splash Dam CWFs, ash deposition in both radiant and convection zones was light and had little impact on performance at the temperature present in most oil-designed utility boilers. For the Upper Freeport feed coal, moderate slagging and fouling was observed at conditions representative of units designed with relatively high thermal loadings. Low-to-moderate slagging was observed for the Cedar Grove fuels and the microfine Alma fuels.

Atomizer spray quality was the most influential factor on combustion and fly ash size. Firing at similar atomization quality, the initial coal size appeared to have little effect on resulting fly ash size or ash deposit characteristics.

The ash quality of the feed coals determines the slagging and fouling characteristics of the CWFs. Ash deposition behavior was slightly better when fired as CWF than fired as dry, pulverized fuel at similar furnace conditions.

CWF manufacturing techniques did not appear to have a strong direct impact on ash deposition characteristics for the fuels studied. However, slurry type did have a significant effect on atomization properties which could indirectly impact other performance characteristics.

Preheating the MCWF to temperatures above 200°F significantly improved combustion and fireside performance. Secondary atomization caused by thermal effect is thought to be the reason for this improvement.

Fly ash erosion characteristics were similar during comparable CWF and pulverized coal firings. Ash impact velocity, ash loading, ash size distribution and quartz content in the ash are principal factors influencing fly ash erosion characteristics.

Coal beneficiation improved the slagging, fouling and fly ash erosion characteristics of the test fuels. The most significant improvements were reductions of convection tube deposit buildup and fly ash erosion rates.

Fly ash characteristics which are dictated by coal type, slurry properties, and firing conditions have a strong impact on ESP performance. ESP collection efficiencies were slightly higher during CWF firing compared to baseline pulverized coal. The collection characteristics of CWF ashes have a high potential to deviate from those predicted based on pulverized coal experience, since electrical resistivity (due to carbon content) and particle size distribution are highly dependent on slurry properties, atomization quality and firing conditions.

In summary, selection of a high quality feed coal, control of coal fineness, coal loading and fuel preheating to optimize atomization quality can minimize performance impacts for oil-designed boilers and increase economic attractiveness for conversion to coal-water fuels.

Section 5

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APPENDIX A

ATOMIZER TEST FACILITY

The Atomizer Test Facility (ATF) is designed to quantitatively characterize the atomization quality of full scale (10 gpm) burner atomizers. It is uniquely configured to obtain droplet size distribution and droplet ballistics (velocity and trajectory) information from fuel sprays. A schematic of this facility is shown in Figure A-1. Figure A-2 through A-6 show the results for the CWFs tested at the 4.1×10^6 Btu/hr. firing rate.

The facility operates in a cold flow (non-combustion) mode and has provisions for studying both conventional liquid and slurry fuels. Provisions of slurry fuels include a 700 gallon transportable fuel tank for storing and heating fuels prior to ATF testing. The tank is equipped with a mixer and recirculation system to minimize potential slurry solids stratification.

Test atomizers are centrally located in the spray chamber and spray vertically downward, thus minimizing the effect of gravity in atomization droplet ballistics measurements. Also, a constant velocity profile (10 ft/sec) airflow passes by the atomizer during testing to prevent potential droplet recirculation which would otherwise bias droplet trajectory information. Large windows in the spray chamber permit optical access across the atomized sprays. Optical spray diagnostic equipment is located on the two benches as shown. A laser diffraction technique is used to determine the spray droplet size distribution and a high speed double spark photographic technique is utilized to define droplet velocity and trajectory. Once data is obtained from the spray, the fuel droplet-laden air flow is demisted and exhausted from the facility. The collected fuel is then stored in drums for disposal and or future use.

