COMBUSTION AND FUEL CHARACTERIZATION
OF COAL-WATER FUELS
VOLUME 1
FINAL SUMMARY REPORT

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PREPARED BY
COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT 06095

PROJECT MANAGER
M. J. HARGROVE

PRINCIPAL INVESTIGATORS

O. K. CHOW
G. W. GRALTON
Y. V. LACHOWICZ
R. C. LAFLESH
A. A. LEVASSEUR
G. N. LILJEDAHN

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ABSTRACT

This five-year research project was established to provide sufficient data on coal-water fuel (CWF) chemical, physical, and combustion properties to assess the potential for commercial firing in furnaces designed for gas or oil firing. Extensive laboratory testing was performed at bench-scale, pilot-scale (4×10^6 Btu/hr) and commercial-scale (25×10^6 to 50×10^6 Btu/hr) on a cross-section of CWFs. Fuel performance characteristics were assessed with respect to coal properties, level of coal beneficiation, and slurry formulation. The performance of four generic burner designs was also assessed. Boiler performance design models were applied to analyze the impacts associated with conversion of seven different generic unit designs to CWF firing. Equipment modifications, operating limitations, and retrofit costs were determined for each design when utilizing several CWFs.

Results demonstrated that available burner designs can fire CWF with satisfactory turndown stability and carbon conversion efficiencies. CWF combustion behavior was strongly influenced by atomization quality and slurry formulation. CWF ash performance characteristics were highly dependent on feed coal properties. This project clearly indicates that the viability of coal-water fuels as commercial alternatives to gas and oil is highly dependent on boiler design, differential fuel cost and fuel quality. Economic and performance factors have been shown through extensive tests and analyses to be critically sensitive to fuel characteristics.

Unit performance analyses showed significantly better load capacity for utility and industrial boilers as the CWF feed coal ash content is reduced to 5% or 2.6%. In general, utility units had more attractive capacity limits and retrofit costs than the industrial boilers and process heaters studied. Economic analyses indicated that conversion to CWF firing generally becomes feasible when differential fuel costs are above $\$1.00/10^6$ Btu.

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INTRODUCTION

Coal-water fuel mixtures (CWFs) which typically contain 70% pulverized coal, 30% water, and less than 1% chemical additives have the potential of replacing fuel oil in commercial furnaces. Use of these coal-based fuels could lessen U. S. dependency on imported oil and reduce power generating costs.

Commercial development of CWF has been impeded by technical and economic uncertainties. The key technical question concerns the impact an ash-bearing CWF would have on furnaces originally designed for ash-free or very low ash fuels. Economic feasibility - in terms of boiler derating, equipment modification, and retrofit costs - will largely depend upon the degree to which CWF affects boiler performance. Resolution of these unanswered technical and economic questions is an essential prerequisite to the commercial development of CWFs as alternatives to fuel oil.

In response to this need, the Pittsburgh Energy Technology Center (PETC) of the Department of Energy initiated a comprehensive effort in 1982 to develop the necessary performance and cost data and to assess the commercial viability of CWFs as applied to representative utility and industrial units.

Combustion Engineering, Inc. (C-E) was contracted to conduct the project. The effort comprised 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. Extensive bench, pilot and commercial-scale tests were performed by C-E to develop necessary CWF combustion and fireside performance data for the subsequent boiler performance analysis and retrofit cost estimates. Gulf Research and Development Company, Energy International, Inc., and the Adelphi Center for Energy Studies provided essential sub-contract support in various aspects of source coal characterization and selection, fuel preparation and procurement, and the determination of detailed fuel properties. CWFs were prepared for this project by Advanced Fuel Technology, Atlantic Research, CoalLiquid, Ergon, and OXCE Fuel Company.

This Summary report (Volume 1) provides a general overview of the project and a summary of principal results and conclusions. Primary emphasis is placed on the impacts which CWF combustion and performance characteristics have on commercial unit operation and retrofit economics. Detailed information regarding technical approaches, test equipment, test procedures, test data and analyses relating to specific aspects of the work from each individual task are provided in the following volumes.

- Volume 2 - Task 1: Selection and Procurement of Candidate
& Task 3 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 5 - Task 5: Pilot-Scale Ash Deposition and Performance
Testing of Coal-Water Fuels
- Volume 6 - Task 6: Commercial Application and Economics of
Coal-Water Fuels

PROJECT SUMMARY

The project was organized to respond directly to the probable needs of CWF users. Five major tasks were defined to establish the technical data base necessary for boiler performance analyses. Established boiler performance models then utilized these data, in a sixth task, to establish specific load-limiting factors and to determine consequent equipment modification and retrofit costs. Finally, economic feasibilities in terms of payback periods were estimated for several boiler types and CWF properties based upon fuel price differentials.

To ensure commercial relevance, criteria consistent with the expected market were defined for each task. Coal resources, beneficiation processes, and coal-water fuel producers were evaluated and selected on the basis of availability, suitability (as measured by test criteria), and other commercial considerations. Engineering evaluations of atomization, combustion, and fireside performance of the selected CWFs were based upon test equipment and procedures used regularly for coal-fired and oil-fired boiler performance tests.

Overall program logic is reflected in the task responsibilities illustrated in Figure S-1. The activities and key results from these tasks are summarized below. More detailed summations of these and related task activities are presented later in this report.

SELECTION OF TEST FUELS

The fuels tested were CWFs having formulations representative of those that are expected to become available commercially. The selected CWFs were made from five coal sources, two levels of beneficiation, and five commercial suppliers.

Based upon published data, twenty coals from the Eastern United States were initially selected and subjected to first level screening tests. Key criteria included commercial significance, beneficiation potential, ash content and

**FIGURE S-1 OVERVIEW OF COMBUSTION AND FUEL CHARACTERIZATION
PROJECT ACTIVITIES**

quality, sulfur content, volatile matter content, and char reactivity. Since coal beneficiation is expected to play a major role in the commercial use of CWFs, the selection process considered the anticipated characteristics of the coal after beneficiation. As part of these screening tests, gravity separation (14 mesh at 1.3 specific gravity) and subsequent analysis of the two density fractions plus the raw coal were performed.

Based upon results of the first level screening tests, eight coals were selected for second level screening tests. These tests consisted of detailed "washability" and fuel analyses.

The results of the second level screening tests (Table S-1) were used to select four source coals for beneficiation and for preparation of CWFs for large-scale testing. The "combustion" rating refers to char reactivity during thermogravimetric analyses. The comments on "manufacturing" are based on the processing results of the CWF vendors. A fifth source coal was added later in the project for preparation of a microfine CWF.

The Cedar Grove, Splash Dam, and Upper Freeport CWFs were tested at bench-scale, pilot-scale and full-scale. The Lower Kittanning coal and Alma coal were used to make CWFs for bench-scale and pilot-scale tests. These selected coals provided a range in fuel characteristics including varying volatile matter content and ash quality.

BENCH-SCALE CHARACTERIZATION

Comprehensive bench-scale testing was conducted on a cross-section of CWFs to provide the bases for CWF selection for large-scale testing. Four source coals were beneficiated to reduced ash concentrations by selected pilot-scale froth flotation and heavy medium cyclone processing to provide seven test coals. These coals were extensively characterized with respect to essential chemical and physical properties which are relevant to environmental impacts, slurryability, combustion, ash deposition and ash erosion.

TABLE S-1
GENERALIZED CANDIDATE COAL RATINGS

Coal	Combustion	Manufacturing	CWF Comments
Cedar Grove ⁽¹⁾	Marginal	Acceptable	Potential Low Fuel Reactivity
Lower Elkhorn	Moderate	Marginal	Questionable Slurry- ability
Black Creek	Good	Unacceptable	
Splash Dam ⁽¹⁾	Moderate	Excellent	
Lower Kittanning ⁽¹⁾	Moderate	Marginal	Reference CWF Coal
Western Kentucky #11	(2)	(2)	Oxidized Coal in Feed
Upper Freeport ⁽¹⁾	Good	Acceptable	High Sulfur; Poor Ash Liberation
Pittsburgh #8	(2)	(2)	High Sulfur; Poor Ash Liberation
Alma ⁽¹⁾	Good	Acceptable	High Sulfur, Poor Ash Liberation
			Microfine CWF

(1) Selected As Source Coal For Beneficiation and CWF Preparation

(2) Not Analyzed

Eleven test CWFs were prepared from these coals by five commercial CWF producers. In addition, one CWF was prepared from a microfine ground coal for evaluation. Representative 5-gallon samples of these slurries were extensively characterized to establish essential physical and rheological data with respect to storage, transportation, aging, weather (i.e. freezing/thawing), atomization, combustion, and environmental impact.

The test fuels were prepared by established producers using their own technical approach (coal particle size distribution and loading, chemical additive package, etc.). Principal requirements were high solids loading, stabilized commercial fuels; particle top size control to avoid atomizer plugging; and assurance of pumping and handling capability. Typical properties of these fuels along with those of the twelfth microfine CWF added later in the project are summarized in Table S-2. Each fuel is identified by coal type, ash level and producer code letter. For example, LK 6.0 C is made with Lower Kittanning coal at 6 percent ash produced by Vendor C. This identification system is used throughout the test program. It should be noted that the ash content of a given CWF type varied between tasks as the fuels were prepared from different batches. The stated ash content reflects the actual quantity of ash in each test fuel.

In general, the participating producers were able to prepare CWFs suitable for transportation, storage, handling and firing with process adjustments for each new coal. Cross-country shipping of two CWFs by truck had no apparent effect on settling. The amounts of settling under the stationary storage and their transit conditions were generally insignificant as the CWFs could be restored to their original state with minor stirring. Changes in temperatures and exposures to freeze/thaw cycles also showed little effects on CWF stability.

TABLE S-2
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	66	69	66	70	69	70	71	69	70	69	68	67
pH	8	8	8	9	9	9	6	8	8	9	9	8
CWF Screen Analysis												
260 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
60x100 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	4.0
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	68.1	88.0	72.6	65.9	67.9	82.5	75.2	95.0
Coal Particle MMD (μ)	15	50	25	15	33	15	35	30	29	32	25	11
Viscosity @ 100 sec ⁻¹ (1)	1500	840	860	640	1400	610	1610	1700	1600	1830	1060	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 (1)				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	-
% by weight droplets >320	.01	.01	0.00	0.00	0.37	0.02	0.22	3.43	2.19	0.02	.04	0.0
% by weight droplets >225	1.18	0.98	0.40	0.22	5.07	1.28	3.83	14.61	9.64	1.00	1.64	0.8

(1) Rotational Viscometer @ 20°C.

(2) Extrusion Rheometer @ Room Temp.

(3) Variable High Shear Viscometer @ 20°C

The viscosity results indicated the CWFs varied considerably in rheological characteristics. Low shear as well as high shear tests showed a wide range of viscosities for the CWFs (600 cps to 3,000 cps). Atomization quality generally improved with decreasing viscosities. However, accurate predictions of atomization quality could not be made from the bench-scale viscosity data due to the CWFs complex rheology.

Typical analyses of the feed coals on a moisture free basis are shown in Table S-3. The feed coals varied in ash content from 2.6% to 13.7% Ash chemistry and ash fusibility temperatures varied between coal types as well as with level of beneficiation. The ash slagging and fouling characteristics of Lower Kittanning, Splash Dam, and Cedar Grove coals would generally be

TABLE S-3

TYPICAL 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	76.7	81.6	85.7	72.3	79.1	76.7	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

considered low for steam coals, while the Alma and Upper Freeport coals have moderate ash deposition characteristics. Bench-scale results indicate all eight coals have fairly similar ignition and char combustion reactivities which are typical to those of high volatile bituminous coals.

More detailed fuel reactivity data were obtained on the coals using a drop tube furnace to provide necessary inputs for combustion process modeling. The effects of furnace operating parameters and CWF properties on carbon loss were examined using established modeling procedures. In general, atomization quality/char particle size and furnace residence time were found to be the most important parameters influencing combustion efficiency.

COMBUSTION EVALUATION/ATOMIZATION AND BURNER TESTS

The combustion performance characteristics of four generic burner designs for retrofit to oil-designed units were evaluated. Each burner was initially evaluated through a series of preliminary tests to identify potential design deficiencies which could be modified prior to detailed performance characterization. The preliminary tests included cold flow atomization testing, combustion shakedown/optimization testing and an abbreviated performance characterization. Following the preliminary tests, all burners were evaluated with the same reference fuel in C-E's Industrial Scale Burner Test Facility (ISBTF) at 25×10^6 Btu/hr firing rate. A generic burner design was subsequently selected for application to the multiple CWF combustion tests at a 50×10^6 Btu/hr firing rate.

The burners selected for testing at 25×10^6 Btu/hr included:

1. High-Swirl Wall Fired (HSWF)
2. Tangentially-Fired (TAN)
3. Refractory Chamber (REF)
4. Combination of refractory and register types (REF/REG)

All these burner systems tested were capable of firing the reference CWF. Each burner configuration exhibited unique performance characteristics that can be attributed to fundamental differences in burner atomization properties and/or near-field thermal/aerodynamic characteristics.

Atomizer performance in terms of fuel and air pressures, and spray quality measured in a non-combustion environment varied substantially between the different designs. Overall, the HSWF and TAN atomizer produced finer sprays (mass mean diameter of 60 microns MMD at 100% capacity) compared with the REF and REF/REG atomizers (140-160 microns at 100% capacity). Of particular importance was the concentration of larger droplets produced. The HSWF and TAN atomizer generated sprays with less than 1% of the spray droplet above 320 microns, while the REF and REF/REG atomizers produced 5% to 9% and 14% to 18% greater than 320 microns, respectively. These atomization data correlate directly with combustion results reflecting the increase in time required to dry and burn out larger CWF droplets.

The combustion performance testing under specific, controlled conditions showed the HSWF burner could operate with good flame stability over a 2.5 to 1 turndown range and achieve carbon conversion efficiencies in excess of 97% at 100% load and 99% at reduced load. The TAN burner demonstrated carbon conversion efficiencies up to 99.9% at full load, with a turndown range of 2-to-1. The REF burner exhibited the highest turndown capability of 4-to-1, but relatively low carbon conversions of 86% at full load and 95% at reduced load. The REF/REG burner achieved carbon conversions up to 98%, but could be operated with only limited turndown.

Based upon the overall performance and general commercial considerations, the HSWF burner design was selected and scaled-up for use as the test burner for 50×10^6 Btu/hr testing of five selected CWFs. This single burner with essentially fixed burner settings was employed to allow direct comparisons of the atomization and combustion behavior of the various CWF formulations.

Results of these tests showed significant differences in combustion performance between CWFs (Figure S-2). The slight variations in the chemical make-up of each feed coal, relative combustion reactivity/devolatilization and swelling properties did not appear to influence the comparative combustion performance of the CWFs tested. Changes in feed coal particle size distribution, within the range evaluated during these tests (microfine grind and standard boiler grind), did not show direct impact on the comparative combustion performance of the CWFs evaluated. Spray atomization quality in

FIGURE S-2 EFFECT OF EXCESS AIR AT 100%
LOAD ON CARBON CONVERSION

the combustion environment, not the feed coal particle size, appeared to determine the specific CWFs combustion characteristics. This is attributed to the fact that CWF spray droplets and the coal particles within them tend to burn as agglomerates, and not as individual coal particles.

Combustion performance results for the five CWFs tested indicated that atomization quality, as defined in a non-combustion environment, can be unreliable when attempting to predict the performance between different CWF formulations (Figure S-3). CWF atomization quality observed in the hot furnace environment can differ greatly from atomization quality defined in an ambient temperature test facility. Fuel spray quality for all five CWFs tested as defined in an ambient temperature test facility were nearly equivalent, with the exception of the fuel UF6.2C. Fuel UF6.2C produced finer sprays on average than the other four test fuels. Contrary to these cold flow results, the carbon conversion efficiency for UF6.2C was much poorer on average than for the other four fuels. Consistent predictive trends could not be found between the remaining four CWFs' cold flow atomization quality and their respective combustion performance.

However, atomization quality measurements made in an ambient temperature environment on a single CWF formulation can effectively predict a specific CWF's combustion performance trends. A reduction in average spray droplet diameter consistently resulted in an improvement in carbon conversion efficiency when considering a single fuel formulation at a time (Figure S-3).

Examination of fly ash/char samples extracted during testing suggests significant differences in CWF atomization/char combustion process between different CWF formulations under hot combustion conditions. The presence of long, cylindrical coal char particles suggest incomplete breakup of the CWF ligaments into droplets. This appears to be attributed to insufficient time for breakup as fuel is heated, dries and agglomerates upon leaving the atomizer. Differences in the atomization behaviors and fuel agglomerating characteristics during the combustion process appear to have been primary factors controlling overall combustion performance of these CWFs.

FIGURE S-3 EFFECT OF SPRAY DROPLET DIAMETER ON CARBON CONVERSION

ASH DEPOSITION AND PERFORMANCE TESTING

The fireside performance behavior of a cross-section of coal-water fuels was investigated during comprehensive pilot-scale testing at approximately 4×10^6 Btu/hr. Data were obtained from twelve different CWFs as well as three baseline pulverized coals. Ash slagging, fouling, erosion, and precipitator collection data were collected under highly controlled test conditions simulating those representative of typical oil designed boilers. Testing focused on generation of quantitative data required to establish operational limits and to provide direct input to boiler models for prediction of equipment performance.

CWFs from three coal types at different beneficiation levels were test fired to allow assessment of the effects of coal cleaning on performance. Five CWFs were prepared from the same feed coal by different producers to evaluate the effects of slurry processing. Both standard grind and microfine CWFs were included. A microfine CWF was fired at fuel temperatures up to 220°F to improve atomization.

Cold flow atomization characteristics of each CWF were assessed prior to combustion testing to determine and control spray quality. The purpose of these tests was to establish atomizer settings to maintain similar spray quality during each of the fireside performance tests.

All of the CWFs tested could be effectively atomized and burned during the pilot-scale tests. Flame stability was generally good during all of the test runs and carbon conversion efficiencies were typically greater than 99.5%. Test results showed the importance of atomization quality on combustion efficiency and resulting fly ash properties (Table S-4). Degradation in atomization quality resulted in greater carbon loss and larger fly ash size. Coal particle size did not significantly affect the fly ash size generated from the CWFs under similar atomization conditions.

TABLE S-4

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

FUEL TYPE	SOLID CONTENT (%)	FIRING RATE 6 (10 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	1.26	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	16	86	9	99.9
LK6.0C	66.0	4.1	2840	0.99	15	88	14	99.0
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 4.5A	69.5	4.1	3050	0.97	24	98	8	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
CG7.9A	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	65	19	99.5
AL p.c. Std.	--	4.1	2990	1.00	39	--	6	99.8
AL p.c. Fine (1)	--	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 (2)	64.0	4.1	2980	0.95	7	61	9	99.6
AL 5.9C (3)	64.0	4.1	2990	0.96	7	73	7	99.9
AL 5.9C	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

Heating the CWF prepared from Alma microfine coal (AL5.9C) to fuel temperature of approximately 220°F significantly reduced fly ash size compared to that from the unheated fuel. This improvement was attributed to secondary atomization effects due to flashing of a portion of the water in the fuel upon exit from the atomizer. Heating the fuel to temperatures up to 150°F had no appreciable effect on performance. Dilution of this CWF from 67% solids loading to 64% solids was necessary to improve combustion characteristics. The apparent poor atomization quality of the higher solids loading slurry under hot combustion conditions (large sparklers and char particles extracted from flame) was not indicated by the cold flow atomization tests.

Waterwall Slagging Characteristics: The ash slagging characteristics of each fuel were assessed as a function of firing conditions. Waterwall slagging behavior was characterized by determining deposit coverage, the effect on waterwall panel heat flux, deposit cleanability and deposit physical and chemical characteristics. The effects of deposits on waterwall heat transfer and the cleanability of waterwall deposits were the primary data used in assessing slagging potential. Slagging potentials of the CWFs were found to be primarily dependent upon ash characteristics of their respective parent coal (Table S-5). Waterwall deposit characteristics observed during both the Lower Kittanning and Splash Dam CWF tests indicated low slagging potential. Moderate slagging was experienced during Cedar Grove CWF tests and high slagging during the Upper Freeport CWF tests. The Alma coal, fired only as a microfine CWF, exhibited relatively low slagging potential in relation to its predicted performance based on bench-scale ash analyses.

On the basis of tests conducted on two coals (AL 5.9 and SD 5.7), slagging propensity was found to be less for CWF firing than dry pulverized coal firing. Reasons for the improved CWF behavior are not clearly evident. Differences in time-temperature history which the coal mineral matter undergoes during firing could, however, account for the superior performance of the CWF form. An additional reason for the improved behavior

TABLE S-5

FURNACE SLAGGING CHARACTERISTICS OF CWFs

FUEL TYPE	FIRING RATE (10 ⁶ Btu/hr)	FURNACE TEMP. (°F)	DEPOSIT PHYSICAL STATE	DEPOSIT COVERAGE (%)	DEPOSIT THICKNESS (in)	DEPOSIT CLEANABILITY	ESTIMATED 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 7.9 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 (3)	4.1	2990	Molten	40	<1/2	Good	
AL 5.9 C	4.1	3000	Molten	40	<1/2	Good	

(1) At 80°F Fuel Temperature

(2) At 150°F Fuel Temperature

(3) At 220°F Fuel Temperature

could be reduced mineral size in the CWFs due to finer coal grinding. The lower than indicated slagging behavior of the AL 5.9 fuel is consistent with this explanation.

Preheating the AL 5.9 fuel to 220°F did not noticeably affect slagging behavior; but, again, it should be noted that this fuel exhibited good slagging performance despite its relatively unfavorable ash characteristics.

Variations in CWF particle size distribution and additive package did not have a strong direct influence on slagging performance. It should be noted, however, that tests were performed with uniform atomizer spray quality and under very good combustion conditions. These results may not apply to different coal types or different additive packages. The effects of formulation on combustion behavior of CWFs in a particular firing system can be significant as shown during the 50×10^6 Btu/hr combustion tests. Changes in combustion behavior can in turn impact ash behavior.

