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COMBUSTION AND FUEL CHARACTERIZATION OF COAL-WATER FUELS

VOLUME 3

BENCH-SCALE CHARACTERIZATION OF CHEMICAL, PHYSICAL AND COMBUSTION PROPERTIES OF COAL-WATER FUELS

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DISCLAIMER

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SUMMARY

Comprehensive bench-scale testing was conducted on a cross-section of coal-water fuels (CWFs) to define general fuel properties and to provide the bases for fuel selection for large-scale testing. Representative CWF samples were extensively characterized to establish essential chemical and physical properties, rheological data, stability with respect to storage, transportation, aging, weather (i.e. freezing/thawing), atomization, combustion, ash deposition and ash erosion.

The CWF fuels were prepared by established producers using their own technical approach (coal particle size distribution and loading, chemical additive package, etc.). Principle requirements were high solids loading, stabilized commercial fuels; particle top size control to avoid atomizer plugging; and assurance of pumping and handling capability.

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 CWFs by truck had no apparent effect on settling. The amounts of settling under the stationary storage and the transit conditions were generally insignificant as 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.

The viscosity measurements indicated that 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). Some of the CWFs exhibited pseudoplastic behavior while others showed dilatent characteristics. 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 complex rheology of CWFs.

CWF 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 considered low for steam coals, while the Alma and Upper Freeport coals have moderate ash deposition characteristics. Bench-scale results indicate all CWF feed 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 CWF feed 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.

Section 1

INTRODUCTION

Coal is one of the most economically attractive alternatives to oil or gas. However, to fire coal-based fuel in gas or oil designed boilers requires careful consideration of potential performance impacts and evaluation of plant modifications needed for conversion. In order to assess the commercial viability of coal-water fuels (CWFs), both combustion and fireside performance behavior must be evaluated to enable the prediction of potential unit derating, equipment modification and associated retrofit costs.

Combustion Engineering (C-E) was awarded a contract through the direction of U.S. Department of Energy, Pittsburgh Energy Technology Center (PETC), to characterize and evaluate the combustion performance of a significant cross-section of CWFs. The main objective was to develop a broad technological data base to assess the commercial application of these fuels.

As part of the overall program, C-E teamed with Gulf Research and Development Company (GR&DC) to conduct the bench-scale CWF characterization task (Task 2). Five high volatile, low sulfur bituminous coals from the Eastern United States were selected as CWF feed coals to provide a range of commercially significant fuel properties for testing. Detailed bench-scale handling, rheology, atomization, combustion, ash deposition and ash erosion data on the CWFs produced using these coals were obtained under this task. These data were subsequently used to develop testing strategy during other tasks, and to assist in interpretation of atomization and combustion test results.

This report (Volume 3) provides a review of the bench-scale characterization tests. Other results of the project are provided in the following volumes:

Volume 1	Task 1 to 6	Final Summary Report
Volume 2	Task 1 & Task 3	Selection and Procurement of Candidate Coal-Water Fuels with Commercial Potential

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	Commerical Application and Economics of Coal-Water Fuels

Section 2
TECHNICAL APPROACH

Task 2 was designed to provide detailed bench-scale data on transportation, storage, pumping, atomization, combustion, ash deposition and ash erosion properties of a cross section of CWFs. The characterization tests conducted are identified and briefly described below.

CWF Rheology/Atomization Characteristics

The CWFs were prepared from beneficiated coals by established producers using their own technical approach (coal particle size distribution, solids loading chemical additive package, etc.). These fuels were analyzed and tested for general CWF specifications which included the following.

Solid Loading:	68-70%
Particle Size:	<0.001% plus 30 mesh
	<0.05% plus 60 mesh
Viscosity:	<2800 Cp at 100 sec^{-1}
	<1.2 Power Law Exponent (0-100 sec^{-1})

Bench-scale viscosity tests were conducted over a range of low-to-high shear rates with the ultimate goal of correlating CWF rheology to piping, pumping and atomization qualities similar to those observed for commonly used fuel oils.

Variable low shear viscosity was measured in a Haake RV-100 viscometer over a range of 0 to 190 sec^{-1}, at 20°C, 30°C and 40°C. Viscosity at constant shear rate was also obtained at 100 sec^{-1} for 9.9 minutes to determine the shear sensitivity of CWFs.

Viscosity at higher shear rate ranges (1000 - 5000 sec^{-1}) was determined by Adelphi Center for Energy Studies (ACES) using an extension rheometer and a variable high shear viscometer. High shear viscosity measurements were made to better represent the conditions encountered in a CWF atomizer mixing chamber and existing orifice.