FIGURE A-1 ATOMIZER TEST FACILITY

ATOMIZER TEST DATA

Figure A-2

Figure A-3

COLD FLOW ATOMIZATION TEST RESULTS FOR SPLASHDAM CWFS IN THE ATF

(AT EQUIVALENT $4.1 \times 10^{+6}$ BTU/HR FIRNG RATE)

Figure A-4

**COLD FLOW ATOMIZATION TEST RESULTS FOR
UPPER FREEPORT CWFS IN THE ATF**

(AT EQUIVALENT $4.1 \times 10^{+6}$ BTU/HR FIRING RATE)

Figure A-5

COLD FLOW ATOMIZATION TEST RESULTS FOR CEDAR GROVE CWFS IN THE ATF

(AT EQUIVALENT $4.1 \times 10^{+6}$ BTU/HR FIRING RATE)

Figure A-6

COLD FLOW ATOMIZATION TEST RESULTS FOR ALMA SEAM CWFS IN THE ATF

APPENDIX B

FIRESIDE PERFORMANCE TEST FACILITY DESCRIPTION

Fireside Performance Test Facility (FPTF) is located in Kreisinger Development Laboratory in Windsor, CT. The FPTF is used primarily to assess fuel properties which influence fireside performances. These include furnace slagging, convective pass fouling and fly ash erosion. It is comprised of a complete handling system for solid and liquid fuels, air preheater and a vertically fired test furnace.

The FPTF solid fuel handling and preparation system consists of realistic material handling equipment which includes a conveyor belt and a bucket elevator transport system, a raw fuel storage hopper, a bowl mill and a pulverized fuel silo. Crushed coal (1-1/2" top size) is fed from a 5-ton capacity storage hopper to a C-E Model 271 Bowl Mill where it is pulverized to the desired fineness. The pulverized coal is pneumatically transported to a cyclone collector where most of the coal is dropped into a 3-ton capacity storage hopper. Fines in the cyclone effluent are collected in a bag filter and returned to the storage hopper. Pulverized coal is fed by a belt type gravimetric feeder from the hopper into a rotary air lock, from which it is pneumatically transported into the furnace.

The FPTF Coal-Water Fuel (CWF) handling system is assembled from commercially available components commonly used to handle heterogeneous fluids in various industries. CWF is transported by tanker truck to the facility. It is stored in a 5,500 gallon storage tank. A progressive cavity pump is used to transfer the CWF from the storage tank through a duplex strainer to a 1,500 supply tank. A progressive capacity high pressure pump is used to transfer CWF from the supply tank into the furnace. CWF flow rate is controlled by either a back pressure control valve or by adjustment of the variable speed fuel pump outlet. Fuel mass flow measurement is accomplished by a Micro Motion mass flowmeter. Provisions are made for fuel recirculation from the storage tank to the supply tank, and from the supply tank to the burner. Water and air purging are available to each of these loops for fuel line prewetting and cleaning. The CWF recirculation to burner is provided for fuel transition and light off.

FIRESIDE PERFORMANCE TEST FACILITY FUEL HANDLING SYSTEMS

SOLID FUEL HANDLING SYSTEM

LIQUID FUEL HANDLING SYSTEM

The FPTF furnace is fired from the bottom through a single, swirl-type burner. This burner can be used either for pulverized coal or for CWF testing. The maximum capacity of the furnace is approximately 5.0×10^6 Btu/hr. Firing in this test furnace is designed to simulate commercial boiler time-temperature history. Firing rate can be varied to obtain a wide range of conditions (flame temperatures from 1900°F to 3000°F and residence times from 1 sec. to 2.5 sec.). Secondary air can be heated up to 1100°F in an indirect gas fired air heater.

Located at different elevations from above the burner zone to the furnace outlet plane are four waterwall test surfaces. These waterwall test panels are used for the study of lower furnace ash deposition and are capable of providing detailed data on the slagging characteristics of a test fuel. Each panel section is cooled by fluid passing through serpentine tubing. The metal temperature of the panel is typically controlled at 700°F to simulate the conditions in the lower furnace of a commercial boiler. A high boiling point organic liquid is utilized as coolant and flows in a closed cycle through the panel. The heat absorption rate of the panel is continuously monitored by recording the coolant flow rate and temperature changes through the panel.