The effects of coal beneficiation were assessed for the Splash Dam, Upper Freeport, and Cedar Grove CWFs. Overall, slagging characteristics improved with increased level of beneficiation for each fuel at the high firing rate. In general, the more beneficiated CWFs exhibited lower ash deposition rates and generated deposits which were less fused and more readily cleanable than the respective higher ash CWF.

Convection Pass Tube Fouling Characteristics: The ash fouling performance of the test fuels was assessed as a function of firing conditions by examining deposits generated on a series of convective pass probe banks. Convective 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 temperature was the most important operating parameter influencing convection pass 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, and, for a given coal type, deposit accumulation rates decreased as the ash levels in the CWF coals decreased due to beneficiation.

The relative fouling characteristics of each CWF were influenced by the properties of its feed coal. Test results indicated that the fouling potential for the Lower Kittanning, Splash Dam, and Cedar Grove fuels were low; and for the Upper Freeport low to moderate. The Alma MCWF had low fouling potential despite the fact that its ash analysis indicated somewhat higher potential. Table S-6 summarizes fouling characteristics of the fuels.

TABLE S-6
CONVECTIVE PASS FOULING CHARACTERISTICS

FUEL TYPE	FIRING RATE (10 ⁶ Btu/hr)	GAS TEMP. AT PROBES (°F)	RELATIVE BUILDUP	DEPOSIT	DEPOSIT CLEANABILITY
			RATE (TIME BETWEEN SOOT BLOWINGS, Hr)	BONDING STRENGTH	
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	<1	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
JF 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		Very Good

1. Standard grind dry, pulverized coal (8 75% less than 200 mesh)
2. Fine grind dry, pulverized coal (8 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

Lower Kittanning fuels had excellent ash fouling characteristics. Very little ash deposition occurred below gas temperatures of 2300°F. The fouling performance of the Splash Dam fuels was also very good. CWF formulation did not appear to have a strong impact on fouling characteristics, as all of the Splash Dam CWFs exhibited low convection pass tube deposit buildup rates and weakly bonded, friable deposits up to the maximum gas temperature (2350°F) tested. During all the Splash Dam CWF tests, convection tube deposits could be readily removed by soot blowing. Deposit-to-tube bonding strength measurements were very low.

The fouling characteristics of the Upper Freeport CWFs varied significantly between firing rates and between levels of beneficiation. Ash deposition increased with firing rate illustrating the combined effect of increased gas temperatures and increased ash loading. An improvement in fouling was observed with the Upper Freeport beneficiated to deeper level. Soot blowing requirements at similar firing conditions indicate ash buildup rates were reduced by about 50 percent for the more beneficiated fuel.

Overall, the relatively low fouling characteristics for the coal types evaluated is not unusual, considering the low concentrations of alkali and alkaline earth constituents in these fuels. High volatile bituminous coals from the Appalachian region have typically low fouling potentials.

Fly Ash Erosion Characteristics: Relative fly ash erosion characteristics were studied using tube specimens of carbon steel directly exposed to the particulate laden flue gas stream. Data were obtained at high gas velocities (160 - 275 ft/sec) in order to accelerate wear and provide measurable erosion over an 80-hour test period.

Erosion wear data for the Splash Dam, Upper Freeport, Cedar Grove and Alma fuels along with relevant fly ash properties are summarized in Table S-7. Data indicated a strong dependency of erosion on gas velocity and ash loading.

TABLE S-7

FLY ASH EROSION CHARACTERISTICS

FUEL TYPE	FIRING RATE	QUARTZ IN CWF ASH (%)	ASH INPUT (LB/HR)	GAS VELOCITY (FT/SEC)	COAL MMD (μ)	FLY ASH MMD (μ)	CARBON CONVERSION (%)	NORMALIZED WEAR ⁽¹⁾ (MILS/10,000 HR)
SD 6.0 p.c. ⁽²⁾	4.1	-	17.1	245	52	13	99.8	0.6
SD 5.7 E	4.1	19.8	16.8	255	25	16	99.5	0.4
SD 4.5 A	4.1		12.6	260	24	34	99.8	0.4
SD 6.7 F	4.1		19.6	255	35	13	99.5	0.5
SD 2.6 C	4.1	7.0	7.1	265	15	53	99.2	<0.1
UF 13.7 A	4.1	13.8	42.5	265	30	20	99.4	2.9
UF 6.8 A	4.1	11.7	19.3	275	29	18	99.7	0.6
CG 7.1 A	3.1	18.5	24.0	180	32	23	99.5	1.4
CG 7.1 A	4.1	18.5	24.0	265	32	34	99.1	1.7
CG 4.8 A	4.1	15.1	14.0	260	25	19	99.8	0.4
AL 5.9 p.c. ⁽²⁾	4.1	18.5	17.8	220	7	6	97.7	1.2
AL 5.9 p.c. ⁽³⁾	4.1		17.8	220	7	4	99.9	0.4
AL 5.9 C ⁽⁴⁾	3.8		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 ⁽⁶⁾	4.1		17.8	240	49	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

Coal beneficiation had a very significant impact on erosion characteristics (Figure S-4). At similar gas velocities, the 55 percent reduction in ash loading due to beneficiation of the Upper Freeport fuel resulted in about a 60 percent decrease in erosion. For the Cedar Grove fuel, the 45 percent reduction in ash loading due to beneficiation resulted in more than a 70 percent decrease in erosion. The normalized erosion rates of the lowest ash fuel, SD2.6C, were very low even if projected to the high gas velocities in oil designed units.

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 feed coal produced similar erosion, and all three CWFs yielded similar erosion results as the parent coal fired in a dry pulverized state.

FIGURE S-4 EFFECT OF BENEFICIATION ON FLY ASH EROSION RATE

Although there were significant differences between the coal particle size distribution in the CWFs, results do not show a strong relationship between coal size and erosion. For pulverized coal firing, as indicated by the Alma standard and fine grind pulverized coal test results shown in Figure S-5, the fly ash size and erosion decreased with decreases in coal particle size. This does not appear to be true for the CWF firing due to the manner in which these fuels burn. As CWF is sprayed into a combustion chamber, the coal particles within a given spray droplet tend to agglomerate during drying. Therefore, the CWF droplet size has a very strong effect upon the resulting fuel/char particle size which influences fly ash size.

Changes in fly ash characteristics resulting from diluting or heating the microfine A1 5.9C CWF had a significant impact on erosion (Figure S-5). Dilution of the fuel from 67 percent to 64 percent solids improved combustion and decreased the fly ash size which caused a reduction in erosion rates by approximately 45 percent. Heating the 64 percent solids fuel also provided a significant change in performance. The fly ash produced during the 220°F fuel test showed lower carbon content and finer fly ash which caused about a 70 percent lower erosion rate than that during the ambient fuel tests.

COMMERCIAL APPLICATION AND PERFORMANCE PREDICTIONS

Seven oil-designed units, as shown in Figure S-6, were selected to represent the retrofit market:

- Unit A - 600 MW closed-coupled screen utility steam generator
- Unit B - 400 MW box type utility steam generator
- Unit C - 850 MW closed-coupled arch utility steam generator
- Unit D - 100,000 lb/hr shop-assembled industrial boiler
- Unit E - 400,000 lb/hr field-assembled industrial steam generator
- Unit F - 71 million Btu/hr cylindrical crude oil heater
- Unit G - 142 million Btu/hr cabin type crude oil heater.

*NORMALIZED TO A GAS VELOCITY OF 60 FT/SEC

FIGURE S-5 ALMA MICROFINE CWF FLY ASH EROSION CHARACTERISTICS

UTILITY STEAM GENERATOR UNIT DESIGNATIONS

SHOP ASSEMBLED INDUSTRIAL BOILER

FIELD ASSEMBLED INDUSTRIAL BOILER

PROCESS HEATER TYPES

FIGURE S-6 SELECTED STUDY UNITS

Selection criteria for the utility and industrial steam generators ensured the greatest possible coverage of the subject classes of existing oil-fired equipment. The criteria included age, location, configuration, and environmental limits.

Based on the fireside performance data, unit performance was predicted for the seven study units firing six different CWFs. Five fuels were selected such that the effect on performance of beneficiation level and ash fusibility temperatures were assessed. A sixth fuel was evaluated to assess the effects of CWF prepared from microfine ground coal in three of the units. This analysis defined the load capability of each particular unit for each CWF. The analytical procedure examined several potential load-limiting factors, and determined which ones were critical in requiring the unit to be derated. The following list shows some of the potential load-limiting factors:

- Furnace slagging
- Convection pass fouling
- Inadequate furnace residence time for complete combustion
- Erosion in the convection sections
- Tube metal overheating
- Inside tube film temperature (process heaters only)
- Working fluid overheating
- Control flow limits

The performance analyses were sensitive to both the quantity and quality of the ash contained in the various CWFs. If the load limit defined by one factor was significantly lower than the others, analysis of possible improvement methods was studied. Economics were the deciding factor as to whether the proposed change was effective. The performance analysis also included an estimate of SO_x , NO_x , and particulate emissions.

Performance Analyses Results

The results of performance analyses for the seven units firing the six fuels selected for this study are shown in Table S-8. The deratings for standard grind CWFs ranged from zero (for the two process heaters) to 77% of capacity (for the Type-A-shippable unit).

TABLE B-8 GENERAL RESULTS OF PERFORMANCE ANALYSIS

UNIT	TYPE	CWF	MAX LOAD (%)	LOAD LIMITED BY
A	U	UF6.8	33*	Clear Space at Upper Finishing SH
A	U	SD5.7	74	Clear Space at Upper Finishing SH; Gas velocities at RH Front Crossover, Rear LTRH, WW Screen
A	U	CG7.9	44	Gas velocity at RH Front Crossover, WW Screen, Rear LTRH
A	U	CG4.8	71	Clear Space at Upper Finishing SH; Gas velocity at RH Front Crossover, Rear LTRH, WW Screen.
A	U	AL5.9	73	Clear Space at Upper Finishing SH; Gas Velocities at RH Front Crossover, Rear LTRH, WW Screen
B	U	UF6.8	30	Clear Space at Finishing Reheater
B	U	SD5.7	50	Gas Velocity at Rear LTSH
B	U	CG7.1	31	Gas Velocity at Rear LTSH
B	U	CG4.8	48	Gas Velocity at Rear LTSH
C	U	UF6.8	45	Clear Space at SH Platen
C	U	SD5.7	73	Gas Velocity - LTSH Cold (SH pass), Horiz RH #2 (RH Pass) Burner Zone Release Rate Limit
C	U	CG7.1	46	Gas Velocity - Horiz RH #2 (RH pass)
C	U	CG4.8	70	Gas Velocity - LTSH Cold (SH pass), Horiz RH #2 (RH Pass)
C	U	SD2.8	95	Clear Space, SH Platen; Gas velocity, Horiz RH #2 (RH pass)
C	U	AL5.9	71	Gas Velocity - LTSH Cold (SH Pass), Horiz RH #2 (RH Pass); Burner Zone Release Rate
D	I	UF6.8	23	Clear Space at Boiler Bank
D	I	SD5.7	30	Furnace liberation (BTU fired/furnace volume)
D	I	CG7.1	29	Furnace liberation
D	I	CG4.8	30	Furnace liberation
E	I	UF6.8	33	Clear Space at Spaced SH
E	I	SD5.7	54	Clear Space at Spaced SH
E	I	CG7.1	52	Clear Space at Spaced SH
E	I	CG4.8	53	Clear Space at Spaced SH
E	I	AL5.9	52	Clear Space at Spaced SH
F	P	UF6.8	100	No Limit
F	P	SD5.7	100	No Limit
F	P	CG7.1	100	No Limit
F	P	CG4.8	100	No Limit
G	P	UF6.8	100	No Limit
G	P	SD5.7	100	No Limit
G	P	CG7.1	100	No Limit
G	P	CG4.8	100	No Limit

"TYPE" code: U - Utility I - Industrial P - Process Heater

Based on ash analysis alone, it was expected that the Alma 5.9 would perform like Upper Freeport 6.8 with regard to slagging, fouling, and erosion. The fact that Alma 5.9 (at 220°F fuel temperature) performed more like Splash Dam 5.7 must have been the strong influence of its microfine particle and droplet size.

A summary of derating results by unit type is presented below:

UTILITY UNITS

<u>Unit</u>	<u>Configuration</u>	<u>% Load to Grid</u>	<u>Comments</u>
A	Close-coupled Screen	33 - 74	% load-to-grid limits are very unit specific. Load loss picked up by other units.
B	Box	30 - 50	
C	Close-coupled Arch	45 - 73 95 (SD2.6)	

INDUSTRIAL UNITS

<u>Unit</u>	<u>Configuration</u>	<u>Generation</u>	<u>% Max. Steam Comments</u>
D	Type-A Shippable	23 - 30	Compact design of most industrial units results in low CWF loads. Load loss picked up by other units.
E	VU-60 Modular	33 - 54	

CRUDE OIL HEATERS

<u>Unit</u>	<u>Configuration</u>	<u>% Load</u>	<u>Comments</u>
F	Vertical Cylindrical	100	Close to 100% availability. This is a prime requirement for most crude oil heaters. No spare capacity.
G	Horizontal Cabin		

In general, the UF6.8 fuel represented the most restrictive fuel. This was because of the Clear Space Temperature Limit for this fuel, which was 200°F lower than the Limit for the remaining fuels. In contrast, the SD2.6 fuel used for the special study on Unit C represented the best fuel from the derating standpoint due to the high allowable Gas Velocity Limit (129 ft/sec). The SD5.7 fuel caused the minimum derating of the remaining four fuels because of its high allowable Gas Velocity Limit (79 ft/sec) compared to other fuels. The CG4.8 fuel usually came close to the SD5.7 fuel in maximum load since its slagging and fouling characteristics closely approximate SD5.7 and its allowable Gas Velocity Limit is almost the same (76 ft/sec).

The CG7.9 fuel usually fell between the UF6.8 and CG4.8 fuels in derating. This was mainly because of its low allowable Gas Velocity Limit (51 ft/sec) compared to CG4.8's (76 ft/sec), and its Clear Space Temperature Limit (which was 200°F higher than for the UF6.8 fuel).

The AL5.9 CWF, in the absence of fine grinding, would be expected to have performance characteristics similar to UF6.8. Fine grinding, however, permits an improved allowable Gas Velocity Limit (84 ft/sec) compared to UF6.8 (69 ft/sec). Also, the Clear Space Temperature Limit is set at the same level as the Cedar Grove and Splash Dam - based fuels. It is likely that without fine grinding the Clear Space Temperature Limit would be 150°F lower.

For five fuels - UF6.8, SD5.7, CG7.1, CG4.8 and AL5.9 - the Utility units showed a wide range of derating requirements ranging from 26% to as much as 70% load derating. This range reflects the wide variety of configurations which are encountered in this type of service. These units are not easily characterized and must be analyzed on a case-by-case basis. For the special study of SD2.6 fuel on Unit C, the derating was only 5% due to the extra low ash and low erosion potential of this fuel.

Both Industrial Units required significant load derating, due primarily to the high furnace heat loadings which generally have been incorporated into these boilers since 1960. The load derating ranged from 46% to as much as 77%.

The crude oil heaters appeared to require no derating. This is due to the very low furnace heat loadings and gas velocities, which are generally characteristic of this equipment.

Plant Retrofit Modifications: In general, retrofit work fell into the following categories:

- o CWF storage
- o CWF transfer
- o Boiler island modifications
- o Particulate removal
- o Flue gas desulfurization
- o Ash handling system

During the retrofit studies particular attention was directed to the modifications to the boiler island equipment. Items which often required modification or replacement included the following:

o Furnace Hopper Slope/Jet System	o Structural Supports
o Soot and Slag Blowers	o Ductwork
o Burners and Windbox	o Fans
o Burner Controls	o Steam Air Heater
o Economizer	o Convection Sections
o Ash Hoppers	

As illustrative examples of boiler island retrofit selections, Figures S-7, S-8, and S-9 depict the modifications which were specified for Utility Unit A, Industrial Unit E, and Process Heater F.

Economic Evaluation

The capital cost estimates were developed using various sources depending on unit class (Utility, Industrial or Process Heater). The cost estimates covered the retrofit modifications listed in the preceding section.

FIGURE S-7 MAJOR BOILER ISLAND MODIFICATION - UTILITY UNIT A

FIGURE S-8 MAJOR BOILER ISLAND MODIFICATION - UNIT E

FIGURE S-9 MAJOR MODIFICATION - UNIT F

The developed cost estimates are similar to the Class II preliminary estimate defined in the EPRI "Premises". All estimates are based on mid 1985 wage and price levels.

The capital cost estimates for each fuel and each unit are presented in Table S-9 as "Total Capital Requirement." The fuels which allow higher load capacity require more total capital. The higher costs associated with fuels UF6.8, CG7.1 and AL 5.9 reflect the requirement for flue gas desulfurization systems. "Specific capital costs" are also presented in graphical form in Figure S-10. The total capital requirement represents all the capital needed to complete the project and is the sum of the total plant investment (TPI) plus the preproduction costs.

An industrial unit conversion is about 1.5 to 2 times more costly than a utility unit conversion when comparing capital costs on an energy output basis (\$ per 10^6 Btu/hr fired, for example). Thus, the large utility units have a significant economy of scale.

TABLE S-9
TOTAL CAPITAL REQUIREMENT FOR RETROFIT TO CWF
(All costs in \$1000, BASED ON Mid 1985 wage and price levels)

<u>UNIT</u>	<u>UF6.8</u>	<u>SD5.7</u>	<u>CG7.1</u>	<u>CG4.8</u>	<u>SD2.6</u>	<u>AL5.9</u>
A	65494	76694	76699	47548	---	124321
B	51599	37923	51094	37386	---	---
C	90831	47267	92213	46340	48606	117199
D	2839	2990	3029	3014	---	---
E	10703	9843	12731	9850	---	12845
F	7161	7161	7161	7161	---	---
G	11292	11292	11292	11292	---	---

FIGURE S-10 SPECIFIC CAPITAL COSTS VS LOAD CAPABILITY

The total capital required to convert utility units ranges from about \$60 to \$420 per kilowatt of derated capacity, or between \$60 to \$140 per kilowatt of nameplate capacity. For industrial units, specific capital requirements for conversion range from \$40 to \$125 per lb/hr steam derated output, or from \$25 to \$32 per lb/hr steam of nameplate capacity.

The variables which most strongly influence the economic feasibility of CWF conversion are load capability, retrofit capital costs, and Differential Fuel Cost (DFC). Economic incentives to switch a given unit from fuel oil to a specific CWF will depend critically upon the DFC.

Therefore, commercial evaluation requires realistic assessment of economic incentives in relation to the DFC. This was the approach taken in the analyses. First year incremental operating and maintenance cost savings were balanced against total capital requirements to determine a simplified payback period as a function of DFC.

For the units which experience a load derating (utility and industrial), operating mode is an important consideration. For the utility units two basic modes of operation are possible with CWF firing. In the first mode the retrofitted plant is assumed to burn CWF, but switches completely to fuel oil at peak demand. This operating mode assumes that the plant is derated on CWF but can regain its maximum capacity when switched to fuel oil. By designing the retrofit modifications with this dual fuel capability, it is possible to eliminate the necessity for the utility to purchase additional generating capacity to make up for the loss of capacity due to the derating. The alternative operating mode is retrofitting to burn CWF 100% of the operating time. This would require purchase of replacement power, but, at the same time, provide fuel cost savings by eliminating the usage of fuel oil in the retrofitted unit.

It was beyond the scope of this study to compare these two utility operating modes in detail. Only the oil switching operating mode has been studied for comparison with the base case (where the unit burns fuel oil 100 percent of its operating time).

For the industrial steam generator units, it was assumed that the customer could afford to operate the derated unit on CWF 100 percent of its operating time with no need to switch to oil at peak load demand. Also, no additional capacity requirement is assumed. This case is compared to the base case where the unit is fired with oil 100 percent of its operating time.

For the process heaters, for which there was no derating, the basis of the calculations assumes the heaters operate 95 percent of any calendar year (95 percent overall availability). The total number of hours per year that the heaters operate while firing CWF and utilizing the air preheat system and flue gas clean-up equipment is 90% of a calendar year. The number of hours that the heaters operate while firing fuel oil and without the air preheat system and flue gas cleanup equipment in operation is 5 percent of any calendar year.

The results of the economic evaluation of four fuels in four units are presented in Figures S-11 through S-14. These figures show the payback period in years as a function of differential fuel costs. In addition, Figure S-15 shows payback period for utility units as a function of unit load capability. Figure S-16 shows the same data for the industrial units. Although not shown on the payback curves, AL5.9 is expected to have economics which fall approximately halfway between SD5.7 and UF6.8.

Many commercial plant operators require payback in less than five years. The three cleanest standard grind fuels, SD2.6, SD5.7 and CG4.8, appeared economically attractive at \$1.50 DFC or higher in Units A, C, and E. Economic incentives to convert the selected process heaters to CWF firing are diminished by an unfavorable balance between equipment modification costs and potential fuel cost savings. This reflects the relatively low fuel consumption rates of those units as compared to utility-sized installations.

FIGURE S-11 PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST ($\$/10^6$ BTU) - UNIT A

FIGURE S-12 PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST ($\$/10^6$ BTU) - UNIT C

FIGURE S-13 PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST (\$/10⁶ BTU) - UNIT E

FIGURE S-14 PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST (\$/10⁶ BTU) - UNIT F

FIGURE S-15 ECONOMIC EVALUATION RESULTS - UTILITY UNITS

FIGURE S-16 ECONOMIC EVALUATION RESULTS - INDUSTRIAL UNITS

CONCLUSIONS AND RECOMMENDATIONS

This project provided essential information concerning numerous facets of bench-scale characterization techniques, the importance of CWF properties on various aspects of fuel utilization, and the impacts of CWF performance characteristics on commercial unit operation and retrofit economics. Although several general conclusions can be drawn from the results of this project, they must be limited to the scope of fuels and equipment design conditions investigated.

Twelve CWFs were systematically selected and evaluated under this project. These fuels were prepared from commercially significant Eastern bituminous coals beneficiated using available gravity separation or floatation processes. The fuels were prepared by commercial CWF producers using their own formulations. The CWFs assessed provide a significant range in ash content (2.6% to 13.8% ash, dry basis), as well as differences in ash quality (fusibility and ash chemistry), coal particle size distribution, and slurry rheology.