CWF Transportation and Storage Characteristics

A monitoring system designed by GR&DC (Figure 2-1) was used to evaluate the effects, if any, of transportation variables (i.e., time, temperature changes and vibration during transit, etc.) upon the properties of CWFs. Continuous measurements of outside ambient temperature, internal CWF temperature, vibration and tank pressure were performed during two cross-country journeys, each approximately 2,700 miles and one week duration. Periodic CWF sampling at different levels were conducted to obtain stability/settling data during transit.

Freeze-thaw tests and 16 day storage tests at constant temperatures of 20°C, 40°C and 60°C were run on several CWFs to evaluate storability. Settling rates at these temperatures were determined by periodically analyzing samples from the top, middle, bottom and drain of a 65 cm x 7.5 cm jacketed column. All CWF batches were tested after receipt for contamination.

CWF Piping, Pumping, Corrosion and Erosion Characteristics

Bench-scale tests were also conducted to evaluate the shear sensitivity, erosion and corrosion characteristics of CWFs. Test fuels were pumped and recycled through a test loop which contains a metal loss detector at high shear rates for five hours. The test metal specimen was weighed before and after exposure to the CWFs for abrasion/corrosion determination.

Fuel Combustion Reactivity

The relative ignition and burnout characteristics of the CWF feed coals were evaluated using proximate and ultimate analyses, and the volatile matter calorific value. In addition, a variety of supplemental tests were conducted to provide more detailed combustion information on these fuels. These tests included:

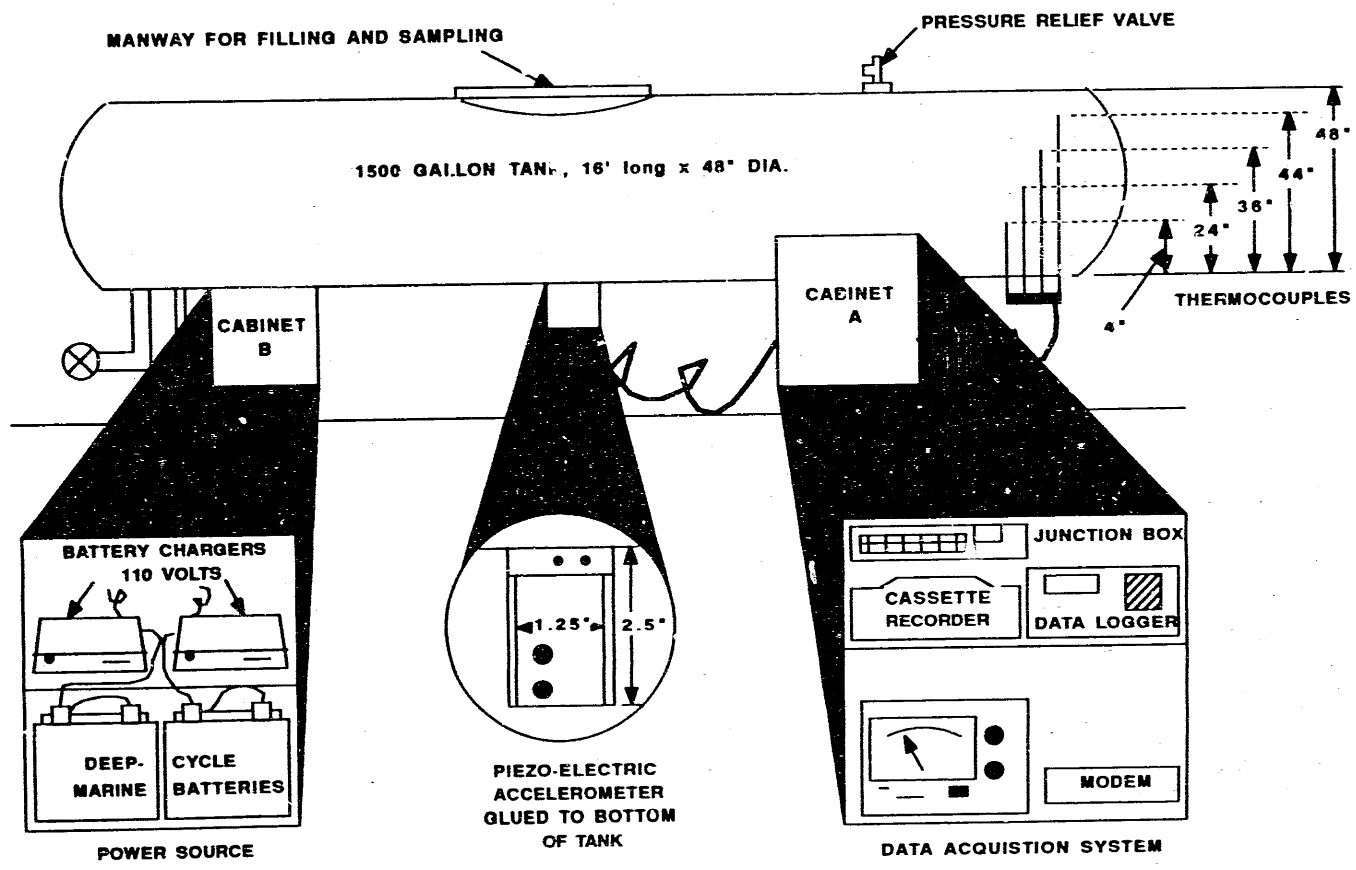

FIGURE 2-1 CWF TRANSPORTATION MONITORING SYSTEM

Flammability Index. The Flammability Index test was developed to provide relative ignition characteristics of a coal. Testing involves firing 0.2 gram of 200x0 mesh fuel in an oxygen atmosphere through a preheated furnace. The temperature of the furnace is increased until a point is reached where the fuel will ignite. This temperature is called the Flammability Index. The value of the Flammability Index compared to those of other fuels indicates the ignition temperature/flame stability on a relative basis.

Thermogravimetric Analysis (TGA). This technique was developed to provide a measure of fuel reactivity under controlled conditions. Char is prepared from coal in a nitrogen atmosphere at high temperature (2650°F) using a drop tube furnace system. It is then sized to obtain a 200 x 400 mesh fraction. This size fraction sample is placed in the Thermogravimetric Analyzer and heated to 1292°F in the presence of nitrogen. After stabilization at this temperature air is introduced to burn off the fixed carbon. A percent weight loss as a function of time thermogram is obtained and subsequently used to determine the char's relative burn-off rate.

Specific Surface Areas. This technique uses the principle of gas adsorption to measure the surface area of a coal's char. The surface area is one of the parameters which can be used to assess the char's apparent reactivity. Data obtained from nitrogen adsorption at 77°K were used in conjunction with the Brunauer Emmett and Teller (BET) equation to determine the specific surface area of coal char samples.

Drop Tube Furnace System (DTFS) Tests. The CWFs were evaluated in the DTFS for pyrolysis and combustion characteristics. Figure 2-2 shows a schematic of the DTFS. Detailed description of the facility is provided in Appendix A. The tests conducted in the DTFS are summarized in Table 2-1. Seven CWFs were carefully dried, broken up and size graded to obtain the 200 x 400 mesh and 100 x 200 mesh fractions for the pyrolysis tests in 100% nitrogen medium and the combustion tests in 5% oxygen/95% nitrogen medium respectively. The high temperature (2650°F) pyrolysis and combustion tests were conducted on each coal whereas low temperature (1900°F) tests were conducted on three coals

(Splash Dam high ash (SD5.7), Cedar Grove high ash (CG7.1) and Cedar Grove low ash (CG4.8)).

The swelling factors of three parent coals, Splash Dam High Ash (SD5.7), Upper Freeport Low Ash (UF6.8), and Cedar Grove High Ash (CG7.1) were also determined. This parameter is important from a combustion process modeling standpoint, because it dictates the particle size distribution of a char right after devolatilization of its parent coals; it, therefore, influences the char combustion rate. The swelling factor (α) was determined by a correlation established by C-E (1).

$$\alpha = \{(x_4 + x_8 + x_{16})/3\}x_0$$

where x_4, x_8, and x_{16} are the Rosin-Rammler mean weight particle sizes of pyrolyzed coal chars obtained at 4-, 8-, and 16-inch reaction zones of the DTFS, and X_o is the mean weight particle size of the feedstock.

Table 2-1

TEST MATRIX FOR PYROLYSIS AND COMBUSTION OF CWF COALS IN THE DROP TUBE FURNACE SYSTEM

Coal	Gas Temperature (°F)	Pyrolysis 200x400 Mesh (100% N_2)	Combustion 100x200 Mesh (5% O_2/95% N_2)
Lower Kittanning (LK 6.0)	2650	x	x
Splash Dam High Ash (SD 5.7)	1900 2650	x x	x x
Splash Dam Low Ash (SD 2.6)	2650	x	x
Upper Freeport High Ash (UF13.6)	2650	x	x
Upper Freeport Low Ash (UF 6.8)	2650	x	x
Cedar Grove High Ash (CG 7.1)	1900 2650	x x	x x
Cedar Grove Low Ash (CG 4.8)	1900 2650	x x	x x

CWF Combustion Process Modeling

CWF combustion process modeling was conducted 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 2-2. Essentially, the global char combustion kinetic information (i.e., apparent activation energy and frequency factor) and coal swelling factor determined from a drop tube furnace system (DTFS) are used in conjunction with fuel and boiler information via 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.