Flue gas leaves the combustion zone at a right angle through a horizontal water cooled superheater duct. A water cooled transition section surrounds the entrance of the superheater duct. The duct section of the furnace can be designed to simulate the convection sections of a commercial pulverized coal or oil-fired unit, and consists of five sections totaling 13 ft. in length. Air cooled probes are used to simulate superheater tubes. Each bank contains two rows of probes. Probe metal temperatures are controlled at 1100°F. Typical gas temperatures and gas velocities at the probe banks range from 2300°F to 1300°F and 70 ft./sec. to 30 ft./sec., respectively.

Located downstream of the FPTF is a high velocity section. A specially prepared convection tube is used in this section for erosion study. A surface activation technique is used to determine metal loss on tube specimens after exposure. This method measures the changes in the intensity of emitted gamma rays to determine erosion. The object to be measured is made radioactive by

LOWER FURNACE FEATURING WATERWALL TEST PANEL

UPPER FURNACE SECTION OF FPTF AND SUPERHEATER DUCT

impinging a particle beam on the surface. The metal temperature is controlled at 800°F. As the surface is eroded after exposure the level of gamma radiation emitted decreases. The change in radioactivity is related to the depth of material loss.

A flue gas sample is obtained downstream of the FPTF convective pass probes. The sample is conditioned to remove fly ash and water vapor before being introduced into the individual dedicated gas analyzers for measurements of O_2 , CO_2 , CO , NO_x , SO_2 and SO_3 . The facility is fully instrumented and equipped with automated data acquisition system to accurately monitor and record all fuel and air inputs. Cooling flows and temperatures are measured to obtain mass and energy balances around the furnace.

GAS ANALYSIS SYSTEM

APPENDIX C

PILOT-SCALE ELECTROSTATIC PRECIPITATOR

Pilot-Scale Electrostatic Precipitator. The ESP facility was constructed to simulate a full size ESP as closely as possible with the small flow of gases from the FPTF. Because of the limited amount of flue gas, the vertical height of the facility was shortened to maintain the same gas velocities as would be present in a commercial ESP. The collecting plates and energizing electrodes are identical to commercial units except for their height. In addition, the width was decreased to include two side collecting plates, and a center collecting plate. The length of the facility is the same as a commercial ESP. This provides for a close simulation of a commercial ESP except for the aspect ratio of height to length. The overall specification of the ESP facility are as follows:

Collecting Modules	2	20 ft. long
Fields	4	2 field/module
Collecting Plate Construction		flat plate
Collecting Plates per Field	3	(5 panels per plate)
Collecting Plate Overall Length	9	ft. 11 inches
Collecting Plate Height	2	ft. 3 inches
Total Collecting Plate Area Per Field		89.62 sq.ft.
Total Collecting Plate Area Per Module		179.24 sq.ft.
Total ESP Collecting Plate Area		358.50 sq.ft.
Discharge Electrode Construction frame		Rigid support wire
Electrodes Per Frame	2	
Electrode Wires Per Frame	26	
Electrode Wire Length		2 ft. 6 inches
Individual Voltage Controllers	4	(1 per module)
Individual Pneumatic Rapper Controllers	4	discharge and collection

Four independent transformer-rectifiers sets and automatic voltage controllers

provide and control the high D.C. voltage necessary for electrostatic precipitation. Each automatic voltage controller (AVC) meters primary and secondary current and voltage, controls the operating power levels and provides diagnostic information in the event of equipment malfunction (such as low primary voltage, high transformer temperature, etc.).

Electrode cleaning, required for optimum collection, is accomplished by pneumatically rapping each of the collecting and discharge assemblies. The on and off rapping time can be independently set for each assembly and can be automatically or manually activated.

ESP TEST FACILITY PLAN AND ELEVATION VIEWS

-END-

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