Seven generic commercial unit designs used by electric utilities and by industry for steam generation or process heating were selected and analyzed for CWF retrofit. Selection criteria imposed three principal requirements: (a) originally designed for oil and/or gas firing, (b) currently dependent upon fuel oil or other low-ash fuel, and (c) possessing at least 20 years of remaining useful life.

Within the limits of the fuel characteristics and commercial unit design conditions evaluated, principal conclusions from this project are summarized below:

- o Results of extensive laboratory testing and unit performance modeling indicate that CWF can be produced and fired in commercial oil designed furnaces using currently available technologies. Although results clearly demonstrate the general technical feasibility of CWF utilization at the ash levels tested, significant load reductions would often be required to avoid severe operating problems such as erosion, fouling,

slagging and excessive unburned carbon loss. The level of capacity derating as well as the degree of equipment modifications required are highly dependent upon both fuel properties and specific unit design features.

- o Results of comprehensive pilot-scale fireside performance testing (4×10^6 Btu/hr) indicate that CWFs prepared from judiciously selected and beneficiated feed coals can be efficiently burned under conditions typical of many oil designed commercial units without severe slagging and fouling behavior. Increased coal beneficiation improved ash slagging, fouling and erosion characteristics. For the fuels studied, coal beneficiation provided the greatest improvements in the areas of reducing convection pass tube deposit buildups and fly ash erosion rates. Substantial improvements in ash erosion (greater than that proportional to reduced ash loadings) can result in significant commercial unit operational advantages.
- o CWF ash slagging, fouling and erosion characteristics determined through pilot-scale fireside performance testing were primarily dependent on feed coal ash properties and atomization quality during combustion. CWF manufacturing techniques did not appear to have a strong direct impact on ash performance. Slurry formulation can however, have a strong impact on atomization behavior which in turn can influence combustion and ash performance.
- o Preheating CWF prepared from a micronized coal to temperatures in excess of 220°F resulted in significant improvements in combustion and fly ash erosion performance. These improvements were attributed to a thermal flashing effect causing secondary atomization of the CWF spray droplets. Both char particles collected from various regions of the flame and fly ash at the furnace outlet had significantly finer size distribution during heated (220°F) fuel tests compared to those conducted at equivalent conditions with ambient temperature fuel. Tests performed with fuel preheated to 150°F showed no appreciable improvement in performance over the ambient fuel.

- o Commercial-scale combustion testing (25×10^6 Btu/hr) demonstrated that CWF could be successfully fired using four different generic burner designs. Performance varied significantly between designs (carbon conversion efficiencies at 100% capacity ranged from 86% to 99.9%) which was primarily attributed to the differences in each burner's atomization and/or near-field thermal/aerodynamic characteristics.
- o Both pilot-scale (4×10^6 Btu/hr) and commercial-scale (50×10^6 Btu/hr) combustion testing indicated that atomization quality in the combustion environment has a dominant effect on carbon conversion efficiency and fly ash characteristics. Bench-scale rheological data as well as full-scale cold flow atomization characteristics were unreliable in predicting the behavior of different CWF formulations. However, project results clearly demonstrate that cold flow atomization characteristics are effective in predicting changes in the combustion behavior for a single CWF. Reductions in spray droplet size distribution consistently resulted in improved combustion performance when considering a single fuel formulation.
- o Significant differences in CWF combustion efficiencies were observed under similar combustion conditions for different CWF formulations. Results from combustion tests suggest that differences in CWF atomization behaviors and coal particle agglomerating characteristics within the combustion environment were primarily responsible for this behavior. The coal particles within individual CWF spray droplets agglomerate to form a single char particle upon heating in the combustion environment. The size of the resulting char particles has a direct effect on time required for burnout, and thus the overall combustion efficiency. Differences in CWF formulation appear capable of significantly influencing the atomization/char formation process which subsequently controls combustion performance. Combustion efficiency differences could not be attributed to variations in particle size distribution, char reactivity of the feed coal, or cold flow atomization characteristics.

- o Commercial application performance analyses, based upon pilot-scale test data, indicated that conversion of the three utility boiler designs studied to CWF firing would often necessitate significant derating (generally between 30 percent and 73 percent of rated capacity) depending upon design details and CWF fuel quality. For the most beneficiated fuel studied (2.6% ash), the reduction of output was only 5 percent for one of these boilers.
- o CWF firing reduced the maximum load capability of the two packaged industrial boiler designs to between 23 percent and 53 percent of rated outputs. The two process heaters had no loss in capacities, but retrofit costs and potential availability loss reduce attractiveness in this market.
- o Clear space and gas velocity limitations accounted for most of the capacity losses. Fouling data set the clear space limits, while fly ash mass flow and fly ash erosion characteristics resulted in the velocity limits. However, for packaged industrial boiler designs, furnace residence time can limit capacity regardless of ash characteristics.
- o From the equipment design perspective, the following general conclusions apply for the fuel quality conditions evaluated:
 1. Utility units are likely to have higher CWF load limits than industrial units.
 2. The principal load limiters for utility units are often clear space and gas velocity limits.
 3. The principal load limiters for industrial units are often furnace liberation or clear space limits.
 4. Crude oil heaters are likely to be able to operate at their required 100% MCR ratings.

The load limits determined for each of the utility units generally reflect specific details of each design, such as clear spaces or free gas areas at certain banks in the convection pass. Design details are unit-specific and do not necessarily resemble the general characteristics of the three unit types studied. For example, it should not be

assumed that close-coupled arch units will always be able to operate at higher CWF loads than box units.

- o Variables which most strongly influence the economic feasibility of CWF conversions are load capability, retrofit capital costs, and differential fuel cost (DFC) between the price of oil and CWF. Retrofit costs varied widely with fuel cleanliness and unit design.
- o The economic analyses showed that conversion of utility boilers to CWFs often becomes feasible when the DFC is above \$1.00/10⁶ Btu. The four cleaner fuels were capable of attaining greater than 70 percent of rated capacity in the most liberally designed utility boiler (850 MW). Three of these fuels had payback periods of 2-1/2 years or less at a DFC of \$1.00/10⁶ Btu. The cleanest fuel (2.6 percent ash) had a payback period of only 1.8 years at a DFC of \$1.00/10⁶ Btu illustrating the potential benefit of higher coal beneficiation targets, if they can be reached at reasonable costs.
- o Payback periods for the industrial units were extremely sensitive to load capacity and DFC. For the most favorable case a 4-year payback period was projected at a DFC of 1.00/10⁶ Btu. This was approximately halved at a \$2.00 DFC. The application in this case was a modular field assembled 400,000 lb/hr industrial steam generator. In general, industrial conversions were found to cost as much as twice those of the utilities on an equivalent basis (e.g., \$ per 10⁶ Btu/hr fired), reflecting economy of scale.
- o Payback periods for the two crude oil heater designs evaluated were found to exceed the maximum limit (1.5 to 2.0 years - considered acceptable by the hydrocarbon industry) by a factor of at least 2.0. This resulted from the relatively high specific capital costs for these small units.

- o Analyses of the study units frequently identify various fuel-equipment related interactions emphasizing some important economic trade-offs. Retrofit costs, for example, could be significantly reduced if a cleaner CWF would not require added ESP capacity. Similarly, lower sulfur CWFs may be able to eliminate or reduce the need for supplemental SO₂ scrubber equipment. The cleaner fuels can reduce the need for convection bank changes to allow higher gas velocities or clear space temperatures.
- o Analyses of commercial coal beneficiation processes indicate that costs associated with cleaning the CWF feed coals to the lower ash levels studied were generally justified by operational savings derived from improved performance characteristics. Limited data on the use of heated, microfine fuel also showed performance benefits and potential economic advantages.

This project clearly indicates that the viability of coal-water fuels as commercial alternatives to gas and oil is highly dependent on differential fuel cost and fuel quality. Economic and performance factors have been shown through extensive tests and analyses to be critically sensitive to fuel characteristics such as total ash, ash chemistry, coal particle size distribution, and atomization/combustion quality.

Several areas of additional research could further advance coal-water fuel commercialization prospects. Recommended areas in which attention should be focused are summarized below:

- o Small-scale CWF characterization techniques must be developed to more accurately predict combustion performance. Extensive rheological characterization as well as full-scale cold flow atomization testing did not provide acceptable correlation with CWF combustion behavior. Large-scale combustion testing is still the only reliable means of

determining CWF combustion performance. Additional research is needed to better understand the influence of variations in slurry formulation on CWF performance characteristics. More work is needed to develop inexpensive predictive tests which can accurately define CWF atomization and combustion under commercial conditions.

- o The performance and commercial impacts of additional CWFs prepared from more highly beneficiated coals should be further assessed. Overall analyses of the fuel (SD2.6C) containing the least ash clearly showed the potential for significant performance improvements with increased beneficiation. Essential quantitative fireside performance data (ash slagging, fouling, and erosion characteristics) should be established and boiler performance and economic factors should be developed. Attention should also be given to fuel costs/performance trade-offs associated with increased coal processing. The cost differences, for example, should be assessed for fuel prepared with 5%, 3% and 1% ash, using some of the same coals included in the present project.
- o Demonstration testing should be conducted in representative, tightly designed oil-fired boilers to establish actual field operating limits and provide full-scale experience on carbon loss and long term ash effects. The performance guidelines developed for the project were based upon laboratory results and predicted unit load capacities were intentionally somewhat conservative. Additional field data may permit refinement of laboratory scale-up factors which may result in relaxing some of the operational penalties applied during the feasibility analysis.

SUMMARY OF PROJECT TASKS

The following sections summarize activities and key results for each task of this project. More detailed descriptions of the approach and procedures applied, as well as more in-depth discussion of results, can be found in Final Report Volumes 2 - 6 covering specific task results.

TASK 1 SUMMARY: SELECTION OF FUELS AND SUPPLIERS

In order to evaluate the commercial potential of CWFs as replacement fuels in oil-burning plants, a detailed investigation was required of the physical, chemical and combustion properties of the CWFs. This also required detailed investigation of coals and their impact on CWF properties.

The primary objective of Task 1 was to provide test CWFs representative of those expected to become commercially available. Coals suitable for CWF were evaluated and selected. CWF vendor capabilities were reviewed and selected vendors then prepared test batches of CWF from the selected candidate coals.

COAL SELECTION PROCESS

The initial phase of this project involved an evaluation of published data regarding chemical, physical and combustion properties of source coals. Twenty coals were selected for the initial screening/washability tests. Key criteria used in selecting candidate coals included commercial significance, ash content and ash quality, sulfur content, volatile matter content, and char reactivity. Since coal beneficiation is expected to play a major role in the commercial use of CWFs, the selection process considered the anticipated separation yield and characteristics of the coal after beneficiation. As part of these screening tests, gravity separation (14 mesh at 1.3 specific gravity) and subsequent analysis of the two density fractions plus the raw coal were performed (Tables 1-1 and 1-2).

TABLE 1-1

CANDIDATE ROM COAL ANALYSES

<u>Coal Seam</u>	<u>Ash % dry</u>	<u>VM % dry</u>	<u>Sulfur % dry</u>	<u>Heating Value (Btu/lb) dry</u>	<u>Moisture % AR</u>
Cedar Grove	4.70	35.79	0.59	14,637	3.29
Lower Elkhorn	11.16	30.85	0.68	13,685	4.99
Black Creek	6.27	33.57	1.20	13,798	6.96
Splash Dam	21.73	27.15	0.57	11,822	3.30
Kentucky #11	20.84	26.01	4.70	11,188	9.15
Lower Kittanning	13.40	31.51	0.79	13,113	3.93
Pittsburgh #8 (OH)	14.18	34.47	1.37	12,331	7.50
Upper Freeport	18.55	32.34	1.18	12,290	4.97
Kentucky #9	11.26	39.52	4.73	12,810	8.42
Waynesburg #2 Split	9.83	30.77	2.13	13,914	3.37
Pittsburgh #8 (PA)	17.03	32.49	2.25	12,448	4.40
No. 2 Gas	34.03	24.65	0.85	10,195	4.26
Castle Gate "D" plus Sub-seam 3	14.05	40.86	0.48	12,384	3.52
Hazard #4	40.00	27.41	1.07	8,381	9.12
Elkhorn #3	28.08	29.68	1.47	10,542	5.64
Illinois #6	17.55	35.75	3.92	11,372	10.06
Illinois #5	19.77	35.02	4.74	11,102	8.55
Mary Lee	38.95	23.65	0.76	8,667	5.24
Pocahontas #3	22.92	17.97	0.76	11,532	9.30
Jaw Bone	33.08	20.03	0.69	10,228	5.34

TABLE 1-2

ANALYSES OF 1.3 FLOAT FRACTIONS FROM CANDIDATE COALS CRUSHED TO MINUS 14 MESH
(Initial Screening)

<u>Coal Seam</u>	<u>Ash % dry</u>	<u>VM % dry</u>	<u>Sulfur % dry</u>	<u>Ash Fusion Reduction</u>		<u>Free Quartz (% Ash)</u>
				<u>Initial</u>	<u>Fluid</u>	
Cedar Grove	1.56	37.06	0.60	2291°F	2508°F	17.6
Lower Elkhorn	1.47	36.13	0.63	2635°F	2700 ⁺ °F	9.1
Black Creek	2.27	35.88	0.80	2357°F	2634°F	4.1
Splash Dam	1.78	32.67	0.61	2259°F	2700 ⁺ °F	8.8
Kentucky #11	3.58	42.50	2.51	2375°F	2570°F	13.2
Lower Kittanning	2.40	37.26	0.78	2700 ⁺ °F	2700 ⁺ °F	11.0
Pittsburgh #8 (OH)	3.73	39.39	1.02	2600°F	2700 ⁺ °F	17.7
Upper Freeport	3.48	37.62	0.68	2477°F	2700 ⁺ °F	10.3
Kentucky #9	4.09	43.20	2.43	2428°F	2585°F	10.0
Waynesburg #2 Split	3.20	26.07	1.54	2662°F	2700 ⁺ °F	7.4
Pittsburgh #8 (PA)	3.58	32.66	1.04	2700 ⁺ °F	2700 ⁺ °F	14.0
No. 2 Gas	3.02	34.00	0.79	2660°F	2700 ⁺ °F	13.0
Castle Gate "D" plus Sub-seam 3	4.18	45.78	0.55	2121°F	2341°F	20.0
Hazard #4	3.22	41.52	0.91	2495°F	2700 ⁺ °F	8.6
Elkhorn #3	2.64	42.96	1.06	2207°F	2550°F	7.9
Illinois #6	2.73	43.73	2.63	1975°F	2260°F	14.0
Illinois #5	2.78	43.91	2.51	1972°F	2256°F	15.0
Mary Lee	3.20	34.37	0.84	2485°F	2700 ⁺ °F	9.8
Pocahontas #3	3.45	22.63	0.59	2300°F	2594°F	13.0
Jaw Bone	4.77	26.50	0.72	2410°F	2699°F	12.0

Based upon results of the first level screening tests, eight coals were selected for second level screening tests. These tests consisted of detailed laboratory "washability" and fuel analyses. Each coal was to be beneficiated to two levels in order to evaluate the influence of ash on both manufacturing and combustion of the CWFs. The desired levels of beneficiation were as follows:

1. 7% ash on a dry basis, $\pm 10\%$, i.e., 6.3 to 7.7% range.
2. 2% ash on a dry basis, $\pm 20\%$, i.e., 1.6 to 2.4% range.

Table 1-3 provides a summary of the estimated separation yields and qualities of each of these coals. The results of the second level screening tests were used to select source coals for beneficiation and for preparation of CWFs for large-scale testing.

Five coals emerged from the final selection process as meeting the slurryability, combustion and environmental criteria. These coals were the Lower Kittanning, Splash Dam, Cedar Grove, Upper Freeport and Alma. On the basis of the selection data, 800 tons of Lower Kittanning coal with about 7 percent ash were purchased from Armco Coal Company, Mine #25, in Montcoal, West Virginia and sent to vendors for preparation of CWF. None could produce a CWF that had 70% solids and met the viscosity guidelines using this coal. Subsequent investigations indicated that outcropped, oxidized coal was inadvertently included in the shipment and that it was responsible for the slurryability problems. However, when the solids loading was reduced to 66%, a CWF was produced that had the other desirable properties. Since the 66% solids loading was lower than the desired CWF specifications for this project, Lower Kittanning coal was only used for bench and pilot-scale tests and was eliminated from further evaluation. An examination of this problem is provided in Volume 2.

Splash Dam, because of its excellent slurryability, cleanability, and other properties, was chosen as the reference coal for use during large-scale burner tests and it was sent to each vendor along with suggested specifications for

TABLE 1-3
GENERALIZED CANDIDATE COAL RATINGS

Coal	Washability a 1-3		Combustion	CWF Manufacturing	Comments
	Recovery, %	Ash, %			
Cedar Grove ^b	85.2(64.6)	2.00(2.00)	Marginal	Acceptable	Potential Low Fuel Reactivity
Lower Elkhorn	64.9(52.3)	2.00(2.14)	Moderate	Marginal	Questionable Slurryability
Black Creek	76.5(49.9)	2.00(1.97)	Good	Unacceptable	
Splash Dam ^b	50.9(35.2)	2.00(2.14)	Moderate	Excellent	Reference CWF Coal
Lower Kittanning ^b	25.5(20.0)	2.00(2.61)	Moderate	Marginal	Oxidized Coal in Feed
Western Kentucky #11	53.6(38.1)	3.62(3.77)	c	c	High Sulfur, poor Ash Liberation
Pittsburgh #8	36.6(27.2)	3.48(3.85)	c	c	High Sulfur, poor Ash Liberation
Upper Freeport ^b	41.7(29.6)	3.49(3.73)	Good	Acceptable	High Sulfur, poor Ash Liberation
Alma ^b	c	c	Good	Acceptable	Microfine CWF

a Theoretical yield and ash content based on bench-scale analyses and ()
estimated yield and ash content based on beneficiation process results (See Volume 2).

b Selected as source coal for beneficiation and CWF preparation.

c Not Analyzed.

the product CWF. This coal originated at the Black Watch Coal Company preparation plant in Grundy, Virginia, and it had an ash content of approximately 6 percent. For the preparation of low ash CWF this coal was beneficiated with the goal of reaching the two percent ash level using a heavy media cyclone circuit at the Energy & Minerals Resources Research Institute of Iowa State University at Ames, Iowa. Satisfactory CWF's were produced from both products.

The third coal meeting most of the selection criteria was the Cedar Grove coal, mined by the Chafin Coal Company in Logan, West Virginia. The original coal had an ash content of about 7 percent which was reduced to about 5 percent by a froth flotation process for the low ash CWF. Although in initial screening this coal exhibited relatively low fuel reactivity, the CWF produced from it combusted well.

These three coals combusted with a relatively low degree of slagging and fouling even at the higher ash levels. In order to establish the benefit of reducing the ash level of a coal with a greater degree of slagging and fouling, an Upper Freeport coal with 17.8% ash from the Spring Church mine, Clarksburg, Indiana County, Pennsylvania was selected. It was beneficiated by froth flotation to about 14 percent and 7 percent ash for CWF preparation by one vendor and beneficiated to 5.8 percent by Iowa State University utilizing a heavy media circuit for CWF preparation by another vendor.

The final coal selected for this project from the Alma seam was mined and cleaned at the Leatherwood Preparation Plant in Eastern Kentucky. The cleaned feed coal had approximately 6% ash. It was selected for use in preparing microfine CWF based primarily upon its moderate ash slagging and fouling properties as well as availability and slurryability.

BENEFICIATION PROCESSES

Two of the objectives of this project were to relate the beneficiation level of the CWF to fouling and slagging during combustion, and to examine the cost trade-offs associated with the performance benefits of lower ash levels versus the costs of beneficiation. In the most probable approach to commercial CWF production, conventional and advanced coal cleaning processes will be employed to obtain target ash and sulfur levels. Because advanced processes were still in the development stages the conventional gravity-based processes were utilized in this program. Three CWFs were manufactured for comparison from coal beneficiated by froth flotation. The information required for the design of these beneficiation processes was developed from laboratory separations (washability data) on which recovery at specified ash levels can be predicted. This washability data was generated for the candidate coals and was paramount in selecting the coals recommended for the program. This data can be found in Volume 2.

The washability studies identified those coals that possessed the potential of being beneficiated to 2 percent ash at the lowest cost. A request for proposal including this data and the required delivery schedule were sent to sixteen potential beneficiators. The Energy and Minerals Resources Research Institute (EMRRI) of Iowa State University, Ames, Iowa was selected as best fitting all the requirements of the program. The coal preparation circuit employed by EMRRI consisted of scalping and desliming screens, followed by an 8 inch heavy medium cyclone operating at 1.3 specific gravity. The overflow product was separated from the magnetite media and dewatered with a combination of a sieve level and a drain and rinse screen.

Separations were carried out utilizing the washability data to provide the operational parameters required to produce the desired products. Testing of five-ton samples showed that after being crushed to 3/8" top size, five of the eight coals can be used as suitable feeds for producing a ~2% ash product, although the Lower Kittanning coals was marginal in this respect (Table 1-3).

Based on this information production quantities of 7 percent ash Splash Dam were then processed to 2 percent ash; and the 18 percent ash Upper Freeport coal was reduced to 6 percent ash.

A proprietary froth flotation process was applied by another vendor to the Cedar Grove and the Upper Freeport coals. The ash level of the Cedar Grove was reduced from about 7 percent to approximately 5 percent. With the Upper Freeport coal two ash level products were intentionally produced. The 17.9 percent ash run-of-mine Upper Freeport coal was beneficiated to levels of about 14 percent and 7 percent. Details of the vendor's proprietary process were not available.

CWF PRODUCERS

Established CWF producers were surveyed to determine their interest in participating in the project, and to review production capabilities, experience, and scheduling availability. The following producers were selected to prepare test fuels based primarily upon their experience, fuel properties, and ability to produce sufficient quantities of CWF for large-scale combustion testing.

Advanced Fuel Technology (SOMIO)

Atlantic Research Corporation

CoaLiquid, Inc.

Ergon, Inc.

OXCE Fuel Company

Selected CWF producers provided direction and analytical information on the suitability of candidate coals for CWF formulation. CWFs were prepared by each producer for bench-scale and pilot-scale testing.