CWF Ash Properties

The behavior of the mineral matter in the CWF feed coals has a strong impact on retrofit performance, unit availability and life of steam generator components for CWF applications. Bench-scale analyses were conducted in order to provide information on the ash properties of the CWF feed coals.

Bench-scale ash slagging potentials were assessed by comparison of ash fusibility temperatures, ash content and conventional slagging indices such as base-to-acid ratio, iron-to-calcium ratio, etc., developed based upon the composition of the coal ash. In addition, gravity fractionation analysis was conducted to determine the amount of large, discrete pyrite particles in the fuel which have been shown to have a marked impact on furnace slagging.

Bench-scale ash fouling potentials were assessed by considering ash deformation and softening temperatures, and alkali content in the ash. In addition, weak acid leaching analysis was conducted to provide information on the form in which the alkalies are present in the fuels. Alkalies extracted during leaching (solubles) are considered to be present in active forms which are released during combustion and be instrumental in deposit formation, whereas the insolubles are considered present in stable forms and less active.

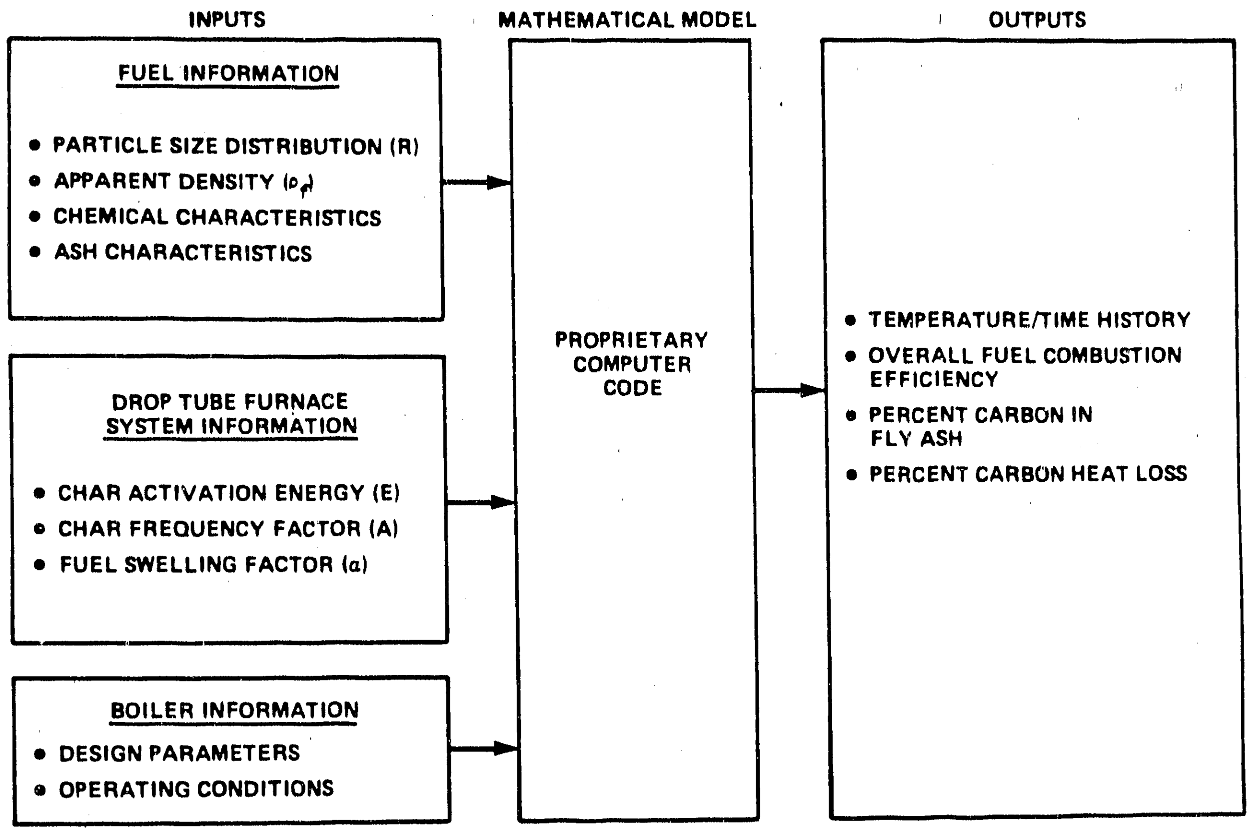

FIGURE 2-2 FLOW DIAGRAM FOR BOILER COMBUSTION PERFORMANCE MODEL SIMULATION

X-ray diffraction analysis was conducted to determine the quartz content in the CWF feed coal fly ashes. The quartz concentration can provide a relative indication of fuel and fly ash erosion potential.