NOTE: The letter code used to designate test CWFs in the following tasks does not correspond to the producer order listed above.

TASK 2 SUMMARY: BENCH-SCALE CHARACTERIZATION TESTS

A cross section of coal-water fuels (CWFs) were characterized through a series of bench-scale tests to assess their transportation, storage, pumping, atomization, combustion, ash deposition and ash erosion properties. These CWFs were prepared by participating producers using their own technical approach (coal particle size distribution and loading, chemical additive package, etc.). The analytical data of the CWFs are listed in Table 2.1. Each fuel is identified by coal type, ash level and CWF producer code letter. For example, LK 6.0 C is made with Lower Kittanning coal at 6% ash by producer C.

TRANSPORTATION AND STORAGE

The principal concern during transportation and storage is that the CWF at the end use point be uniform and maintain its original properties. CWF must be free from hardpack, should exhibit minimal coal particle settling, and must not undergo significant changes in viscosity or pH during the transportation and storage phases. Changes in temperature, and even a freeze-thaw cycle, should not seriously change the CWF properties.

In general, the participating producers were able to produce CWFs suitable for transportation, storage, handling and firing with process adjustments for each new coal. Care must be exercised to avoid large particles and contaminants which could cause atomizer pluggage during combustion. Cross-country shipping of two CWFs by truck had no apparent effect on settling. The amounts of settling under both stationary storage and the transit conditions were insignificant. Changes in temperatures and exposures to freeze/thaw cycles also showed little effects on CWFs stability.

CWF RHEOLOGY/ATOMIZATION CHARACTERISTICS

The CWF combustion characteristics are significantly influenced by fuel atomization quality and coal reactivity. Atomization quality is extremely important during CWF firing since smaller droplets produce better combustion

in the furnace. Ignition, flame stability, and carbon burnout are all improved as atomization quality improves. However, the properties of the coal used to prepare the CWF also significantly affect how easily the fuel ignites and greatly influences the rate at which the fuel burns at a given set of operating conditions.

Ideally, one should be able to predict atomizer performance as a function of fuel rheology. Bench-scale viscosity tests were conducted over a range of low to high shear rates (0 to 4000 sec^{-1}) with the ultimate goal of making a CWF viscosity/atomization quality correlation similar to that observed for commonly used fuel oils.

TABLE 2-1

COAL-WATER FUEL PROPERTIES

Fuel Code	LK6,0C	SD5,8D	SD5,8E	SD5,8C	SD4,5A	SD2,8C	SD6,7F	UF13,7A	UF6,8A	CG7,1A	CG4,8A	AL5,9C
% Solids	66	69	66	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
60x100 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	4.0
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	68.1	88.0	72.6	65.9	67.9	62.5	75.2	95.0
Coal Particle MMD (μ)	15	50	25	15	33	15	35	30	29	32	25	11
Viscosity @ 100 sec^{-1} (1)	1500	840	880	640	1400	610	1810	1700	1800	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} (1)				983			2074			1953	1152	2010
Viscosity @ 2000 sec^{-1} (2)				1700			2800			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	78	72	100	83	93	118	98	75	85	72
Droplet SMD (μ)	72	63	62	56	75	65	70	82	66	56	63	-
% by weight droplets >320	.01	.01	0.00	0.00	0.37	0.02	0.22	3.43	2.19	0.02	.04	0.0
% by weight droplets >225	1.18	0.98	0.40	0.22	5.07	1.28	3.83	14.61	9.64	1.00	1.64	0.8

(1) Rotational Viscometer @ 20°C.

(2) Extrusion Rheometer @ Room Temp.

(3) Variable High Shear Viscometer @ 20°C

The viscosity results showed the CWFs varied considerably in rheological characteristics. Low shear as well as high shear tests showed a wide range of viscosities for the CWFs (600 cp to 3000 cp). Atomization quality generally improved with decreasing viscosities. However, accurate predictions of atomization quality could not be made from the bench-scale data (Figures 2-1 and 2-2). 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 atomization performance.

COAL COMBUSTION REACTIVITY

Typical analyses of the feed coals on a moisture free basis are shown in Table 2-2. The relative ease in which a coal ignites is strongly influenced by the quantity and quality of volatile matter in the fuel, and the rate in which these volatiles are released. A direct measurement of the coal's relative ignition characteristics is provided by its Flammability Index. This index reflects the temperature at which a suspension of dried, pulverized fuel ignites in an oxygen atmosphere. In general, the lower the flammability temperature the easier to ignite. The flammability indices of the test fuels were all within a narrow range of 980°F to 1070°F, indicating the ignition characteristics of these fuels would be similar. This range was also comparable to that of typical high volatile U.S. bituminous coals considered to have good ignition stability and turn down characteristics.

Fuel burnout characteristics were evaluated through analysis of chars generated at high temperatures (>2650°F) in C-E's Drop Tube Furnace System (DTFS). Since burnoff of the char remaining after devolatilization/ignition requires the greatest time of the combustion process, it is generally the controlling factor dictating the overall combustion efficiency. Char reactivity was assessed by measuring its burnoff rates through thermogravimetric analysis (TGA) and by measuring the surface area of the char utilizing the BET-gas adsorption technique. Char surface area is a physical property which is indicative of reactivity. Generally, the higher the surface area the greater the char reactivity. Results showed that the char surface areas of the test fuels were all very similar and should have comparable reactivity.

FIGURE 2-1 EFFECT OF LOW SHEAR VISCOSITY ON ATOMIZATION

FIGURE 2-2 EFFECT OF HIGH SHEAR VISCOSITY ON ATOMIZATION

TABLE 2-2

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	76.7	81.6	85.7	72.3	79.1	76.7	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 ⁶ (lb/10 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

TGA results are consistent with surface area data, also indicating very similar char reactivity. Figure 2-3 contains char burnoff plots under isothermal conditions at 700°C in air. Burn-off for char from the test chars and four reference coal chars are shown. The burn-offs of all test fuels fall into a relatively narrow band straddling the reference high volatile A bituminous coal. These TGA results as well as the char surface area data indicate all test coals have similar reactivity and should exhibit similar burnout characteristics under similar firing conditions.

COMBUSTION PROCESS MODELING

Combustion process modeling was also conducted under this task to examine the effects of operating parameters and CWF properties on boiler performance with respect to carbon loss. The modeling approach is depicted in Figure 2-4. Essentially, the global char combustion kinetic information (i.e., apparent activation energy and frequency factor) and coal swelling factor are used in conjunction with fuel and boiler information and a proprietary mathematical model, known as the Lower Furnace Program-Slice Kinetic Model (LFP-SKM), to simulate the combustion of a given fuel under specific boiler operating conditions.

A 600 MW unit (designated Unit A in Task 6) originally designed for oil-firing was used in this study. Its retrofit design information developed during Task 6 was used as input to the LFP-SKM. The following assumptions were also made during the prediction of carbon loss from CWF:

- o Atomizers droplet size distributions were used as model inputs in the form of Rosin-Rammler Parameters.
- o Instant water vaporization was assumed, and, therefore, a 30% reduction was applied to CWFs droplet size distribution right after introducing CWF in the burner zone. This 30% reduction is based on the fact that CWF contains about 30% moisture and a CWF droplet yields a single agglomerated particle.
- o Char reactivity parameters (activation energy and frequency factor) were selected from the C-E data bank based on a bench-scale reactivity comparison between the CWFs chars and the data bank's coal-chars.

FIGURE 2-3 RELATIVE TGA CHAR BURNOFF RATES FOR CWF FEED COALS

FIGURE 2-4 FLOW DIAGRAM FOR BOILER COMBUSTION PERFORMANCE MODEL SIMULATION

A parametric study was conducted to determine the effects of CWF droplet size distribution, flue gas recirculation, and volumetric heat release rate on carbon loss. Two sets of combustion kinetic parameters from high volatile bituminous coals (one having higher reactivity than the other) were selected from C-E's data bank for this study.

Figures 2-5 and 2-6 illustrate the results from this parametric study. In general, the predicted carbon content in fly ash is inherently higher due mainly to the fact that the CWF has very low ash content, and hence, a higher carbon-to-ash ratio than typical pulverized coal at equivalent combustion efficiency. Carbon heat loss is exacerbated the most by coarse droplet size followed by high volumetric heat release rate, and high gas recirculation. The adverse impact of the gas recirculation is due to the fact that this inert gas is a diluent in the combustion system. Therefore, these parameters should be controlled in concert to minimize carbon heat loss.

ASH PROPERTIES

The ash quality of the feed coals was evaluated by bench-scale techniques to assess their slagging and fouling potentials. Behavior of the mineral matters in the feed coals primarily determines the retrofit performance, availability and life of steam generator components for CWF applications. Management of the ash produced during combustion generally dictates the amount of unit derating and necessary equipment modifications. Ash deposition can significantly reduce heat transfer, restrict gas flow through convection passes, and cause physical damage to furnace components through slag falls. Ash deposition can be separated into two categories: slagging, which is associated with deposit formation in high temperature furnace radiant sections, and fouling, which is associated with deposit formation in convection sections at somewhat lower gas temperatures.

Ash Slagging Potential

Coal ash slagging potentials of the feed coals were evaluated by their ash fusibility temperatures, ash content and conventional slagging indices,

FIGURE 2-5 EFFECTS OF GAS RECIRCULATION AND MEAN WEIGHT DROPLET SIZE ON PREDICTED CARBON HEAT LOSS FOR CWF FROM hvB COALS

FIGURE 2-6 EFFECTS OF VOLUMETRIC HEAT RELEASE RATE AND FUEL REACTIVITY ON PREDICTED CARBON HEAT LOSS FOR CWF FROM hvB COALS

such as base-to-acid ratio, iron-to-calcium ratio, etc. In addition, gravity fractionation analyses were conducted on the fuels to determine the amount of large, discrete pyrite particles which have been shown to have a marked impact on furnace slagging.

The slagging characteristics of each test fuel are summarized in Table 2-3. 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 ashes (softening temperatures $\geq 2600^{\circ}\text{F}$); and the Upper Freeport (UF 13.6 and UF 6.8) and Alma Seam (AL 5.9) 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 in the ash of the 2.9 sink fuel fraction, ranging from 76.1% to 96.0%. These values would normally be associated with moderate to high slagging potential. However, the quantity of material recovered from the 2.9 sink coal fraction is low for each fuel, ranging from $<0.1\%$ to 1.6% of total coal, indicating that the influence of segregated iron on slagging would be minimized.

Overall, based on these bench-scale analyses, the Upper Freeport fuels exhibited moderate slagging potential, the Cedar Grove and Alma Seam 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.

Ash Fouling Potential

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 fuel to provide information on the form in which the alkalies 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.

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 2-4). 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 in all of the fuels is primarily in an inactive form. The percentage of total sodium which exists in an active form varies between coal types and with level of beneficiation. However, the concentration of leachable/active alkalies was very low for all the fuels, indicating a low potential for alkali induced fouling. The weak acid leaching results are consistent with observed fouling performance as well as results typically obtained for low-fouling Eastern U.S. bituminous coals.

Fly Ash Erosion

Convection tube erosion resulting from fly ash generated during combustion is often 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 distribution 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 2-2. Both ash contents and the concentration of quartz in the feed coals varied significantly between coal types and with level of beneficiation. In general, quartz content reduced with increasing beneficiation level for each coal type, hence the ashes generated from the more beneficiated coals would be expected to have lower erosiveness.

TABLE 2-3

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
LK6.0	>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
UF13.6	2260	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 2-4

BENCH-SCALE ASH FOULING CHARACTERISTICS

COAL TYPE	IDT (°F)	ST (°F)	TOTAL ALKALI (%)	Leachable Na ₂ O (%)	Leachable K ₂ O (%)	FOULING POTENTIAL
LK6.0	2320	>2700	2.0	0.4	<0.1	Low
SD5.7	2440	2610	2.8	0.2	0.1	Low
SD2.6	2270	>2700	3.0	0.7	0.1	Low
UF13.6	1990	2260	3.1	0.1	<0.1	Moderate
UF6.8	1980	2270	2.9	0.4	<0.1	Low/Moderate
CG7.1	2510	2600	2.6	0.4	0.1	Low
CG4.8	2290	2650	2.3	0.7	0.1	Low
AL5.9	1920	2240	2.0	0.5	<0.1	Low/Moderate

TASK 3 SUMMARY: CWF PREPARATION AND SUPPLY

The purpose of this task was to provide representative samples of CWFs required for the test program. Activities consisted of coordination and supply of the appropriate slurries, in the required quantities and, in the proper time frames. The work was divided into four parts:

1. Coal Acquisition - This activity included the acquisition and beneficiation of parent coals in the quantities required for evaluations and tests. Requirements included coals for the 18 candidate CWFs selected for bench-scale testing; the 5 CWFs tested during the combustion evaluation; and the 12 CWFs evaluated during the performance testing.
2. Beneficiation of Test Coals - Selected raw coals were beneficiated at conventional coal cleaning plants, and the products used to prepare CWFs for the large-scale combustion tests.
3. CWF Preparation - Clean coals were shipped to the selected slurry manufacturers who prepared CWF in the required quantities for the tests.
4. CWF Supply - Representative test samples of each CWF were shipped to appropriate testing facilities for laboratory analysis or combustion testing as required during execution of the project.

Batches of CWF were procured from five CWF vendors, who used feed coals obtained by Gulf Research and Development Company (GRDC). The coordination of scheduling, shipping and storing was also done by GRDC, to match the test schedules.

Four coals were obtained to produce eighteen small batches of CWF for bench-scale screening tests. Three of these four coals were used to produce large batches of CWF for the commercial-scale combustion tests under Task 4. A beneficiated microfine coal was obtained in addition to the four coals to produce twelve CWFs for the pilot-scale slagging and fouling evaluation under Task 5.

Most coals were washed by the coal companies, while several batches were beneficiated by CWF vendors or Iowa State University. Three coals were shipped directly to C-E for baseline dry pulverized coal tests. Figures 3-1, 3-2 and 3-3 illustrate the histories of the Splash Dam, Cedar Grove, and Upper Freeport coals used in the project. The Alma coal used for microfine CWF production was shipped directly from the mine/cleaning plant to the CWF manufacturer to C-E.

FIGURE 3-1 HISTORY OF SPLASH DAM CWF PROCUREMENT

FIGURE 3-2 HISTORY OF CEDAR GROVE CWF PROCUREMENT

FIGURE 3-3 HISTORY OF UPPER FREEPORT CWF PROCUREMENT

TASK 4 SUMMARY: COMBUSTION EVALUATION/ATOMIZATION AND BURNER TESTS

The combustion performance characteristics of four generic burners for retrofit to oil-designed units were evaluated under Task 4. Each burner was initially evaluated through a series of preliminary tests to identify potential design deficiencies which could be modified prior to detailed performance characterization. The preliminary tests included cold flow atomization testing, combination shakedown/optimization combustion testing and an abbreviated performance characterization with each burner vendor's representative in attendance. Following the preliminary tests, all burners were evaluated with a single CWF formulation as reference fuel in C-E's Industrial Scale Burner Test Facility (ISBTF) at a 25×10^6 Btu/hr firing rate. A generic burner design which met specific commercial and performance criteria was subsequently selected for application to the multiple CWF formulation combustion trials at a 50×10^6 Btu/hr firing rate.

BURNER SELECTION

Selection of burners was based on current market share, suppliers' manufacturing capabilities, previous experience with slurry fuels and unique design approaches. Descriptions of the four test burners are provided as follows:

High Swirl Wall-Fired Burner (HSWF)

This burner features a central primary air register, which houses a primary air swirler through which a portion of the combustion air is passed (Figure 4-1). This swirling air exits the burner register through a refractory lined divergent exit nozzle. The primary air register is centrally located within an angular secondary air register through which the remainder of the combustion air is passed. This air register is equipped with co-rotational swirl vanes, which impart additional swirl to the total combustion air flow.

FIGURE 4-1 SCHEMATIC OF HIGH SWIRL WALL-FIRED BURNER (HSWF)

FIGURE 4-2 SCHEMATIC OF REFRACTORY CHAMBER BURNER (REF)

The atomizer for this burner is of the air-assisted, "Y-jet" type, specifically developed for CWF firing. The fuel stream is directed into a pressurized air stream. The shear forces which develop at the fuel/air interface initiate fuel stream atomization. The atomizer features tungsten carbide inserts in critical wear areas to extend atomizer life.

Refractory Chamber Burner (REF)

The refractory chamber burner's design (Figure 4-2) features swirled primary combustion air in the refractory lined combustion chamber. A portion of the primary air passes through a centrally located vane swirler into the combustion chamber. The remainder of the primary air passes through a series of "tunnels" between the primary air register and the combustion chamber. These "tunnels" are angled such that they impart additional swirl to what can be referred to as secondary combustion air. Additional combustion air is added downstream to help combustion.

The atomizer for this burner is of the external mix, air assisted variety. Pressurized air is directed radially inward towards a central fuel stream. Shear forces at the fuel/air interface initiate atomization of the fuel stream.

Tangentially Fired Burner (TAN)

This burner is a swirl stabilized unit configured for tangential corner firing (Figure 4-3). The principal elements of the burner are: a refractory-lined divergent nozzle, a fixed vane tangential swirler through which the primary combustion air stream is passed and secondary combustion air nozzles above and below the burner through which the balance of the combustion air is ducted (unswirled).

The atomizer for this burner is of the air-assisted "Y-jet" type and was identical to the atomizer used in the HSWF burner.

FIGURE 4-3 SCHEMATIC OF TANGENTIALLY FIRED BURNER (TAN)

FIGURE 4-4 SCHEMATIC OF REFRACTORY/REGISTER BURNER (REF/REG)

Refractory/Register Burner (REF/REG)

The refractory/register burner (Figure 4-4) utilizes a single air plenum for its source of combustion air. Primary air passes through an adjustable angle vane swirler, into the register tunnel and out through a refractory quarl. Secondary air is added through an annulus around the burner quarl. A slotted metal cone located on the end of the CWF gun acts as a bluff body to help stabilize the flame. The atomizer for this burner is of the air-assisted "Y-jet" variety.

In order to provide the burner vendor's with performance targets, C-E established a list of Preliminary Performance Objectives (PPOs) which would guide each burner vendor in the selection of appropriate burner hardware. The PPOs were as follows:

- o Combustion air preheat requirements: less than 500°F
- o Turndown without support fuel: greater than 4:1
- o Excess combustion air requirements: less than 40% at 100% load
- o Ignition requirements: less than 20% of full load heat input in a cold boiler for 30 minutes
- o Carbon conversion efficiency: greater than 98% at 100% load
- o Confirmed scanner signal over turndown range
- o No atomizer pluggage during 8 hour test
- o Atomized spray droplet mass mean diameter should be less than 200 microns at 100% load
- o Atomizer assist fluid consumption: less than 0.25 lbs/lb of fuel at 100% load
- o Windbox air pressure: less than 16 inches H₂O at 100% load
- o No excessive burner coking during 8 hour test

Each of the four burners was tested with a single CWF formulation that was produced by an established fuel manufacturer to obtain comparative performance data. Splash Dam coal mined in Buchanan County, Virginia and beneficiated to 5.7% by weight ash was selected and used to produce the reference CWF.

COMPARATIVE BURNER PERFORMANCE

The comparative burner tests were initiated following identification of participants and their burners. Atomization tests were first conducted to quantify spray quality differences between each generically different atomizer.

Relative Atomization Performance

All atomization tests were conducted in C-E's Atomizer Test Facility (ATF). The facility is uniquely configured to obtain spray droplet size distribution and droplet ballistics (velocity and trajectory) information. The facility operates in a cold flow (non-combustion) mode and can be used to quantify any atomizer's performance.

A laser diffraction based instrument is used to determine spray droplet size distribution using a Rosin-Rammler model. Size distribution histograms were summarized and reported in terms of spray droplet mass mean diameter (MMD) and the weight percentage of droplets which exceeded 300 microns in diameter. These comparatively large diameter droplets are believed to have a negative impact on both CWF ignition and carbon conversion, based on established pulverized coal firing practice. A high speed, double image photographic technique was also employed in the ATF to characterize differences in spray droplet ballistics between the generically different test atomizers.

CWF spray droplet size has been shown to have a direct impact on CWF ignition and burnout characteristics. In addition to droplet size, droplet ballistics must also be considered in defining the rear-burner aerodynamics required for effective combustion. Carbon burnout and burner ignition stability can be favorably influenced by finer spray droplet size and by minimizing the number of high momentum droplets which move rapidly out of the burner's primary aerodynamic recirculation zone.

Table 4-1 outlines spray quality observations made as a result of this test program. All three of the atomizers tested met the PPO criteria of less than 200 microns MMD at an atomizing media to fuel mass flow ratio (A/F) of less than 0.25. However, there were significant differences in spray quality, and fuel and air pressures between atomizers. Overall, the HSWF atomizer produced significantly finer sprays at 100% load at any given A/F ratio. At 100% load and an A/F ratio of 0.20, the HSWF atomizer produced an MMD of about 60 microns while the REF and REF/REG atomizer produced MMDs of 145-155 microns. Similar, although less pronounced, trends are shown in the 50% and 25% load curves (Figure 4-5).

Droplet size distribution data showed the HSWF/TAN atomizer produced negligible quantities of droplets above 300 microns (<1%), while the REF and REF/REG atomizers produced 5.5% to 8.7%, and 14% to 18%, respectively, in the greater than 300 micron range. Similar trends can be seen in the data presented for 50% and 25% loads. This data correlates directly with the combustion results, as will be discussed later.

Table 4-1

ATOMIZER SPRAY QUALITY OBSERVATIONS

Atomizer Type	Firing Rate 100% = 25×10^6 Btu/hr	Atomizing Media/ Fuel Mass Flow Ratio (A/F)	Spray Droplet MMD (Microns)	Spray Droplets >300 μ (% Wt)
HSWF & TAN	100%	.27-.10	51-91	.01-.12
REF	100%	.65-.37	98-143	5.5-8.7
REF/REG	100%	.19-.09	142-175	14-18
HSWF & TAN	50%	.59-.28	48-63	.00-.09
REF	50%	1.37-.31	70-94	1.0-5.1
REF/REG	50%	.37-.22	92-137	10-15
HSWF & TAN	25%	1.29-.65	46-52	.04-.33
REF	25%	2.7-.62	41-87	.26-1.28
REF/REG	25%	.88-.47	81-117	5-12

FIGURE 4-5 COMPARISON OF MASS MEAN DIAMETER VERSUS ATOMIZING MEDIA/FUEL (A/F) MASS FLOW RATIOS FOR CWB BURNERS

Figure 4-6 summarizes diameter vs. velocity information obtained for the HSWF, TAN, and REF atomizers. In general, the detected droplet velocities for the test atomizers ranged between 2-13 meters/sec. These velocity measurements were made at least 140 nozzle diameters (at least 30cm) downstream of the nozzle exit. The REF atomizer tended to generate somewhat higher velocities on average. This could be attributed to the fact that the REF atomizer's operating A/F ratio was over twice that of the HSWF/TAN atomizer (0.5 vs. 0.2). The greater momentum of the REF atomizer's air assist stream as compared with that of the HSWF/TAN atomizers may increase the total momentum (mass, velocity product) of the partially atomized fuel stream. This may increase measured droplet velocities downstream of the atomizer exit, and could potentially have a negative impact on flame stability.

It should also be noted that the measured droplet trajectories for the HSWF, TAN, and REF atomizers tended to predictably follow the streamlines of a freely expanding jet, where the droplets tended to follow a conical trajectory with a 15° included angle.

Burner Combustion Performance Test Program

Preliminary shakedown tests were conducted to provide each burner manufacturer the opportunity to modify equipment. The burners then underwent more detailed combustion performance testing in the C-E's Industrial Scale Burner Test Facility (ISBTF) at a 25×10^6 Btu/hr firing rate. This facility simulates a front wall, horizontal fired industrial type boiler environment. Prior to testing, insulation was added to the ISBTF walls and ceiling to obtain a volumetric heat release rate of approximately 30,000 Btu/hr - Ft³ and furnace outlet temperatures of 2400°F to 2500°F. The bulk gas residence time was on the order of 1.7 seconds. These conditions were chosen as being representative of oil-fired boilers and process heaters which represented the greatest potential for CWF retrofit in 1983.

Results showed that at 100% load, the HSWF burner was capable of achieving carbon conversion efficiency (CCE) levels close to the PPO target of 98%,

FIGURE 4-6 DROPLET VELOCITY VERSUS DROPLET DIAMETER AT 100% LOAD

while the TAN burners performance (greater than 99%) exceeded PPO expectations. The REF/REG burner, using the best atomizer supplied by the burner vendor, was capable of CCEs in excess of the PPO target level of 98%, contrasting with the REF burner which achieved CCEs on the order of 86% at 100% load firing conditions. CCE for the REF burner improved to the 95% level at reduced firing rates, but it appeared that the REF burner would benefit from additional development in order to improve CCE.

All four burners were sensitive to excess air level, increasing excess combustion air tended to improve CCE in all cases. Figure 4-7 summarizes the measured effect of excess air on CCE. All tested burners can operate within the PPO target envelope with a 40% excess air upper limit.

A series of test runs were conducted in order to quantify the effect that combustion air preheat has on burner operation. The PPO target for preheat called for combustion air temperature not to exceed 500°F. This value is usually practical to achieve in CWF conversions, although some cases are limited in air heating capability.

The HSWF burner operated with acceptable flame stability at combustion air temperatures as low as 300°F. The CCE degraded by 0.4% when the HSWF burner was operated with combustion air temperatures below 500°F.

The TAN burner was capable of operation at combustion air temperatures down to 250°F. The CCE was not affected by combustion air temperature for the TAN burner over a temperature range of 250°F to 600°F.

The REF and REF/REG burners operated stably at the combustion air temperature of 500°F. The REF burner's flame stability degraded at temperatures below 500°F. The REF/REG burner vendor did not recommend burner operation with combustion air temperature below 500°F, as a result of observed flame stability problems.

The PPO target for burner turndown ratio was to achieve a firing rate turndown ratio in excess of 4 to 1 without any support fuel or

FIGURE 4-7 EFFECT OF EXCESS AIR ON CARBON CONVERSION
AT 100% LOAD CWF FIRING

supplementary ignition sources. The test burners' turndown performance was found to vary widely. For example, the REF burner was capable of achieving 4 to 1 turndown with acceptable flame stability, the HSWF burner and TAN burner achieved turndowns of 2.5 to 1 and 2 to 1, respectively. The REF/REG burner's turndown was limited to 1.5 to 1 at best.

The PPO target for burner ignition energy was that each burner should achieve stable operation after providing ignition support energy equivalent to 20% of full load heat input (5×10^6 Btu/hr) for a period not to exceed 30 minutes in a cold boiler. All four test burners were successful in meeting this ignition energy guideline.

Combustion air windbox pressure requirements were noted for each generic burner. It is desirable from an overall plant efficiency standpoint to minimize burner windbox pressure, the PPO target for each burner was to not exceed 16 inches H_2O windbox pressure. Relative ranking of the burners with respect to operating windbox pressures were 1) TAN (5.1" H_2O @ 44% excess air), 2) HSWF (9.8" H_2O @ 44% excess air), 3) REF/REG (19.5" H_2O @ 48% excess air) and 4) REF (17" H_2O @ 30% excess air).

Flame scanners are an integral component in burner management and safety systems, tests were conducted to quantify relative compatibility of each burner's flame scanning system to CWF firing. Two generic flame detection systems were employed by the burner vendor's participating in these tests. The HSWF and TAN burners use a visible light intensity/frequency monitor, while the REF and REF/REG burners use infrared detectors. Based on this test program, it appears that both visible light intensity/frequency monitors and infrared scanners can be successfully employed with CWF firing systems.

A factor which may limit the potential for CWF burner retrofit is that additional burner/boiler maintenance may be required as compared with existing oil fired burners. The reason for this concern is derived from the fact that the pulverized coal in CWFs contains varying quantities of mineral matter which can be potentially erosive and can form deposits on burner/boiler surfaces. Two PPO targets were established with respect to the

above: 1) that no excessive coking (deposition) occurred on burner surfaces during eight (8) hours of steady burner operation; and 2) that no atomizer pluggage or erosion occurred after eight (8) hours of steady burner operation.

No burner coking or deposition was observed with either the HSWF or TAN burners. Some limited deposition was observed with both the REF and REF/REG burners, however, the deposition observed did not impede burner operation.

The HSWF, TAN, and REF atomizer's did not experience any atomizer pluggage or erosion over eight (8) hours of burner operation. These atomizers were fabricated of erosion resistant materials specifically for CWF application. The REF/REG burners' atomizers which were fabricated of carbon steel were not erosion resistant and tended to wear after only three (3) hours of operation. Had the REF/REG atomizers been fabricated with erosion resistant materials, atomizer life would have improved dramatically.

The final PPO burner performance target addressed atomizer energy consumption requirements. All burners in the test program employed air-assisted atomizers; compressed air is used to provide fuel atomization energy. Since the amount of compressed air per unit mass of fuel affects overall plant efficiency, a PPO target limit A/F ratio of 0.25 was set for atomizer air consumption.

A/F ratio typically has a first order effect on atomization quality in twin-fluid atomizers; atomization quality normally improves with increases in A/F ratio. This phenomena was observed for all burners in the test program. The HSWF and TAN atomizer's met the PPO guideline, the REF/REG atomizer for the most part operates within an acceptable A/F ratio range. The REF atomizer only operated at A/F ratio's which exceeded the PPO limitation. The optimum performance for each burner type was achieved at the following A/F ratios:

<u>Burner Type</u>	<u>A/F Ratio Range</u>
HSWF	0.19 - 0.22
REF	0.53 - 0.55
TAN	0.19 - 0.22
REF/REG	0.19 - 0.29

In summary, all burners in the program were capable of firing the reference CWF, however, each burner demonstrated unique performance characteristics. No tested burner concept could be deemed wholly inadequate for CWF service. The HSWF and TAN designs appear suitable for immediate commercial CWF retrofit application. The REF and REF/REG burners demonstrated promising performance, but would benefit from further development. It should be noted that the REF and REF/REG burner manufacturers had no significant experience with CWF firing prior to this test program.

MULTIPLE CWF COMBUSTION TESTS

The High-Swirl Wall Fired (HSWF) burner was chosen for application to the multiple CWF combustion test program since the HSWF burner design operated within most PPO target performance levels. The HSWF generic design is also suitable for use in a high percentage of CWF retrofit situations.

The HSWF burner manufacturer fabricated a 50×10^6 Btu/hr capacity burner and made improvements to minimize required burner windbox pressure. Specifically, the tertiary air swirler was eliminated from the design, which effectively allowed the burner to operate at windbox pressures below those previously observed (i.e., less than 9.8" H₂O @ 44% excess air).

Five CWFs representing three different coal types and three different CWF producers were tested using the HSWF burner. The laboratory analyses of these fuels are summarized in Table 4-2.

Atomization Characterization

A parametric study was carried out on the five CWFs in the ATF to quantify the effect that various CWF formulations would have on atomization quality. Performance comparisons were drawn between each fuel as all CWFs were atomized under identical conditions using the same 50×10^6 Btu/hr, Y-jet CWF nozzle.

Table 4-2

SUMMARY OF LABORATORY FUEL ANALYSES

Fuel	SD6.3C	SD5.2A	CG5.3C	UF6.2C	SD7.1F
Solids (Wt%)	69.7	69.9	70.1	69.9	70.8
Coal Size Distribution					
+50 mesh (300 microns)	0.0	Trace	Trace	0.0	0.6
+100 mesh (150 microns)	0.2	2.8	1.4	0.1	3.7
Average MMD (microns)	6.5	31.0	27.0	6.5	30.0
Coal Volatile Matter (Wt%)	29.5	29.3	30.5	37.8	30.4
Ash Content (WT%)	6.3	5.2	5.3	6.2	7.1
Higher Heating Value (Btu/lb)					
Dry Basis	14215	14560	14260	13920	14275
As-received Basis	9900	10180	9999	9735	10105
Viscosity (cp)					
@ 100 sec ⁻¹ 68°F	610	1459	1459	989	1533
@ 3000 sec ⁻¹ 68°F	710	850	860	1300	630
Power Law Index	1.4	1.07	1.07	1.37	1.07
@ 2000 sec ⁻¹ 135°F	500	150	610	220	970

Atomization conducted at 100% load as well as at reduced loads on the five fuel formulations indicated that all five CWFs in an isothermal environment generated similar quality sprays, with the exception that UF6.2C produced smaller droplets (Figures 4-8 and 4-9). It should be noted that the atomization trends observed did not directly correlate with the low shear viscosity measurements made on each formulation. Fuel viscosity normally has a first order effect on atomization quality with Newtonian liquid fuels. The CWFs tested, however, were non-Newtonian in nature, that is, their viscosity characteristics change with changes in shear environment. The rheological and shear dependent properties of the CWFs complicate the atomization performance prediction based on laboratory viscosity measurements which subject the fuels to shear environments that do not accurately reflect the high shear environment when the fuel undergoes atomization. As a result, the laboratory viscosity data did not correlate well with the observed atomization performance of each formulation.

FIGURE 4-8 SPRAY DROPLET MMD VS A/F RATIOS
AT 100% LOAD

FIGURE 4-9 SPRAY DROPLET SIZE DISTRIBUTION
AT 100% LOAD

Combustion Characterization

Subsequent to atomization tests, each fuel was subjected to a series of detailed parametric firing tests conducted in Combustion Engineering's Industrial Scale Burner Test Facility (ISBTF) using the 50×10^6 Btu/hr HSWF burner. The primary objective of these tests was to identify and characterize relative differences, if any, between the performance of the five CWFs when the fuels were fired in a similar furnace environment. Performance differences were quantified through systematic determination of:

- o Carbon conversion efficiency by flue gas analysis at each test condition.
- o Carbon conversion efficiency by particulate chemical analysis at optimum operating conditions for each load.
- o Flue gas emissions of NO_x , SO_2 , and CO.
- o Flame stability and minimum load.
- o Morphology of fly ash emissions (scanning electron microscope).
- o Furnace outlet temperatures and peak flame temperatures.
- o The influence of combustion air temperature on combustion efficiency.
- o The effect of varying atomizer A/F ratio on combustion efficiency.
- o Heat flux along the length of the test facility to determine the heat release profile for each fuel tested.
- o Any fuel specific abnormal handling characteristics, such as atomizer or fuel line pluggage, and fuel settling.

At each test condition the following burner/atomizer operating variables were held constant between all of the fuels tested in order to evaluate the combustion performance of each fuel over a wide range of operating firing rates and excess air levels.

- o Atomizer A/F ratio - 0.19-0.21 at 100% load
0.39-0.41 at 50% load
0.59-0.61 at 33% load
- o Burner Damper Positions
- o Burner Windbox to Furnace Pressure Drop
- o Combustion Air Temperature (500°F)

A total of 99 individual combustion tests were conducted on the five CWFs. A condensed summary of the data obtained for each of the five CWFs at optimum carbon conversion efficiency levels over the maximum achievable firing rate range is given in Table 4-3. With the exception of SD6.3C, all fuels operated over a 3 to 1 turndown range. Fuel SD6.3C was limited to a 2 to 1 turn down range. The reason for this is not apparent from a review of either the laboratory fuel characterization study or the atomization study.

Based on chemical analysis of isokinetically collected fly ash samples, all five fuels were capable of achieving carbon conversions in excess of 98% at all loads tested. However, optimum carbon conversion efficiencies for the five fuels were found to vary over a much wider range (88.5% to 99.6%) when efficiencies were calculated from flue gas constituents. The reason for the discrepancies between the two efficiency determination methods appears to be due to potential particulate sampling errors. It was noted throughout the test program that several of the fuels had a tendency to generate fairly large "agglomerates". These agglomerates were attributed to poor atomization in the hot, combustion environment. Specifically, fuel UF6.2C experienced significant agglomeration under combustion conditions. It is presumed that

TABLE 4-3

SUMMARY OF COMBUSTION TEST RESULTS AT OPTIMUM CARBON CONVERSION EFFICIENCY CONDITIONS

Fuel Identifier	% Excess Air	% Load	% O ₂	% CO ₂	CO, ppm	SO ₂ , ppm	NO _x , ppm	% Carbon Conversion	% Carbon Conversion
					Corr.	Corr.	Corr.	Efficiency	Efficiency
					to 3% O ₂	to 3% O ₂	to 3% O ₂	(gas analysis)	(particulate analysis)
SD6.1C	42	100	5.9	12.6	90	380	621	97.5	90.3
	88	50	9.2	10.0	50	435	596	99.5	99.3
SD5.2A	32	100	4.5	13.9	90	361	469	99.6	98.8
	39	50	5.7	12.9	85	332	436	98.6	99.2
	46	33	6.3	12.4	48	329	700	99.0	99.7
CG5.3C	39	100	6.3	12.3	83	461	491	93.6	90.9
	40	50	6.1	12.4	27	448	600	95.7	99.8
	50	33	7.1	11.8	35	447	447	96.9	99.7
UF62C	40	100	6.9	11.7	42	544	566	88.5	90.1
	61	50	8.2	10.8	27	520	485	92.7	----
	100	33	10.2	8.4	27	492	512	98.3	----
SD7.1F	42	100	6.7	12.1	38	341	688	93.8	99.5
	59	50	7.7	11.2	26	332	562	96.5	99.7
	95	33	9.8	8.4	40	313	394	96.5	----

these "agglomerates" may derive from fuel "ligaments" which issue from the nozzle and remain essentially intact in the high temperature furnace environment, rather than breaking down into small, readily combusted, spherical droplets as has been demonstrated during isothermal atomization testing.

While the specific agglomeration mechanisms have yet to be identified, it is clear from these tests that a significant population of "agglomerates" generated by several fuels were not entrained in the combustion gas stream, but rather fell partially combusted, to the furnace floor. Fly ash samples collected for the fuels having agglomerating tendencies did not accurately represent the high carbon content material which fell to the furnace floor. For this reason, it is assumed that the carbon conversion efficiency data generated via flue gas analysis represent fuel performance more accurately than do the efficiency data derived from collected fly ash samples. With the above analysis in mind, carbon conversion performance trends presented henceforth will be based on carbon conversion efficiencies derived from flue gas analysis.

Figure 4-10 illustrates carbon conversion efficiency data obtained at 100% load as a function of excess air for the five fuels. In general, carbon conversion efficiency improved from all five CWFs with increased excess air. The five fuels can be clearly ranked in terms of achievable levels of carbon conversion efficiency. The highest carbon conversions were achieved with fuel SD5.2A, followed in relative order by fuels SD6.3C, CG5.3C, SD7.1F, and UF6.2C. The fundamental reason(s) for the above fuel ranking, after conducting a detailed review of the laboratory fuel characterization data and the atomization characterization study, is not clearly evident.

Most CWF investigators agree that fine fuel atomization is a precursor to good carbon conversion efficiency. The isothermal atomization data indicated that atomization quality for fuels SD5.2A, SD6.3C, CG5.3C, and SD7.1F was similar. This result does not correlate with the wide range of carbon conversion efficiencies observed for these fuels. Additionally, fuel UF6.2C generated the finest sprays, on average, during isothermal atomization testing; yet this fuel on average generated the lowest levels of carbon conversion.

FIGURE 4-10 EFFECT OF EXCESS AIR AT 100%
LOAD ON CARBON CONVERSION

Based on these results, it would appear that an isothermal measurement of atomization quality cannot be considered the sole predictor of CWF combustion characteristics when applied to differing CWF formulations. However, isothermal spray quality measurements made on a single CWF formulation was effective in predicting the combustion performance of CWF. Figure 4-11 presents carbon conversion efficiencies at 100% load as a function of spray droplet mass mean diameter. As MMD was increased, carbon conversion was found to decrease for fuels SD6.3C, CG5.3C and UF6.2C.

A number of scanning electron micrographs (SEMs) were taken of collected particulate from the combustion study in an attempt to clarify the inconsistencies noted between each CWF's isothermal atomization performance and combustion performance. The photos show evidence of cylindrically shaped char particles which are interspersed amongst fine fly ash particles (Figure 4-12). The shape of these char particles seems to support the previously mentioned presumption that a certain population of long CWF strands or "ligaments" did not completely atomize in the hot furnace. Rather these ligaments, which contain a number of coal particles, tended to dry and burn as agglomerates. Cold flow atomization data would not predict this phenomenon since it was conducted at a distance from the atomizer (far field) which ensured spherical droplet formation.

Burner flame stability was documented photographically for all five of the fuels tested. The luminous flames produced by all fuels, with the exception of UF6.2C, were highly stable in the burner near field. Good flame stability was achieved during initial testing of UF6.2C. However, as testing progressed flame stability degraded. The source of degradation was likely due to the variability in solids loading for fuel UF6.2C. Progressive coal settling was noted in the fuel supply tank during the later portions of the combustion test program.

An interesting flame stability observation was made during the evaluation of SD5.2A. Flame stability was poor for SD5.2A when the burner's atomizer was operated at atomizing A/F ratios of 0.19 to 0.21 at 100% load. The other

FIGURE 4-11 EFFECT OF SPRAY DROPLET DIAMETER ON CARBON CONVERSION

a) 100% LOAD
100X

b) 100% LOAD
100X

c) 100% LOAD
90X

d) 100% LOAD
50X

FIGURE 4-12 SCANNING ELECTRON MICROGRAPHS OF
FLY ASH FROM UF6.2C CWF

four fuels in the program operated successfully at A/F ratios in the 0.19 to 0.21 range. A dramatic improvement in flame stability was achieved when the A/F ratio was reduced to 0.16 for fuel SD5.2A. An explanation for this anomalous behavior may be found from an analysis of the isothermal atomization data. The percentage of spray droplets exceeding 300 microns tended to increase with fuel SD5.2A when the atomizer A/F ratio exceeded 0.18. At an A/F ratio of 0.22, the percentage of droplets exceeding 300 microns was in excess of 1%. It is possible that ignition stability would suffer as a result of the increased population of large droplets generated when fuel SD5.2A was atomized at A/F ratios in excess of 0.18.

The formation of NO_x during combustion is commonly classified in terms of the nitrogen source for the reaction. "Thermal NO_x " refers to NO_x that is formed at high temperatures from nitrogen and oxygen present in the combustion air. NO_x formed in this way has been shown to be a function of temperature, N_2 and O_2 concentrations, and the exposure time of N_2 to O_2 at high temperatures. Temperatures in excess of approximately 2800°F are generally required for this process.

"Fuel NO_x " refers to NO_x formed from organically bound fuel nitrogen. Although the mechanisms of "fuel NO_x " formation are generally not yet fully understood, it is known that its formation is insensitive to flame temperature. However, studies have indicated that up to 80% of the total NO_x can be fuel related.

Extensive furnace temperature mapping data, obtained with a suction pyrometer, indicate that at no time during combustion testing of the five CWFs did flame temperatures exceed the 2800°F necessary for thermal NO_x formation. This indicates that the NO_x emissions measured for all of the fuels was primarily fuel related.

Table 4-4 summarizes the range of NO_x emissions measured for each CWF. Note that no attempts were made in this test program to minimize NO_x levels; test guidelines focused on flame stability and carbon conversion efficiency.

TABLE 4-4

NO_x EMISSIONS FROM CWF COMBUSTION TESTS

Fuel	Nitrogen In Fuel (Wt. %)	NO _x Emissions (1) (lb NO _x /10 ⁶ Btu)
SD6.3C	1.5	0.54-1.13
CG5.3C	1.7	0.64-1.06
UF6.2C	1.5	0.67-0.95
SD7.1C	1.5	0.68-1.06
SD5.2C	1.8	0.54-0.97

(1) Range for all firing rates

Application of commonly known NO_x control technologies such as "staged combustion" would likely reduce the levels of NO_x observed here.

Sulfur dioxide emissions, in general, are not a function of burner/furnace operating conditions. Depending on the amount of sulfur retained by the ash the SO_x generated during the combustion process is almost directly proportional to the amount of sulfur present in the fuel. Any increase or decrease in fuel sulfur should result in a corresponding increase or decrease in SO_x emissions.