Section 3
TEST RESULTS

COAL-WATER FUEL PROPERTIES

The analytical data of the CWFs are listed in Table 3-1. 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. In general the participating producers were able to produce CWFs suitable for transportation, storage, handling and firing with process adjustments for each new coal.

CWF Rheology/Atomization Characteristics

Atomization quality is extremely important during CWF firing since smaller droplets produce better combustion in the furnace. Atomizer spray droplet size dictates the time required to heat and dry the fuel prior to devolatilization and ignition. Spray droplet size also dictates the size of fuel/char particulate which must be burned out.

Ideally, one should be able to predict atomizer performance as a function of fuel rheology. Correlations between fuel oil rheology and atomization quality (for a given atomizer geometry) have been successfully established in the past (2,3,4). Generally, highly viscous fuel oils are difficult to atomize, while low viscosity fuel oils typically atomize well.

Similar correlations between CWF rheology and atomization quality are important for the commercialization of CWF. With this in mind, bench scale tests concentrated on defining CWF viscosity were conducted with the ultimate goal of making a viscosity/atomization quality correlation similar to that observed for commonly used fuel oils.

A summary of the properties and performance of the CWF's evaluated with the same 400 lb/hr (4.1×10^6 Btu/hr) atomizer is shown in Table 3-1. Measured viscosities are reported along with atomizer performance as defined in C-E's

TABLE 3-1

COAL-WATER FUEL PROPERTIES

Coal Ash Vendor 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												
%60 mesh (250μ)	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 (250x150μ)	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 (150x75μ)	0.5	15.5	0.4	3.8	17.4	2.7	12.6	17.5	15.6	19.1	12.5	0.5
200x325 mesh (75x45μ)	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 (5μ)	91.1	62.5	88.1	86.3	68.1	88.0	72.6	65.9	67.9	62.5	75.2	99.0
Coal Particle MMD (μ)	15	50	25	15	33	15	35	30	29	32	25	7
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	-
% droplets >320μ	.01	.01	0.00	0.00	0.37	0.02	0.22	3.43	2.19	0.02	.04	0.0
% droplets >225μ	1.18	0.98	0.40	0.22	5.07	1.28	3.83	14.61	9.64	1.00	1.64	0.2

(1) Rotational Viscometer @ 20°C.

(2) Extrusion Rheometer @ Room Temp.

(3) Variable High Shear Viscometer @ 20°C

Atomizer Test Facility (ATF) using a laser diffraction droplet sizing technique. Spray droplet size distribution information at a selected atomizing air to fuel mass flow ratio (A/F) is shown as the characteristic droplet Mass Median Diameter (MMD), Sauter Mean Diameter (SMD), and percent by weight of droplets in the spray exceeding both 225 microns and 320 microns in diameter. The selected A/F ratios were similar, in effect fixing the available atomizing energy, so that comparisons can be drawn between the atomization quality of each fuel. The overall ATF test data is shown in Appendix B.

The low shear (100 sec^{-1}) viscosity of the tested CWFs varied over a 600 cp - 1700 cp range. Only small changes in atomization were observed for this fairly wide range of viscosities (Figure 3-1). The general overall trend indicated an improvement in atomization quality as low shear viscosity decreased.

A similar trend was observed comparing higher shear viscosity data with atomization quality. Again, over a wide viscosity range, as high shear viscosity (1100 sec^{-1}) decreased, atomization improved (Figure 3-2). The trend is not apparent over a narrow viscosity range. The viscosity measurements made using the extrusion rheometer and variable high shear rheometer (at constant shear rate) did not show one-to-one correlation with each other.

A final observation made as a result of this effort is that the power law exponent, which gives a general indication of the fuel's change in viscosity with shear rate, is not a dependable predictor of CWF atomization quality. Neither pseudoplastic (viscosity decreases with shear rate) nor dilatent viscosity increases with shear rate) behavior over narrow shear ranges showed correlation with atomization performance.

Overall, the CWFs varied considerably in rheological characteristics. The viscosity data showed a wide range at low shear as well as high shear. Atomization quality generally improved with decreasing viscosities. However, accurate predictions of atomization quality could not be made from the

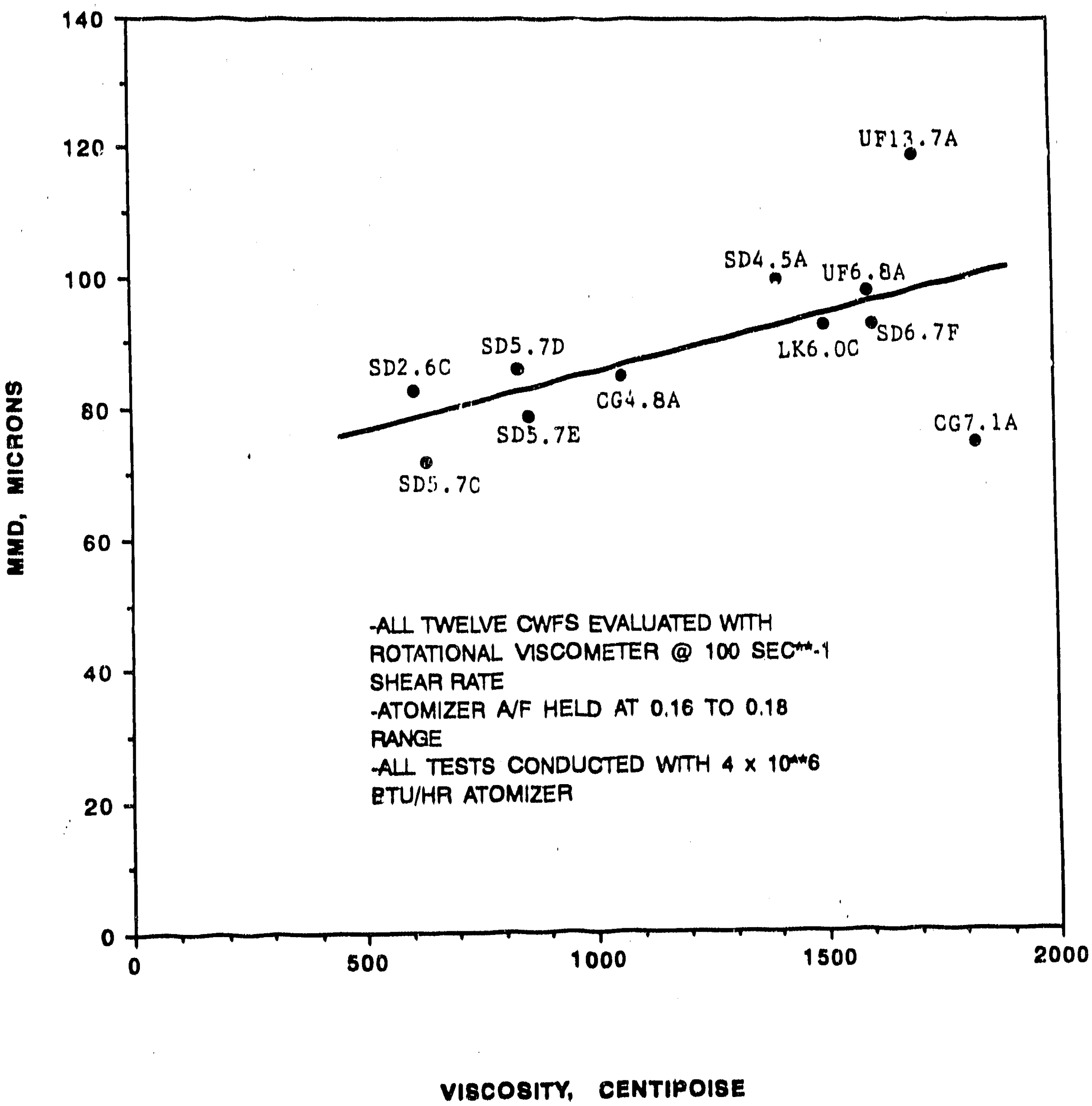

FIGURE 3-1 EFFECT OF LOW SHEAR VISCOSITY ON CWF ATOMIZATION

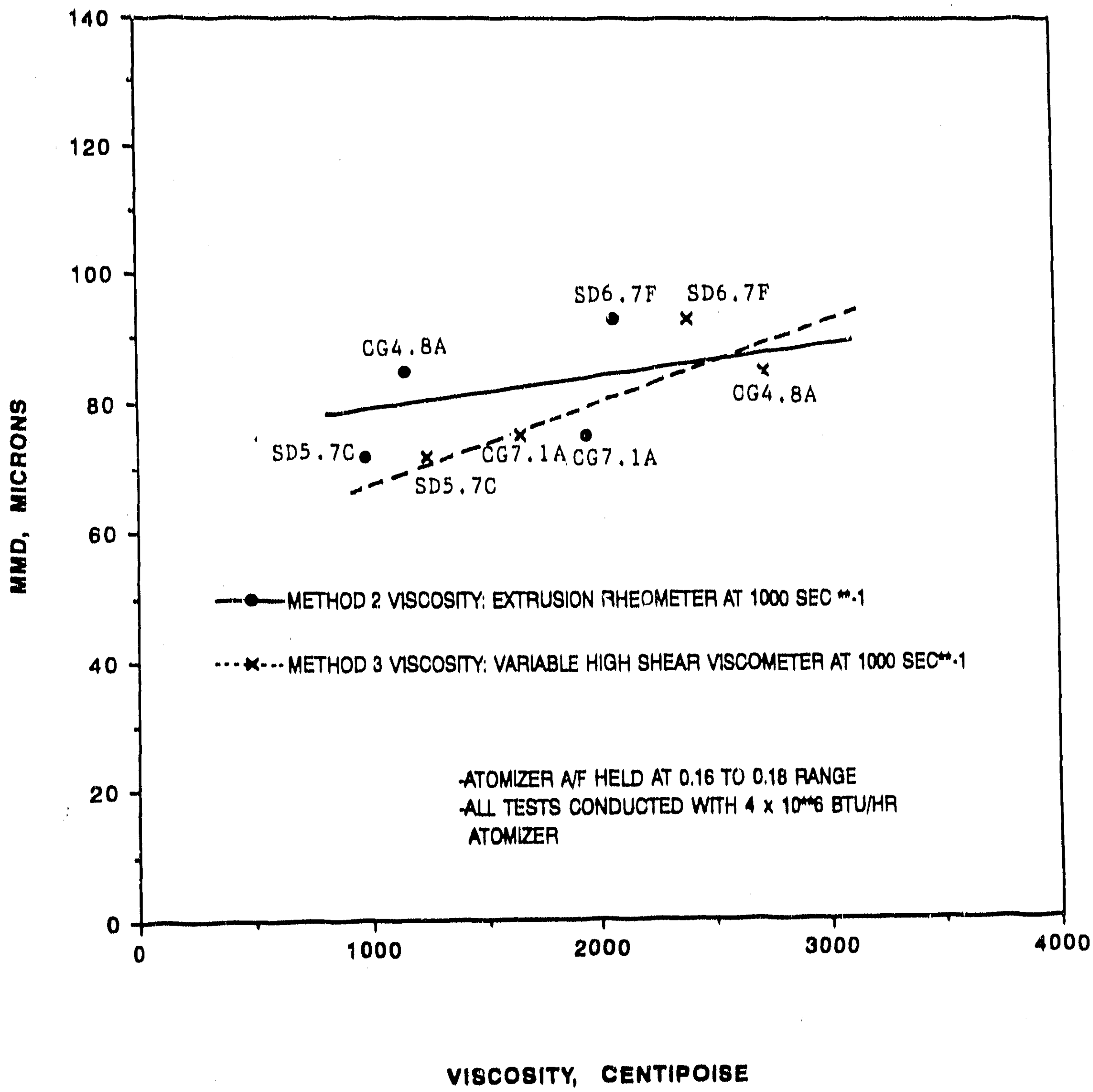

FIGURE 3-2 EFFECT OF HIGH SHEAR VISCOSITY ON CWF ATOMIZATION

bench-scale viscosity data due to the complex rheological properties of these CWFs.

CWF 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. Cross-country shipping of CWFs by truck, during two trips of approximately 2,700 miles each, had no apparent effect on settling. The amounts of settling under both stationary storage and the transit conditions were insignificant. 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 CWFs stability. (See Volume 2 for additional information).

Care must be exercised during production, transportation storage and handling to avoid large particles and contaminants. Microscopic analysis of the +30 mesh and 30x60 mesh sieve samples from the CWFs indicated that agglomeration occurred in some of the CWF batches. The relative amounts of agglomerates found from each size fraction are summarized in Table 3-2. These agglomerates were mainly caused by foreign matter which served as nuclei for growth. The contaminants are believed to be included during operations in the mining, coal transportation and CWF