TASK 5 SUMMARY: PILOT-SCALE ASH DEPOSITION AND PERFORMANCE TESTS

The ash deposition and performance behavior of a cross-section of coal-water fuels were investigated during comprehensive pilot-scale testing under Task 5. Testing was conducted at approximately 4×10^6 Btu/hr in C-E's Fireside Performance Test Facility (FPTF). The facility was designed to simulate important aspects of commercial units and was operated at conditions representative of tightly designed oil-fired furnaces (Figure 5-1).

Data were obtained from twelve different CWFs as well as three baseline pulverized coals and oil (Table 5-1). Three coal types were fired at different levels of coal beneficiation to allow assessment of the effects of coal cleaning on performance. Five CWFs were prepared from the same feed coal by different producers to assess the effects of slurry processing on performance. Both standard grind and microfine CWFs were included. A microfine CWF (MCWF) was fired at fuel temperatures up to 220°F to improve atomization.

COLD FLOW ATOMIZATION CHARACTERISTICS

Prior to combustion testing, cold flow atomization characteristics of each CWF were evaluated in C-E's Atomization Test Facility (ATF) using a laser diffraction droplet sizing technique. The objectives were to determine and control atomizer droplet spray quality during the pilot-scale combustion and ash deposition performance tests. Compressed air was used as the atomizing media. Mass mean droplet diameters were determined over a range of atomizing air-to-fuel ratio (0.05 to 0.20) for each CWF fuel.

Table 5-2 shows ATF cold flow atomization results for each of the CWFs with the FPTF twin-fluid Y jet atomizer at the air-to-fuel ratio used during combustion testing. The cold flow atomization characteristics of the subject CWFs varied significantly in terms of required atomizing air flow rates and pressures to produce similar spray quality. Most of the fuels were atomized to the desired mass mean droplet diameter (MMD) of between 70 and 80 μ . However, some CWFs could not be atomized to MMD of 80 μ using the selected atomizer design with the maximum available atomizing air pressure of 200 psig.

FIGURE 5-1 FIRESIDE PERFORMANCE TEST FURNACE

TABLE 5-1

COAL-WATER FUEL PERFORMANCE TEST MATRIX

TEST NO.	FUEL DESCRIPTION	FUEL TYPE	% ASH	% SOLIDS	FUEL TEMP (°F)	FIRING RATE	
						TESTED (3)	TESTED (4)
						HIGH	LOW
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	AL5.9C	Alma	5.9	67.0	Ambient	X	
17	AL5.9C	Alma	5.9	64.0	Ambient	X	
18	AL5.9C	Alma	5.9	64.0	150	X	
19	AL5.9C	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

TABLE 5-2

CWF COLD FLOW ATOMIZATION TEST RESULTS

AT FUEL FLOW RATE OF 4.1×10^6 BTU/HR.

FUEL TYPE	SOLID CONTENT (%)	FUEL TEMP (°F)	ATOMIZER A/F RATIO (LB AIR/LB FUEL)	SPRAY DROPLET MMD (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
AL5.9C	67.0	80	0.17	72
AL5.9C	64.0	80	0.17	61
AL5.9C	64.0	150	0.17	79
AL5.9C	64.0	220	0.16	78

(1) Maximum Atomizing Air Flow/Pressure Available

The effect of fuel temperature on atomizer performance was 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 bench-scale viscosity data shown in Figure 5-2, 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 solid content for a given atomizing air-to-fuel ratio as shown in Figure 5-3.

CWF COMBUSTION PERFORMANCE CHARACTERISTICS

The combustion behavior of each CWF was evaluated in the Fireside Performance Test Facility 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 5-4. A summary of the combustion results is shown in Table 5-3. In general, the combustion behavior of each CWF was very good during nearly all of the FPTF tests. Good flame stability and carbon conversions were obtained from these tests. 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. Carbon conversion dropped as fuel droplet size increased from 61 microns to 106 microns. Fly ash size also increased due to the coal particle agglomeration and incomplete combustion of larger char particles generated from the coarser spray droplets. Results from this program and others have indicated that coal particles agglomerate to form a single char particle within a CWF spray droplet upon heating.

FIGURE 5-2 EFFECT OF FUEL TEMPERATURE ON VISCOSITY DURING BENCH-SCALE TESTS

FIGURE 5-3 EFFECT OF SOLIDS LOADING ON ATOMIZER SPRAY QUALITY DURING COLD FLOW TESTS IN THE ATOMIZER TEST FACILITY

**FIGURE 5-4 TYPICAL FTF TEMPERATURE PROFILES
DURING CWF FIRING AT LOW AND HIGH
FIRING RATES**

TABLE 5-3

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

FUEL TYPE	SOLID 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.o. Std.	--	3.1	2870	1.26	45	--	8	99.9
LK p.o. Std.	--	4.1	2960	1.10	40	--	13	99.9
LK p.o. Fine	--	4.1	2960	1.10	27	--	14	99.9
LK6.0C	66.0	3.1	2770	1.38	16	86	9	99.9
LK6.0C	66.0	4.1	2940	0.99	15	88	14	99.6
SD p.o. Std.	--	4.1	3070	1.02	52	--	13	99.8
SD p.o. 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 4.5A	69.5	4.1	3050	0.97	24	98	8	98.7
SD 2.6C	69.7	4.1	2970	1.04	15	91	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
CG7.9A	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.o. Std.	--	4.1	2990	1.00	39	--	6	99.8
AL p.o. Fine	--	4.1	2980	1.01	28	--	4	99.9
AL 5.9C ⁽¹⁾	67.0	3.8	2830	1.08	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

During the Alma microfine (MCWF) test AL 5.9 C 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 dramatically improved combustion. Combustion performance of the 64% solids fuel was very good, all large sparklers leaving the furnace were eliminated and carbon conversions increased to 99.6%. The improvement in combustion was attributed to the improved atomization in the combustion environment visually observed. Cold flow atomization results did not indicate the magnitude of the improvement associated with dilutions.

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 5-5). This was attributed 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.

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 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 deposits. The effects of deposits on waterwall heat transfer and the cleanability of waterwall deposits were the primary data used in assessing slagging potential.

CWF feed coal properties played a dominant role on ash deposit behavior of the CWF. The relative slagging characteristics of each CWF corresponded to those of the feed coal's. Waterwall deposit characteristics observed during the Lower Kittanning and Splash Dam tests indicated low slagging potential. Moderate slagging behavior was experienced during Cedar Grove and Alma tests and high slagging during the Upper Freeport tests. The Alma, fired only as

FIGURE 5-5 CARBON CONVERSION OF ALMA SEAM PULVERIZED-COAL AND COAL-WATER FUEL AT VARIOUS FUEL TEMPERATURES

microfine fuels, exhibited lower slagging potential compared to the predicted performance based on bench-scale analyses. A summary of the CWF furnace slagging characteristics are shown in Table 5-4.

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 indicated that slagging behavior of CWF was better than pulverized coal (p.c.) at similar conditions. In general, deposit buildup rates were lower during CWF tests than during corresponding p.c. tests. Waterwall deposits developed from the CWFs were thinner with less coverage on waterwall at a given firing rate (Figure 5-6). Waterwall heat absorption rates measured during these tests further illustrate this difference in slagging behavior (Figure 5-7). Waterwall heat flux decreased more rapidly and reached much lower values during the p.c. tests than the CWF tests.

General conclusions on potential slagging benefits associated with CWF firing cannot be definitely drawn based only on these tests, particularly since all of the above test fuels exhibited relatively low slagging characteristics. Reasons for improvement with CWF are not clearly evident. The time-temperature history which the coal mineral matter undergoes during CWF firing may be significantly different than for p.c. firing, hence influencing ash deposition behavior.

Comparison Between CWF Producers

The effect of slurry types 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 5-8). Based upon the slight differences in waterwall deposit characteristics between the five different slurry types, it appears that the variations in

TABLE 5-4

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 CRITICAL ⁽⁴⁾ 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 cleanable by soot blowers.

Waterwall deposits during Lower Kittanning tests at high firing rate

Waterwall deposit during Splash Dam tests at high firing rate

Waterwall deposit during Alma Seam tests at high firing rate

FIGURE 5-6 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 5-7 COMPARISON OF WATERWALL HEAT FLUX BETWEEN PULVERIZED-COAL AND CWF FIRINGS

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

**FIGURE 5-8 COMPARISON OF FURNACE SLAGGING CHARACTERISTIC
BETWEEN CWF PROCESSORS**

CWF particle size distribution and additive package did not have a major direct influence on slagging performance. However, it should be noted that these tests were intentionally performed with fairly uniform atomizer spray quality and these results may not apply to different coal types of different additive packages.

Comparison Between Coal Beneficiation Levels

The effects of coal beneficiation were assessed for the Upper Freeport and Cedar Grove CWFs. In general, slagging characteristics improved with increasing level of fuel beneficiation. 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.

The difference in physical state and the improvement in deposit cleanability was more pronounced during the Cedar Grove tests than the Upper Freeport tests. At similar conditions, waterwall heat flux recovery 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 5-9).

The slagging characteristics of both Upper Freeport and Cedar Grove CWFs were highly dependent on firing conditions. Significant slagging occurred with CWFs 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. If sootblowers are not effective in controlling waterwall deposition, furnace thermal loadings must be reduced to improve deposit characteristics. 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. Critical furnace temperatures for cleanable deposits with high ash Upper Freeport CWF was 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

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 5-9 COMPARISON OF WATERWALL HEAT FLUX BETWEEN CWF COAL BENEFICIATION LEVELS

estimated between 2950-3000°F, whereas that for the low ash fuel was estimated to be 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, 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 exhibited low to moderate fouling potential. Alma MCWF had low fouling potential despite the fact that its ash analysis indicated somewhat higher potential. Table 5-5 summarizes the CWFs fouling characteristics.

Vendor process did not appear to have a strong impact on fouling characteristics as all the Splash Dam CWFs exhibited low convection tube deposit buildup rate and weakly bonded, friable deposits.

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 5-10). 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

TABLE 5-5

CONVECTIVE PASS FOULING CHARACTERISTICS

<u>FUEL TYPE</u>	<u>FIRING RATE</u>	<u>GAS TEMP. AT PROBES (°F)</u>	<u>RELATIVE BUILDUP RATE (TIME BETWEEN SOOTBLOWING, Hr)</u>	<u>DEPOSIT BONDING STRENGTH</u>	<u>DEPOSIT CLEANABILITY</u>
LK 6.0 p.o. Std. ¹	High	2350	>40	1.8	Good
LK 6.0 p.o. Fine ²	High	2450	>40	0.4	Excellent
LK 6.0 S	High	2280	>40	--	Excellent
SD 6.0 p.o. Std.	High	2300	>40	<1	Excellent
SD 5.7 C	High	2270	>40	<1	Excellent
SD 5.7 D	High	2270	>40	<1	Excellent
SD 5.7 E	High	2350	>40	<1	Excellent
SD 4.5 A	High	2380	>40	<1	Excellent
SD 2.6 F	High	2320	>40	<1	Excellent
SD 6.7 F	High	2240	>40	<1	Excellent
UF 13.7 A	Low	2280	20-30	<1	Excellent
UF 13.7 A	High	2480	4-6	16	Marginal
UF 6.8 A	High	2350	8-10	2	Very Good
CG 7.1 A	Low	2270	>40	<2	Very Good
CG 7.1 A	High	2320	25-30	<2	Very Good
CG 4.8 A	High	2350	8-10	<2	Very Good
AL 5.8 C ³	High	2220	>40	<2	Very Good
AL 5.8 C ⁴	High	2400	>40	<2	Very Good
AL 5.8 C ⁵	High	2240	>40	<2	Very Good
AL 5.8 C ⁶	High	2400	>40		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

UF 13.7A

T = 2260°F

2 HOURS

6 HOURS

14 HOURS

UF 13.7A

T = 2350°F

2 HOURS

4 HOURS

6 HOURS

UF 6.8A

T = 2350°F

2 HOURS

6 HOURS

14 HOURS

FIGURE 5-10 CONVECTION TUBE DEPOSITS DURING THE UPPER FREEPORT CWF TESTING.

temperature). At similar firing conditions, ash buildup rates were about 50% lower for the more beneficiated Upper Freeport fuel which is roughly proportional to the reduction in ash loading between the high ash and low ash fuels.

Coal beneficiation also improved the fouling performance of the Cedar Grove CWFs. Sootblowing requirements were less for the lower ash fuel. Convection tube deposition during the Cedar Grove tests was minimal below gas temperatures of 2200°F and only lightly sintered deposits of less than 1 inch thick were generated at maximum temperatures studied (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 CWF. Ash deposition rate was greater during the pulverized coal tests than observed during the MCWF tests (Figure 5-11). All deposits were readily cleanable as they had low deposit-to-tube bonding strength up to the maximum gas temperature tested (2400°F).

Overall, the relatively low fouling characteristics for the four coal types evaluated are 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 have a strong impact on their behavior.

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 using a surface activation technique at 160 ft/sec to 275 ft/sec gas velocities and gas temperatures between 1000°F and 1400°F. The high gas velocities were used in order to accelerate wear and provide measurable erosion over the 80 hour testing period. A surface activation technique was used to determine the wear around the circumference of the tube. The technique measures the changes in radioactivity as the tube specimen surface is eroded which is then related to the depth of the material loss.

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 5-11 CONVECTION TUBE DEPOSITS DURING THE ALMA SEAM FUELS TESTING.

Results of the erosion testing along with relevant fly ash properties are summarized in Table 5-6. Since FPTF data were obtained at velocities considerably 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) using fly ash collected during FPTF testing. The normalized wear rate allowed more direct comparison between fuels and extrapolation to actual boiler conditions.

Data indicated a strong dependency of erosion upon firing rate. This effect is anticipated due to the combined influence of gas velocity and ash loading. Erosion rates for the Cedar Grove CWFs decreased about 65% with a 25% reduction in firing rate.

Coal beneficiation had a very significant impact on erosion characteristics (Figure 5-12). At similar gas velocities, erosion was reduced by 60% with the lower ash Upper Freeport fuel. Similarly, reduction of ash loading by 45% resulted in more than a 70% decrease in erosion for the Cedar Grove Fuels.

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.

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.

TABLE 5-6

FLY ASH EROSION CHARACTERISTICS

<u>FUEL TYPE</u>	<u>FIRING</u> <u>RATE</u>	<u>QUARTZ IN</u> <u>CWF ASH</u> <u>(%)</u>	<u>ASH</u> <u>INPUT</u> <u>(LB/HR)</u>	<u>GAS</u> <u>VELOCITY</u> <u>(FT/SEC)</u>	<u>COAL</u> <u>MMD</u> <u>(μ)</u>	<u>FLY ASH</u> <u>MMD</u> <u>(μ)</u>	<u>CARBON</u> <u>CONVERSION</u> <u>(%)</u>	<u>NORMALIZED</u> <u>WEAR</u> <u>(1)</u> <u>(MILS/10,000 HR)</u>
SD 6.0 p.o. (2)	4.1	-	17.1	245	52	13	99.8	0.6
SD 5.7 E	4.1	19.9	16.8	255	25	16	99.5	0.4
SD 4.5 A	4.1		12.6	260	24	34	99.8	0.4
SD 6.7 F	4.1		19.6	255	35	13	99.5	0.5
SD 2.6 C	4.1	7.0	7.1	265	15	53	99.2	<0.1
UF 13.7 A	4.1	13.6	42.5	265	30	20	99.4	2.9
UF 6.8 A	4.1	11.7	19.3	275	29	18	99.7	0.6
CG 7.1 A	3.1	18.5	24.0	180	32	23	99.5	1.4
CG 7.1 A	4.1	18.5	24.0	265	32	34	99.1	1.7
CG 4.8 A	4.1	15.1	14.0	260	25	19	99.8	0.4
AL 5.9 p.o. (2)	4.1	10.5	17.8	220	7	6	97.7	1.2
AL 5.9 p.o. (3)	4.1		17.8	220	7	4	99.9	0.4
AL 5.9 C (4)	3.8		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 (6)	4.1		17.8	240	49	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

FIGURE 5-12 EFFECT OF BENEFICIATION ON FLY ASH EROSION RATE

Changes in fly ash characteristics resulting from dilution or heating the Alma MCWF had a significant impact on erosion (Figure 5-13). Dilution of the MCWF from 67% to 64% solids reduced the fly ash size from mass mean diameters (MMD) of about 36 to 9 microns. The corresponding erosion rates 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 finer fly ash (4 versus 9 micron MMD) compared to that from the fuel at ambient temperature 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. Results for the Splash Dam Fuels indicate a slight improvement in fly ash collection efficiencies for CWF compared to those for pulverized coal firing. The behavior of the CWF appeared to be dependent on coal type, CWF properties, firing conditions, fly ash characteristics, and specific ESP design and operating conditions.

The ESP data obtained during the Splash Dam and Cedar Grove tests are summarized in Tables 5-7 and 5-8. Fly ash samples collected from the hopper under each field of the ESP were subjected to laboratory resistivity analysis per 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. Firing conditions, flue gas temperature, flue gas moisture, fly ash chemical composition and particle size distribution can all influence these results. A general trend was not evident for the Cedar Grove test series. However, comparison of the Splash Dam pulverized-coal with CWF firing indicates that the fly ash resistivity is lower with CWF. This is most likely due to the flue gas humidification effect associated with CWF firing.

*NORMALIZED TO A GAS VELOCITY OF 60 FT/SEC

FIGURE 5-13 ALMA MICROFINE CWF FLY ASH EROSION CHARACTERISTICS

TABLE 5-7

ESP PERFORMANCE RESULTS FOR SPLASHDAM

COAL TYPE	SD P. C. HFR		SD2.6C HFR		SD6.7F HFR		
GAS TEMP., F							
INLET	383	362	453	451	534	498	551
OUTLET	263	253	334	398	378	341	406
GAS FLOW, acfm							
INLET	1791	1740	1962	2067	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	9.6	7.8	8.0	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	9.6	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	206	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	5.06	7.79	8.09	11.5	7.37	7.09

TABLE 5-8

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, $ft^2/1000acfm$	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 5-14 and 5-15 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 area, gas flow and average ash particle migration velocity) is also shown for comparison. Results showed 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.

FIGURE 5-14 ESP OVERALL EFFICIENCY FOR SPLASH DAM

FIGURE 5-15 ESP OVERALL EFFICIENCY FOR CEDAR GROVE

TASK 6 SUMMARY: COMMERCIAL APPLICATIONS

The study of commercial applications of CWFs evaluated the technical and economic aspects of the conversion of existing boilers and heaters to CWF firing. This work involved the analyses of seven units of various sizes and configurations firing several selected CWFs. Three utility boilers, two industrial boilers, and two process heater designs were included. Each of the units was considered with four primary selected CWFs. A fifth fuel was considered for one of the utility units. A sixth fuel, a microfine grind CWF, was evaluated on two utility units and one industrial unit. The particular fuels were chosen with the objective of examining the effects of coal source, ash level, ash properties, and beneficiation on the CWF performance and economics of the seven units.

Based on the results of comprehensive pilot-scale testing conducted as part of Tasks 1 through 5, a set of CWF performance guidelines was developed. These guidelines were employed to estimate the performance of each fuel-unit combination. The principal result of these predictions was the load derating requirement expected for each combination. Once a load derating was established for each combination, a retrofit specification was written. Retrofit cost estimates were then developed. The retrofit costs, along with assumed CWF costs, operating costs and unit derating, were used to perform a series of economic analyses. Conclusions were drawn regarding the following aspects of CWF technology:

- o Expected load deratings as affected by CWF characteristics and boiler design.
- o Typical retrofit scope and costs as influenced by CWF and unit type.
- o Economic incentives for CWF conversion as a function of cost and quality of CWF, oil price, and unit type.

Results were reported in detail in Volume 6.

This study of retrofit applications shows that from a technical standpoint all seven units considered appear capable of conversion to coal water fuel (CWF) operation. The potential problems associated with CWF firing can apparently be handled with proper application of current technology, combined with the knowledge gained from the results of the other tasks of this project. This study has shown, however, that considerations beyond the strictly technical ones can make CWF conversion a marginal proposition. It was found that factors such as load derating requirements, long economic payback periods, and reduced unit availability can make CWF conversion of specific units with some fuels an infeasible means of reducing dependence on oil as a primary fuel. For most cases considered, the assumed differential fuel costs between oil and CWF played a critical role in the overall desirability of a CWF conversion project. Differential fuel costs (DFC's) ranging from \$1.00 to \$2.00 per 10⁶ Btu were analyzed.

The scope of conversion work varied considerably from unit to unit and from fuel to fuel. For most cases the retrofit work would be extensive, involving fuel handling and storage, boiler island modifications, particulate removal equipment, SO₂ scrubbers (for some fuels), ash collection systems, and other miscellaneous changes. The choice of CWF has some impact on conversion costs, as does the degree to which the unit resembles a "future coal" design.

Description of Study Units

Seven major fuel burning installations designed for oil or gas, representing three generic classes of oil/gas fired equipment, were selected for CWF performance and economic evaluations. The seven selections are categorized as follows:

- o 3 Utility steam generators
- o 2 Industrial steam generators
- o 2 Crude oil heaters

The major characteristics of these units are listed in Table 6-1. These units were selected to represent a wide range of boiler types and sizes. This variety of capacities and configurations permits conclusions to be drawn on the suitability of CWF conversion for several types of boilers.

TABLE 6-1 STUDY UNIT DESCRIPTIVE DATA

UNIT A

USE: Utility Steam Generator
CONFIGURATION: Close-coupled Screen (See Figure 6-1)
PLANT ELECTRICAL CAPACITY: 600 MW
MANUFACTURER: Combustion Engineering
ORIGINAL FUEL: No. 6 Oil
FIRING SYSTEM: Tilting Tangential Burners (5 Elevations)
STEAM TEMP CONTROL: Burner Tilt, Gas Recirculation,
MAIN STEAM FLOW: 4,200,000 lb/hr
MAIN STEAM TEMP.: 1005 F
MAIN STEAM PRESS.: 2,600 psig
REHEAT STEAM FLOW: 3,881,000 lb/hr
REHEAT STEAM TEMP.: 1005 F
REHEAT STEAM PRESS.: 607 psig
AIR PREHEATERS: Two Regenerative Plus Steam Coils
FLUEGAS CLEANUP: Electrostatic Precipitators

UNIT B

USE: Utility Steam Generator
CONFIGURATION: Box (See Figure 6-2)
PLANT ELECTRICAL CAPACITY: 400 MW
MANUFACTURER: Combustion Engineering
ORIGINAL FUEL: No. 6 Oil
FIRING SYSTEM: Tilting Tangential Burners (4 Elevations)
STEAM TEMP CONTROL: Burner Tilt, Superheat and Reheat Spray
MAIN STEAM FLOW: 2,833,000 lb/hr
MAIN STEAM TEMP.: 955 F
MAIN STEAM PRESS.: 1980 psig
REHEAT STEAM FLOW: 2,734,000 lb/hr
REHEAT STEAM TEMP.: 955 F
REHEAT STEAM PRESS.: 447 psig
AIR PREHEATERS: Steam Coil
FLUEGAS CLEANUP: Electrostatic Precipitators

**FIGURE 6-1
UNIT A
UTILITY STEAM GENERATOR
CLOSE-COUPLED SCREEN**

SIDE VIEW

**FIGURE 6-2
UNIT B
UTILITY STEAM GENERATOR BOX**

TABLE 6-1 (Continued)

UNIT C

USE: Utility Steam Generator
CONFIGURATION: Close-coupled Arch (See Figure 6-3)
PLANT ELECTRICAL CAPACITY: 850 MW
MANUFACTURER: Foster Wheeler
ORIGINAL FUEL: No. 6 Oil
FIRING SYSTEM: Wall-fired Burners (32)
STEAM TEMP CONTROL: Gas Recirculation, Gas Pass Baffling, Superheat and
Reheat Spray
MAIN STEAM FLOW: 6,300,000 lb/hr
MAIN STEAM TEMP.: 1005 F
MAIN STEAM PRESS.: 2480 psig
REHEAT STEAM FLOW: 5,722,000 lb/hr
REHEAT STEAM TEMP.: 1005 F
REHEAT STEAM PRESS.: 693 Psig
AIR PREHEATER: Two Regenerative Plus Two Hot Water Coils
Plus Two Glycol Heaters
FLUEGAS CLEANUP: Electrostatic Precipitators

UNIT D

USE: Industrial Saturated Steam Generator
CONFIGURATION: Type-A Shop-assembled (See Figure 6-4)
MANUFACTURER: Combustion Engineering
ORIGINAL FUEL: No. 6 Oil
FIRING SYSTEM: Wall-Fired Burners (2)
STEAM TEMP CONTROL: None Required
MAIN STEAM FLOW: 100,000 lb/hr
MAIN STEAM TEMP.: 388 F (Saturated)
MAIN STEAM PRESS.: 200 psig
AIR PREHEATERS: None
FLUEGAS CLEANUP: None

SIDE VIEW

**FIGURE 6-3
UNIT C
UTILITY STEAM GENERATOR
CLOSE-COUPLED ARCH**

FIGURE 6-4
UNIT D
INDUSTRIAL SHOP-ASSEMBLED STEAM GENERATOR

TABLE 6-1 (Continued)

UNIT E

USE: Industrial Steam Generator
CONFIGURATION: VU-60 Modular (See Figure 6-5)
MANUFACTURER: Combustion Engineering
ORIGINAL FUELS: (1) 90% Pyrolysis Oil Plus 10% Fuel Gas
 (2) 90% Distillate Oil Plus 10% Fuel Gas
PRESENT FUEL: Natural Gas
FIRING SYSTEM: Tangential Burners (2 Elevations)
STEAM TEMP CONTROL: Superheat Spray
MAIN STEAM FLOW: 400,000 lb/hr
MAIN STEAM TEMP.: 910 F
MAIN STEAM PRESS.: 1550 psig
AIR PREHEATERS: Regenerative
FLUEGAS CLEANUP: Tubular Dust Collector

UNIT F

USE: Crude Oil Heater
CONFIGURATION: Vertical Cylindrical (See Figure 6-6)
DESIGNER: C-E Lummus
ORIGINAL FUEL: Byproduct Oil
FIRING SYSTEM: Hearth-fired Vertical Burners (8)
PROCESS TEMP CONTROL: Firing Rate
PROCESS FLUID FLOW: 494,000 lb/hr
FIRING RATE: 71 MM Btu/hr
AIR PREHEATER: Regenerative
FLUEGAS CLEANUP: None

UNIT G

USE: Crude Oil Heater
CONFIGURATION: Horizontal Cabin (See Figure 6-7)
DESIGNER: C-E Lummus
ORIGINAL FUEL: Byproduct Oil
FIRING SYSTEM: Hearth-fired Vertical Burners (20)
PROCESS TEMP CONTROL: Firing Rate
PROCESS FLUID FLOW: 466,000 lb/hr
FIRING RATE: 142 MM Btu/hr
AIR PREHEATER: Regenerative
FLUEGAS CLEANUP: None

FIGURE 6-5
UNIT E
INDUSTRIAL STEAM GENERATOR MODULAR

FIGURE 6-6
UNIT F
VERTICAL CYLINDRICAL CRUDE OIL HEATER

FIGURE 6-7
UNIT G
HORIZONTAL CABIN CRUDE OIL HEATER

Performance Analysis

The thermal performance of each of the seven study units was analyzed for each of four Coal Water Fuels below. The four CWFs are among twelve CWFs which were tested in Task 5. The four study fuels are:

- * Upper Freeport 6.8% Ash (UF6.8)
- * Splash Dam 5.7% Ash (SD5.7)
- * Cedar Grove 7.9% Ash (CG7.9)
- * Cedar Grove 4.8% Ash (CG4.8)

In addition, a fifth Coal Water Fuel, Splash Dam 2.6% ash (SD2.6), was evaluated for Unit C. This fuel produced considerably less erosion of the test section in the Task 5 portion of the laboratory tests. Unit C was chosen as the one unit having the potential for the greatest load increase with this fuel. Unit B was capable of only a minor load increase, while the remaining units were limited by other criteria. A sixth Coal Water Fuel, Alma 5.9% ash (AL 5.9), was evaluated for utility units A and C and industrial Unit E. The fine grind version of this CWF produced considerably less erosion of the test section used in the Task 5 laboratory tests.

These particular fuels were chosen to provide a basis for predicting the effects of:

- * Ash Slagging and Fouling Characteristics
- * Ash Quantity and the Effect of Coal Cleaning
- * Erosion Potential

The detailed analysis of each fuel is shown in Table 6-2. Each of the CWFs was tested in the C-E laboratory facilities under Tasks 4 and 5. Based on the results of the laboratory testing and on general principles which have been developed for CWF firing and operation, the following guidelines were defined for use in predicting the CWF performance of the units.

TABLE 6-2 ANALYSIS FOR EACH COAL WATER FUEL

Fuel Type	<u>UF6.8</u>	<u>SD5.7</u>	<u>CG7.9</u>	<u>CG4.8</u>	<u>SD2.6</u>	<u>AL5.9</u>
Proximate, Wt. %						
Moisture (Total)	30.4	30.6	30.9	32.1	30.3	36.0
Volatile Matter	23.1	21.0	22.6	23.0	21.6	23.9
Fixed Carbon (Diff.)	41.8	44.4	41.0	41.5	46.3	36.3
Ash	4.7	4.0	5.5	3.3	1.8	3.8
Total	100.0	100.0	100.0	100.0	100.0	100.0
HHV, Btu/lb	9,785	10,125	9,410	9,680	10,535	8,803
LB Ash/MM Btu	4.8	3.9	5.8	3.4	1.7	4.3
Ultimate, Wt. %						
Moisture (Total)	30.4	30.6	30.9	32.1	30.3	36.0
Hydrogen	3.5	3.4	3.5	3.3	3.5	3.0
Carbon	55.0	56.8	53.7	54.3	59.7	50.6
Sulfur	1.2	0.5	.6	.5	0.5	1.0
Nitrogen	1.0	1.0	1.1	1.0	1.3	1.0
Oxygen (Diff.)	4.2	3.7	4.7	5.4	2.8	4.5
Ash	4.7	4.0	5.5	3.3	1.8	3.8
Total	100.0	100.0	100.0	100.0	100.0	100.0
Ash Fusibility, °F						
I.T.	1,980	2,390	2,350	2,350	2,270	1920
S.T.	2,270	2,770+	2,600	2,600	2,700+	2240
H.T.	2,390	2,770+	2,700+	2,700+	2,700+	2390
F.T.	2,460	2,770+	2,700+	2,700+	2,700+	2510
Ash Composition, Wt. %						
SiO ₂	45.3	57.1	54.2	54.2	47.1	48.9
Al ₂ O ₃	24.7	27.2	26.4	26.4	30.8	22.8
Fe ₂ O ₃	21.5	7.4	8.8	8.8	11.7	18.0
CaO	1.6	0.9	2.0	2.0	2.2	3.9
MgO	0.7	0.8	1.0	1.0	0.6	0.7
Na ₂ O	0.4	0.8	.4	.4	1.9	0.7
K ₂ O	2.5	2.1	2.4	2.4	1.1	1.3
TiO ₂	2.1	2.1	2.2	2.2	1.6	1.8
SO ₃	0.6	1.4	1.2	1.2	1.4	1.0
Total	99.4	99.8	98.6	98.6	98.4	99.1

The furnace operating limits and parameters are as follows:

1. Excess Air (Normal Operation): 25%
(If unit loads could be raised by using higher air flow 30% excess air was used.)
2. Minimum Air Preheat Temp.: 300 F
3. Maximum Furnace Liberation (Q fired/furnace volume):
25,000 Btu/hr-ft³
(This was limited to ensure adequate carbon conversion efficiency.)
4. Gas Recirculation - Was limited as a function of furnace liberation, excess air, and injection location to ensure that the gas recirculation did not adversely affect carbon conversion.

With the above operating limits met, carbon conversion efficiency (% of total carbon burned) was estimated to be 99%. This value was used for calculation of boiler efficiency and related operating parameters. For the fine grind AL5.9 CWF, carbon conversion efficiency was estimated to be 99.5%.

Additional furnace operating limits (related to avoiding excessive furnace slagging) were:

1. Net Heat Input/Plan Area: Less than 2.1×10^6 Btu/hr-ft²
2. Burner Zone Heat Release: Less than 650×10^3 Btu/hr-ft²

For the SD2.6 fuel, these limits were relaxed and allowed to increase to 2.36×10^6 Btu/hr-ft² and 860×10^3 Btu/hr-ft², respectively, because of the low ash content of this fuel. Relaxing these limits took advantage of the 129 ft/sec Gas Velocity Limit established for this SD 2.6 CWF.

The convection bank performance limits include:

1. Erosion Velocity Limit

Laboratory tests of erosion potential yielded the following Gas Velocity Limits (based on a 2 mil per 10,000 hr metal loss rate criterion):

	FUEL					
	UF6.8	SD5.7	CG7.9	CG4.8	SD2.6	AL5.9
Velocity Limit (ft/sec):	69	79	51	76	129	84

These limits apply to cross flow conditions and are average velocities at the bank. In certain convection bank arrangements these limits are adjusted to allow for possible high local velocities relative to the average. In addition, allowable velocities are reduced by 10% for load-supporting tubes.

2. Clear Space Limits

To minimize convection bank plugging, limits were established for the maximum gas temperature entering the convection banks. The temperature limits are a function of the clear space between adjacent tube assemblies. These limits are based on lab test results and previous field experience with coal firing.

Due to the present lack of field test results to confirm the laboratory results, a somewhat conservative approach was taken in establishing the guidelines. Use of these guidelines would therefore be unlikely to result in serious overestimation of a particular unit's load capability when firing CWF. On the other hand, there is the distinct possibility that data from future field test programs will justify the use of more liberal load limit criteria. The economic analysis was therefore conducted for two loads with each fuel-unit combination.

* Load based on criteria defined in this section.

* Load based on assumption that a more liberal set of criteria might be valid (a 20% increase in load capacity over the conservative limit was assumed.)

Tables 6-3 and 6-4 summarize general results of performance analyses for six fuels applied to some or all of the seven units selected for this study. A total of 32 combinations were considered. The summary shows that the deratings ranged from zero (for the two process heaters) to 77% (for the Type-A shippable unit). The principal load limiters proved to be:

* Gas Velocity Limit	-	12 cases
* Clear Space Temperature Limit	-	13 cases
* Furnace Liberation	-	3 cases
* Burner Zone Release Rate Limit	-	2 cases
* NONE	-	8 cases
TOTAL		38 cases*

*Note - the total of cases is greater than the total of combinations because on some combinations more than one limiter applied.

In general, the UF6.8 fuel represented the most restrictive fuel. This was usually because of the Clear Space Temperature Limit for this fuel, which was 200 F lower than the Limit for the remaining fuels. In contrast, the SD2.6 fuel used for the special study on Unit C represented the best fuel from the derating standpoint due to the high allowable Gas Velocity Limit (129 ft/sec).

TABLE 6-3 GENERAL RESULTS OF PERFORMANCE ANALYSIS

UNIT	TYPE	CWF	LOAD LIMITED BY	
			MAX LOAD (%)	*
A	U	UF6.8	Clear Space at Upper Finishing SH;	33
A	U	SD5.7	Clear Space at Upper Finishing SH; Gas velocities at RH Front Crossover, Rear LTRH, WW Screen	74
A	U	CG7.9	Gas velocity at RH Front Crossover, WW Screen, Rear LTRH	44
A	U	CG4.8	Clear Space at Upper Finishing SH; Gas velocity at RH Front Crossover, Rear LTRH, WW Screen.	71
A	U	AL5.9	Clear Space at Upper Finishing SH; Gas Velocities at RH Front Crossover, Rear LTRH, WW Screen	73
B	U	UF6.8	Clear Space at Finishing Reheater	30
B	U	SD5.7	Gas Velocity at Rear LTSH	50
B	U	CG7.9	Gas Velocity at Rear LTSH	31
B	U	CG4.8	Gas Velocity at Rear LTSH	48
C	U	UF6.8	Clear Space at SH Platen	45
C	U	SD5.7	Gas Velocity - LTSH Cold (SH pass), Horiz RH #2 (RH Pass)	73
C	U	CG7.9	Burner Zone Release Rate Limit	46
C	U	CG4.8	Gas Velocity - Horiz RH #2 (RH pass)	70
C	U	SD2.6	Gas Velocity - LTSH Cold (SH pass), Horiz RH #2 (RH Pass)	95
C	U	AL5.9	Clear Space, SH Platen; Gas velocity, Horiz RH #2 (RH pass)	71
D	I	UF6.8	Gas Velocity - LTSH Cold (SH Pass), Horiz RH #2 (RH Pass); Burner Zone Release Rate	23
D	I	SD5.7	Clear Space at Boiler Bank	30
D	I	CG7.9	Furnace liberation (BTU fired/furnace volume)	29
D	I	CG4.8	Furnace liberation (BTU fired/furnace volume)	30
E	I	UF6.8	Furnace liberation (BTU fired/furnace volume)	33
E	I	SD5.7	Clear Space at Spaced SH	54
E	I	CG7.9	Clear Space at Spaced SH	52
E	I	CG4.8	Clear Space at Spaced SH	53
E	I	AL5.9	Clear Space at Spaced SH	52
F	P	UF6.8	No Limit	100
F	P	SD5.7	No Limit	100
F	P	CG7.9	No Limit	100
F	P	CG4.8	No Limit	100
G	P	UF6.8	No Limit	100
G	P	SD5.7	No Limit	100
G	P	CG7.9	No Limit	100
G	P	CG4.8	No Limit	100

*Utilities (Units A, B, C) % maximum electrical output to grid. Industrial (Units D, E) % of MCR steam generated

"TYPE" code: U = Utility I = Industrial P = Process Heater

TABLE 6-4 GENERAL SUMMARY OF OPERATING CONDITIONS FIRING CWF

UNIT	TYPE	CWF	MAX LOAD %	MAIN STEAM FLOW (M lb/hr)	FIRING RATE (MMBtu/hr)	EXCESS AIR (%)	GAS RECIRC. (%)	BURNER TILT (DEG)	SHOT (°F)	RHOT (°F)
A	U	UF6.8	33	1386	2083	30	25	+23	1005	952
A	U	SD5.7	74	3024	4263	25	9	-18	1005	960
A	U	CG7.9	44	1806	2705	25	13	+30	1005	955
A	U	CG4.8	71	2898	4127	25	9	-12	1005	955
A	U	AL5.9	73	2967	4285	25	9	-21	1005	977
B	U	UF6.8	30	907	1442	30	0	+13	955	912
B	U	SD5.7	50	1388	2180	25	0	+13	955	930
B	U	CG7.9	31	907	2108	25	0	+30	955	943
B	U	CG4.8	48	1332	1456	25	0	+19	955	936
C	U	UF6.8	45	2709	3941	25	0	0	1005	1004
C	U	SD5.7	73	4410	6096	25	0	0	1005	1005
C	U	CG7.9	46	2835	4043	25	0	0	1006	958
C	U	CG4.8	70	4221	5890	25	0	0	1006	1007
C	U	SD2.6	95	5544	8057	25	9	0	1005	1005
C	U	AL5.9	71	4260	6081	25	0	0	1005	1005
D	I	UF6.8	23	21	26	25	0	0	388	-
D	I	SD5.7	30	28	33	25	0	0	388	-
D	I	CG7.9	29	27	33	25	0	0	388	-
D	I	CG4.8	30	28	33	25	0	0	388	-
E	I	UF6.8	33	132	176	25	0	0	910	-
E	I	SD5.7	54	215	288	25	0	0	910	-
E	I	CG7.9	52	209	283	25	0	0	910	-
E	I	CG4.8	53	210	283	25	0	0	910	-
E	I	AL5.9	52	208	282	25	0	0	910	-
F	P	UF6.8	100	494*	59	30	0	-	-	-
F	P	SD5.7	100	494*	59	30	0	-	-	-
F	P	CG7.9	100	494*	59	30	0	-	-	-
F	P	CG4.8	100	494*	59	30	0	-	-	-
G	P	UF6.8	100	466*	117	30	0	-	-	-
G	P	SD5.7	100	466*	117	30	0	-	-	-
G	P	CG7.9	100	466*	117	30	0	-	-	-
G	P	CG4.8	100	466*	117	30	0	-	-	-

* Denotes Process Fluid Flow

"TYPE" code: U = Utility

I = Industrial

P = Process Heater

The SD5.7 fuel caused the minimum derating of the remaining five fuels, usually because of its high allowable Gas Velocity Limit (79 ft/sec). The CG4.8 fuel usually came close to the SD5.7 fuel in maximum load, since its slagging and fouling characteristics closely approximate SD5.7, and its allowable Gas Velocity Limit is almost the same (76 ft/sec). The AL5.9 fuel had deratings close to SD5.7 and CG4.8 for the three units in which it was studied (Units A, C, and E).

The CG7.9 fuel usually fell between the UF6.8 and CG4.8 fuels in derating. This was mainly because of its low (51 ft/sec) allowable Gas Velocity Limit compared to CG4.8 (76 ft/sec) and its Clear Space Temperature Limit (which was 200°F higher than for the UF6.8 fuel).

Generally speaking, the AL5.9 CWF, in the absence of fine grinding, should have performance characteristics similar to UF6.8. Fine grinding, however, permits an improved allowable Gas Velocity Limit (84 ft/sec) compared to UF6.8 (69 ft/sec). Also, the Clear Space Temperature Limit is set at the same level as the Cedar Grove and Splash Dam - based fuels. It is likely that without fine grinding the Clear Space Temperature Limit would have been 150°F lower.

For five fuels - UF6.8, SD5.7, CG7.9, CG4.8 and AL5.9 - the Utility units showed a wide range of derating requirements ranging from 26% to as much as 70% load derating. This range reflects the wide variety of configurations which are encountered in this type of service. These units are not easily characterized and must be analyzed on a case-by-case basis. For the special study of SD2.6 fuel on Unit C, the derating was only 5% due to the extra low ash and low erosion potential of this fuel.

Both Industrial Units required significant load derating, due primarily to the high design furnace loadings which generally have been incorporated into these boilers since 1960. The load derating ranged from 46% to as much as 77%.

The crude oil heaters appeared to require no derating. This is due to the very low design furnace loadings and gas velocities, which are generally characteristic of this equipment.

Retrofit Equipment Selection

In converting a plant to fire a Coal Water Fuel, the ash content of the fuel is a major factor. A large portion of the cost of most retrofits can be attributed to the need to collect and remove the ash after combustion. Other factors which can be significant include: burner and windbox modifications, SO₂ removal requirements, metal temperature limitations, controls, and fuel supply and storage equipment.

Each of the seven units has been analyzed for the requirements of conversion to CWF firing using the guidelines. The scope of work varies from unit to unit and from fuel to fuel. The major changes to the "boiler island" are shown in Figures 6-8 through 6-14. Descriptions of the changes for Units A, E and G follow the figures.

FIGURE 6-8
UNIT A
MAJOR BOILER ISLAND MODIFICATIONS

HIGHLIGHTS OF RETROFIT SELECTION - UNIT "A"

600 MW CLOSE-COUPLED SCREEN TYPE

FIGURE 6-8

1. FURNACE -- all five fuels studied

The hopper slope is sufficient not to require modification. However, other changes are required as follows:

Install a gas recirculation inlet into the rear side of the hopper mouth. Set back every other tube 12 inches to provide inlet. Modify rear hopper support system to accommodate and support new gas recirculation duct and maintain support of rear lower drum to support tubing from drum, and install new horizontal main buckstay support struts and lateral support beams in the rear lower drum area.

Install gas recirculation duct in dead space between rear furnace slope and furnace rear wall tubes running vertically from rear lower drum. Line with refractory and insulation, and support with hanger rods. Provide two shut-off dampers in GR duct outside of dead space. Run two separate ducts into a single divided duct which connects to existing GR duct. Provide ash collection hoppers at bottom end of GR duct. Install 5 small hoppers having 55 degree slopes to avoid excavation work. Also remove existing GR "box" and duct, relocate seals at outlet of hopper to provide for wet ash collection system, and relocate platform.