manufacturing process. Proper care in handling can avoid these problems. Agglomerates which survived the shear forces of wet screening could result in the atomizer and/or fuel filter plugging.

TABLE 3-2

SCREEN ANALYSIS OF CWF

CWF ID	Date Received		+30 Mesh wt%	30x60 Mesh wt%	Agglomeration* +30 Mesh	Agglomeration* 30x60 Mesh	Comments
Splash DAM CWFs							
SD57A	840328	AR	0.0012	-	All	-	Paint chips
	-	AR	-	0.0082	-	L	Large amount of quartz
	-	F/T	0.0002	0.0051	All	-	Paint chips
SD57C	831019	AR	0.0032	-	M	-	-
	-	AR	-	0.0259	-	S	-
SDxxC	831201	AR	0.0026	-	M	-	-
	-	AR	-	0.0075	-	S	-
SD57C	840328	AR	0.0027	-	L	-	-
	-	AR	-	0.0277	-	S	Lot of fibers, some quartz
	-	AR	-	-	-	S	+70 mesh, 0.11 wt%
	-	60C	-	-	L	-	-
	-	F/T	0.0011	0.0252	L	-	-
	-	F/T		0.0252		S	-
SD64C	840912	AR	0.0028	-	M	-	-
	-	AR	-	0.0240	-	S	Fibers (flaked)
	-	F/T	-	-	L	-	Fibers
	-	F/T	-	-	-	L	Fibers
SD22D	840920	AR	0.0004	-	All	-	-
	-	AR	-	0.0240	-	S	-
	-	F/T	0.0034		L	-	Fibers -
	-	F/T		0.0482	-	L	-
SD63C	850208	AR	0.0037	-	L	-	-
		AR	-	0.0210	-	M	Fibers
SD57D	831202	AR	0.0011	-	S	-	-
	-	AR	-	0.0437	-	S	-
SD57E	831027	AR	0.0011	-	M	-	Fibers
	-	AR	-	0.0244	-	M	Fibers
SD64F	841018	AR	0.0045	-	M	-	Coarse fibers
	-	AR	-	0.4658	-	S	-
	-	F/T	0.0019		M	-	Fibers -
	-	F/T		1.5768	-	M	-