Install "jet system" to assist bottom ash to move down hopper slopes to hopper mouth. Install 3 plenums on each hopper slope. Plenums are 4" OD tube 57 ft long welded to back side of hopper slope tubes. Drill 1/4" diameter holes in fusion welded walls in hopper slope and weld deflector plate over each hole to deflect jet down the slope. Install supply lines, main shut-off valve, on-off control valves, distribution headers, and control panel. Blowing medium is to be steam taken from existing plant steam supply.

2. BLOWERS

New soot blowers, plus pressure parts work at the new sites will be required as follows:

Furnace Wall Blowers - 72 for UF 6.8, CG 7.9; 50 for SD 5.7, CG 4.8, AL5.9

Double side retract blowers - 10 for all five fuels.

3. FIRING SYSTEM

For all five fuels, convert existing 5 elevations of oil burners to 6 elevations of combined oil/cwf burners. The existing windbox opening can be used for firing UF 6.8 and CG 7.9 fuels, but will have to be 4'4" taller for the remaining fuels. Compartment partition plates will have to be relocated, and new secondary air control dampers will be required. New openings will have to be made in waterwalls to accommodate new and/or relocated ignitors. About 20 waterwall tubes will have to be modified for the taller windbox used for the CG 4.8, SD 5.7 and AL5.9 fuels.

4. CONVECTION SECTION MODIFICATIONS

Revise RH crossover arrangement to reduce gas velocities for SD 5.7, CG 7.9, CG 4.8, and AL5.9 fuels. Change material of SH Front Horizontal Spaced Lower Assemblies to accommodate higher metal temperatures as follows: SA 213 TP 304 H for UF 6.8 and CG 7.9.

5. SH or RH Spray

Install larger capacity SH spray control valves.

6. ECONOMIZER

Replace the existing bank by a taller in-line spiral finned bank with wider horizontal spacing between tubes. Replace both inlet and outlet economizer headers.

7. ASH HOPPER REVISIONS

Fabricate new ash hoppers at economizer outlet and in the Gas Recirculation duct.

8. STRUCTURAL SUPPORT

Stiffen support steel in economizer hanger attachment area.

Install support steel for ESP addition (SD 5.7 and AL5.9).

Install support steel for scrubbers required for UF 6.8, CG 7.9, and AL5.9.

Install support steel for revised gas recirculation duct system as discussed in Item 1.

9. PARTICULATE COLLECTOR

For the SD 5.7 and AL5.9 fuels install a 20% addition to the existing electrostatic precipitator. The remaining three fuels do not require changes to the ESP.

10. SO₂ REMOVAL EQUIPMENT

Install a new Dry Scrubber upstream of the existing ESP for the UF6.8, CG7.9, and AL5.9 fuels.

11. DUCTWORK

Install new duct segments to accommodate addition to existing ESP for SD5.7 and AL5.9. For UF 6.8, CG 7.9 and AL5.9 install new ductwork to new scrubber located upstream of existing ESP. Install connecting ductwork from scrubber to ESP, and provide new shut-off dampers so that scrubber can be isolated when firing oil.

SIDE VIEW

**FIGURE 6-9
UNIT B
MAJOR BOILER ISLAND MODIFICATIONS**

FIGURE 6-10
UNIT C
MAJOR BOILER ISLAND MODIFICATIONS

**FIGURE 6-11
UNIT D
MAJOR BOILER ISLAND MODIFICATION**

FIGURE 6-12
UNIT E
MAJOR BOILER ISLAND MODIFICATION

HIGHLIGHTS OF RETROFIT SELECTION -- UNIT "E"
FIELD ASSEMBLED INDUSTRIAL BOILER
FIGURE 6-12

1. FURNACE

Install grate blocks over furnace floor tubes. Every third row of grate blocks to have a jetting block supplied from new headers installed below the furnace floor. The jet system will push the ash toward the furnace floor hopper located adjacent to the lower drum.

2. BLOWERS

Install two elevations of wall blowers above the burners. There will be a total of twelve wall blowers required for the unit - four in each wall. Install two new single side retractable soot blowers between the superheater banks. Make necessary pressure parts alterations at each wall and soot blower penetration. Install new control panel equipment and controls.

3. FIRING SYSTEM

Open existing windbox width from 14 to 16 inches wide. Relocate about six tubes and rework shell and casing on one side of each windbox. Relocate existing 3" pipe ignitors to intermediate auxiliary compartment and aim at CWF guns. Open the four existing 10 inch diameter overfire air ports, and run duct to them from main windbox. Upgrade the control system to accommodate the new firing system.

4. ASH HOPPER

Install ash hopper at the gas outlet adjacent to the boiler bank outlet.

5. PARTICULATE COLLECTOR AND SO₂ REMOVAL

Install an electrostatic precipitator (ESP) for the two fuels which do not require scrubbers (SD5.7 and CG4.8). For the remaining three fuels (UF6.8, CG7.9 and AL5.9) install a "Dry Scrubber/ESP". This device will remove the flyash from the gas stream at the same time it removes the SO₂. A bypass duct will permit the boiler to operate on oil at MCR without passing the gases through the ESP or dry scrubber/ESP.

6. NEW DUCTWORK

Install new bypass ductwork and damper box around air preheater. Remove existing dust collector and relocate stack. Run new ductwork to electrostatic precipitator (ESP) (CG 4.8 and SD 5.7). Run new ductwork to ESP and scrubber (UF 6.8, CG 7.9 and AL5.9). Install ductwork to bypass the new scrubber when original design fuels are in use. Install damper boxes in ductwork to control bypass flow around scrubber when original fuels are in use. The ESP, scrubber, and stack serve two units. Install shut-off dampers for situation when only one of the units is operating.

7. MODIFICATIONS TO EXISTING DUCTWORK

The UF 6.8, CG 7.9 and AL5.9 fuels will require new scrubbers. Modify the existing vertical duct running from the air heater outlet to the lower Electrostatic Precipitators (ESP's) as follows: install a take-off tee in the right and left vertical sidewall of the duct just below the existing lower ESP, so that gas can be passed horizontally to each of the new scrubbers erected to the right and left of the ESP. Above the lower pair of take-off tees, install a pair of return tees to handle the gas downstream of the scrubbers. Install isolation dampers in each take-off and return tee. Adjacent to the tees, install reducer sections configured so that 20 x 20 ft. ductwork can be run to and from the scrubbers. Install about 200 running feet of ductwork, including 8 expansion joints. Provide structural support for the duct runs approximately 70 feet above grade, plus insulation and lagging.

8. ASH REMOVAL

Install a mechanical ash removal system to handle ash from the various hoppers, ESP or dry scrubber/ESP. Ash disposal is to be off site.

9. FUEL SUPPLY AND STORAGE

Install to comply with retrofit Guidelines.

**FIGURE 6-13
UNIT F
MAJOR BOILER ISLAND MODIFICATIONS**

FIGURE 6-14
UNIT G
MAJOR BOILER ISLAND MODIFICATIONS

HIGHLIGHTS OF RETROFIT SELECTION -- UNIT "P"

VERTICAL CYLINDRICAL PROCESS HEATER

FIGURE 6-13

1. FURNACE

Note that this furnace is a cylindrical chamber. Modify the bottom to accept ash removal equipment since ash will collect at the bottom when firing CWF. Since a vertical CWF burner is to be centered in the bottom of the radiant chamber, the ash hopper must form an annulus around the burner.

2. BLOWERS

Install radiant chamber wall blowers - blowers to be conventional coal-fired utility-type units. The dense castable refractory behind the wall tubes can withstand the wall blowing duty and does not need to be changed. Four levels of blowers are required. These blowers will keep the tube surfaces clean in order to avoid heat flux changes and possible decomposition of the process fluid in the tubes.

3. FIRING SYSTEM

Horizontal firing in the vertical cylindrical heater presents a problem, as there is no wall without tubes in front of it and the diameter of the tube circle is not large enough to insure that flame impingement does not occur on the tubes opposite the burner. From a search of the literature, it does not appear that vertical firing of coal has as yet been attempted in process heaters. It is probable that such firing would be successful, however, since C-E's Fireside Performance Test Facility fires pulverized coal and CWF in a vertical burner and has logged many hours of satisfactory operation.

Install a single large-capacity burner centered in the bottom of the radiant chamber. Make provision for dual fuel burner capability (CWF and stand-by oil), and provide a system to insure rapid transition from CWF firing to oil. Provide a new windbox for the burner which must be compatible with the annular ash hopper equipment. Also provide new ignitor and scanner.

This design would permit near optimum uniformity of heat input into the process tubes while allowing maximum room for ash collection.

4. CONVECTION SECTION CHANGES

Although the tube and fin tip clearances and flue gas velocities in the convection sections of both heaters are within the Guidelines, the fin spacing per inch and the staggered arrangement are not.

Replace existing spiral finned staggered-tube banks with shop-fabricated spiral finned in-line banks with fin spacing meeting Guidelines. The new convection section designs are to meet full load oil performance.

5. ASH HOPPER REVISIONS

Since sootblowers will be installed in the air preheaters to provide adequate cleaning, add a new ash collection hopper at the air preheater outlet.

6. FANS

Replace the existing induced draft (ID) and forced draft (FD) fans. The new flue gas cleanup equipment increases the static pressure requirements for the ID fan. The high pressure drop characteristic of the new burner increases the FD fan static pressure requirement. Also install a new standby full capacity FD fan with a different drive to provide standby firing capability should the primary FD fan go out of service.

7. DUCTWORK REVISIONS

Since ductwork was designed for low velocities (30 fps), and there are horizontal sections where flyash can settle, install ash collection hoppers at strategic locations in these ducts. Additional ducts, connecting the new flugas cleanup equipment to the existing equipment, will also be required.

8. PARTICULATE COLLECTOR/SO₂ REMOVAL

The most economical choice of equipment is a wet scrubber which is capable of handling both particulate removal, and SO₂ removal where required.

CWF Retrofit Cost Estimates and Economic Evaluations

The approach for developing capital costs and operating and maintenance cost estimates for the CWF retrofits were similar to the procedures used in EPRI Studies*, with minor modifications where appropriate. An economic evaluation is presented for the seven units. This evaluation defines the incremental costs and savings as a result of the use of CWF as a substitute fuel for oil. The economic results are presented both as first year and levelized costs. The first year incremental operation and maintenance cost savings and the total capital requirement are used to determine a simplified payback period for all seven units. Also calculated for the utility units only are the total levelized annual revenue savings, specific levelized revenue savings, and incremental levelized cost of electricity savings.

There are several uncertainties involved in a study of this type. Two of the major uncertainties are the maximum load capability with CWF and the fuel costs. The predicted load capabilities were calculated using performance guidelines based on data developed in a small laboratory facility (4×10^6 Btu/hr heat input). Data from this laboratory test unit was used to predict slagging, fouling, and erosion behavior for the wide range of unit types and sizes in this study. These fuels have not been fired in units of the sizes or configurations of those used in this study. Because of this, many of the procedures used to develop the Performance Guidelines are not confirmed. Knowing these uncertainties, the developed Guidelines and the predicted load capabilities may be somewhat conservative. For these reasons the economic evaluation presented in this section also considers the sensitivity of higher than predicted load capability and its effect on economic feasibility. Economic evaluation results are presented for both the predicted load and a 20 percent increase over predicted load.

* "Technical Assesment Guide, "EPRI Report P 4463-SR, Volume 1, December, 1986.

The costs for producing CWF fuels in the quantities required for large scale commercial usage are not well established. Also the fairly rapid fluctuations in oil prices make it difficult to set fuel prices which would be appropriate. Because of these two uncertainties, sensitivities of the payback period and total levelized annual revenue savings to a range of differential fuel costs (DFCs) are presented.

In the units which experience a load derating (utility and industrial) the mode of operation is an important consideration. For the utility units two basic modes of operation are possible with CWF firing. In the first mode the retrofitted plant is assumed to burn CWF, but switches completely to fuel oil at peak demand. This operating mode assumes that the plant is derated on CWF but can regain its maximum capacity when switched to fuel oil. By designing the retrofit modifications with this dual fuel capability, it is possible to eliminate the necessity for the utility to purchase additional generating capacity to make up for the loss of capacity due to the derating.

Another possible operating mode would be having the retrofitted plant burn CWF for 100 percent of its operating time without switching to oil. In this mode the utility would have to purchase additional generating capacity.

There is a trade off to be made in comparing these two operating modes. In the second mode (no oil switching) capital costs would be higher due to the purchase of the additional generating capacity. However, since the unit is not required to switch to oil in periods of peak demand, the annual power generation with CWF would be higher and therefore fuel cost savings would be greater.

It was beyond the scope of this study to consider both operating modes for utility units. Only the oil switching operating mode has been studied in comparison to the base case where the unit burns fuel oil 100 percent of its operating time.

For the industrial steam generator units, results for two potential operating modes are considered. In the first operating mode (Case I) it is assumed the customer can afford to operate the derated unit on CWF 100 percent of its

operating time with no need to switch to oil at peak load demand. Also, no additional capacity is assumed to be purchased. In the second operating mode (Case II) it is assumed the customer must switch back to oil firing about 50 percent of the operating time, during which time the unit operates at its original maximum continuous rating. These two cases are compared to the base case where the unit is fired with fuel oil 100 percent of its operating time. The economic evaluation results for the industrial units are presented in terms of simplified payback period.

For the process heaters, for which there was no derating, the basis of the calculations assumes the heaters operate 95% of any calendar year (95% overall availability). A second assumption is that the total number of hours per year that the heaters operate while firing CWF and utilizing the air preheat system and flue gas clean up equipment is 90% of a calendar year (90% availability). A third assumption is that the number of hours that the heaters operate while firing fuel oil and without the air preheat system and flue gas cleanup equipment in operation is 5% of any calendar year. Thus the total availability of the heaters is 95% overall. Besides the primary 90%CWF-5% oil availability assumption, some pay-out period studies were done using 85%CWF-10% oil and 80%CWF-15% oil alternate availability assumptions. Results are discussed and plotted.

Capital Cost Estimates

Capital cost estimates for the CWF retrofit of seven major fuel burning installations were developed. The capital cost estimates for CWF retrofitting are divided into the following six basic categories:

- CWF Storage
- CWF Transfer
- Boiler Island
- Particulate Removal System
- Flue Gas Desulfurization System
- Ash Handling System

The capital cost estimates were developed using various sources depending on unit type (Utility, Industrial or Process Heater). For the utility units, budget capital cost estimates ($\pm 20\%$) were developed for the Boiler Island, Particulate Removal System and Flue Gas Desulfurization System based on drawings, specifications and equipment lists.

The remaining categories for the utility units (CWF Storage, CWF Transfer, and Ash Handling System) were estimated using generalized cost plots as provided in EPRI guidelines*. Capital costs including direct costs, distributables, engineering services, and total contingency were plotted as a function of capacity for the various equipment groups. For this study these generalized costs were escalated from 2nd quarter 1983 to mid-1985 (about 12%).

For the industrial units and process heaters the generalized costs were used only for CWF Storage and CWF Transfer with the remaining categories requiring new estimates. Because of the preliminary nature of this retrofit feasibility study, the developed cost estimates are similar to the Class II preliminary estimate defined in the EPRI "Technical Assessment Guide". All estimates are based on mid 1985 wage and price levels.

Table 6-5 shows the capital costs for each study unit, with each of the four fuels (five fuels for Units A and E, six fuels for Unit C). The costs included the total plant investment, preproduction costs, and total capital requirements for the retrofit equipment described previously.

Figure 6-15 compares Specific Capital Requirements (SCRs) for the three utility units. The SCR ranges from about \$60/KW-derated to about \$420/KW-derated depending primarily on the load capability, or between about \$60-140 based on the nameplate capacity of the unit. The SCR plots for the microfine AL 5.9 fuel lie significantly above the other data for Units A and C respectively. The larger scrubber and the ESP addition contribute to the higher SCR for Unit A, while the larger scrubber requirement on Unit C raises its SCR.

* "CWS Conversion Guidelines", EPRI Report CS-3374, Volume 2, March, 1985.

TABLE 6-5

Total Capital Requirement

For Retrofit to CWF

(All costs in \$1000, BASED ON Mid 1985 wage & price levels)

<u>UNIT</u>	<u>FUEL</u>					
	<u>UF6.8</u>	<u>SD5.7</u>	<u>CG7.9</u>	<u>CG4.8</u>	<u>SD2.6</u>	<u>AL5.9</u>
A	65494	76676	76699	47548	-	124321
B	51599	37923	51094	37386	-	-
C	90831	47267	92213	46340	48606	117199
D	2839	2990	3029	3014	-	-
E	10703	9843	12731	9850	-	12845
F	7161	7161	7161	7161	-	-
G	11292	11292	11292	11292	-	-

FIGURE 6-15
SPECIFIC CAPITAL REQUIREMENT VS. LOAD CAPABILITY

Figure 6-16 shows a similar comparison for the industrial units. Costs range from about \$40 to \$125/lb steam/hr-derated, or from about \$25 to \$32/lb steam/hr based on the nameplate capacity. The primary dependence for the specific capital cost requirement is again load capability. The SCR plots for the microfine AL 5.9 fuel lie within the band of other data since changes in retrofit costs are relatively small regardless of the CWF in this study. Figure 6-17 compares all the unit SCRs on a Btu Fired basis. The smaller industrial units require about 1.5 to 2 times more capital per Btu Fired than do the utility units. The SCR plots for the microfine AL 5.9 fuel lie above the band for Utility Units A and C, and within the band for Industrial Unit E.

Revenue Savings and Payback Period

Using the plant cost and operating data, the impact of CWF firing is presented in terms of a simplified payback period, calculated by dividing the total capital requirement by the first year incremental annual O&M cost savings. Figure 6-18 shows payback periods for the utility Unit A for the study fuels as a function of Differential Fuel Costs (DFC). Figure 6-19 shows these same results in a slightly different manner by plotting payback period as a function of load capability. The top and bottom symbols correspond to DFCs of $1\$/10^6$ Btu and $2\$/10^6$ Btu, respectively. The payback periods run longer for the AL5.9 CWF vs. the others because of the larger scrubber system requirements and ESP addition on Unit A. Figure 6-20 combines and attempts to generalize the utility unit results by showing bands for payback period as a function of load capability at DFCs of $1\$/10^6$ Btu and $2\$/10^6$ Btu. This indicates the relative importance of load capability on the economic feasibility of conversion.

With a DFC of $1\$/10^6$ Btu, payback periods ranging from about 2 to 9 years are shown at load capabilities above 60%. At load capabilities below 50 percent, payback periods increase sharply as load capability is reduced. At the 50 percent load point, the band indicates payback periods from about 7 to 14 years. The band width is relatively narrow (about 3 years) at loads above 60 percent. The variations which cause this band width are due to site or fuel

FIGURE 6-16
SPECIFIC CAPITAL REQUIREMENT VS. LOAD CAPABILITY

FIGURE 6-18
PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST
UNIT A

FIGURE 6-19
PAYBACK PERIOD VS. LOAD CAPABILITY
UNIT A

FIGURE 6-20
ECONOMIC EVALUATION RESULTS UTILITY UNITS

specific differences such as the requirement for a retrofit electrostatic precipitator or flue gas desulfurization system as well as significant differences in unit sizes which reflect some economy of scale.

Results at the $2\$/10^6$ Btu DFC show less variation with payback periods below 6 years at loads above 40 percent. The band width at this DFC is reduced to about 2 years.

Figure 6-21 and 6-22 generalize the results for the two industrial units. For Case I with DFC's of \$1.00 and \$2.00 per million Btu, payback periods are between about 5 to 8 and 2 to 4 years, respectively, for loads greater than 50% MCR. For loads less than 50% MCR, payback periods are between about 8 to 20 and 4 to 8 years, respectively. In contrast, for Case II with DFC's of \$1.00 and \$2.00 per million Btu, payback periods run between about 10 to 20 years and 4 to 8 years, respectively, for loads greater than 50%. For loads less than 50% MCR, the situation is worse with payback periods as high as 22 to over 50 years, and 8 to 22 years, respectively.

All payback periods for the various process heater design combinations (single and twin) and fuel cost differentials are longer than two years - the pay back period considered economically attractive in the hydrocarbon processing industry for modifications of existing equipment. The payback period range is from 3.4 years for twin horizontal cabin heaters with the largest ($\$2.0/10^6$ Btu) fuel cost differential to 17.6 years for a single vertical cylindrical heater with the smallest ($\$1.0/10^6$ Btu) fuel cost differential. As the cost difference between CWF and fuel oil is presently closer to $\$1.0/10^6$ Btu than the pay back period range is more likely from 7.6 to 17.6 years.

Two additional graphs, Figures 6-23 and 6-24, show the effects of the degree of heater availability with regard to fuel use. In these cases, it was assumed that the total availability of the heaters is still 95% (as used earlier), however, the availability to fire CWF and fuel oil with their corresponding fuel consumption is varied from 90% to 85% and to 80%. The

FIGURE 6-21
ECONOMIC EVALUATION RESULTS INDUSTRIAL UNITS
CASE I OPERATING MODE

FIGURE 6-22
ECONOMIC EVALUATION RESULTS INDUSTRIAL UNITS
CASE II OPERATING MODE

FIGURE 6-23
PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST
UNIT F

FIGURE 6-24
PAYBACK PERIOD VS. DIFFERENTIAL FUEL COST
UNIT G

payback periods for the heaters using these alternate availability factors are longer (between 10 and 45 percent) than the payback period for the heaters using the availability factor that was established as the basis of the study.

The other economic consideration in evaluating the modification of the selected heaters for CWF firing is unit downtime to make the modifications. The required modifications are extensive. For the horizontal cabin heater, the modification work to the heater that requires the heater to be out of service includes:

- Removal and replacement of all heater surface, tube supports and refractories in the radiant chamber.
- Replacement of the convection section.
- Installation of hearth ash hopper.
- Addition of radiant sootblowers.
- Relocation of heater burners and fuel system.

These modifications would require at least two months of unit shutdown - more than a month longer than would be normally scheduled for a plant after a year or two of operation. In this particular case, this would result in the loss of production of over 1,140,000 barrels of product per heater that is converted. Using a typical \$1/BBL average product to feedstock price differential, this would result in over a million dollars of lost profit for the plant per heater that is converted while ignoring any additional unit downtime costs. Although these potential profits are not included in the pay back period projections for each heater, they are, in these cases, significant and cannot be ignored in the overall evaluation for converting the heaters to CWF firing.

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