TABLE 3-2 (cont.)

SCREEN ANALYSIS OF CWF

CWF ID	Date Received		+30 Mesh wt%	30x60 Mesh wt%	Agglomeration* +30 Mesh	Agglomeration* 30x60 Mesh	Comments
Cedar Grove CWFs							
CGxxC	840312	AR	0.0043	-	L	-	Some Fibers
	-	AR	-	0.0273	-	L	Fibers, red flakes
CG74A	840718	AR	0.0016	-	L	-	Insect
	-	AR	-	0.3130	-	No	Few Fibers
	-	60C	-	-	L	-	Insect
	-	F/T	0.0005	-	M	-	2 Large clumps
	-	F/T	-	0.2024	-	M	Some quartz
CG49A	840914	AR	0.0003	-	L	-	Fibers
	-	AR	-	0.0320	-	S	Fibers
	-	F/T	0.0008	-	L	-	
	-	F/T	-	0.0221	-	S	
Lower Kittanning CWF							
LK65C	831018	AR	0.0005	-	S	-	-
	-	AR	-	0.0773	-	M	-
Upper Freeport CWFs							
UF69A	840702	AR	0.0047	-	S	-	Paint chips?
	-	AR	-	0.0801	-	M	-
	-	60C	-	-	No	-	+100 mesh
	-	60C	-	-	-	No	100x200 mesh
	-	F/T	0.0015	-	S	M	-
	-	F/T	-	0.0751	-	S	Some fibers
UF115A	840523	AR	0.0004	-	M	-	Some fibers
	-	AR	-	0.5718	-	S	-
	-	60C	-	-	M	-	Some fibers
	-	F/T	0.0013	-	All	-	-
	-	F/T	-	0.2955	-	S	-

AR — As received
60C — 60 C sample after 1 week in 60 C oven
F/T — Freeze/Thaw Sample after three freeze/thaw cycles

*All - All particles
L - Large amount >70%
M - Medium amount >50%
S - Small amount <25%

CWF Piping, Pumping, Erosion and Corrosion Characteristics

Areas of concern when handling CWF include shear sensitivity, corrosion, and erosion. The importance of avoiding high shear handling of CWF's is well known, and only low shear pumps, valves, and instruments are recommended. However, even low shear can significantly influence CWFs. Some CWFs exhibit gradual changes in rheology when exposed to nominal shearing over time. Thus, a "shear thinning" CWF exhibits a decreasing viscosity with time, and a "shear thickening" CWF exhibits increasing viscosity with time. These effects are not problems, unless they are unpredictable and uncontrollable.

An evaluation of corrosion and erosion by CWFs was conducted in a bench-scale test loop. CWFs were pumped through a metal loss detector at high shear rates for a period of approximately five hours. These tests determined total metal loss rates without discriminating the relative effects of corrosion versus erosion. In fact, the metal losses found probably resulted from the combined corrosion and erosion effects.

The results from the test loop corrosion/erosion are summarized in Table 3-3. Velocities and shear rates are higher than normal for fuel piping. The Corrosion/Erosion Index (CIN) for each test is an average of three measurements taken in a short radius bend, a long radius bend, and a straight section. Since no significant differences were noted between these three sections, only the average CIN is shown. Coal particle examinations at several times during the tests showed virtually no change in size and shape. The scatter in some of the data indicates sensitivities to vendor processing and ash levels. The overall CIN results indicated that the CWF corrosion and erosion in piping varied significantly with coal type, ash content and vendor process. The metal loss rates determined from these tests were significantly high to warrant further investigations.

FUEL COMBUSTION REACTIVITY

Stable ignition and efficient combustion of a CWF are obviously critical for effective utilization. For a given firing system, the combustion characteristics of the CWF have a strong impact on resulting performance. CWF

TABLE 3-3

CWF BENCH-SCALE CORROSION AND EROSION TEST RESULTS

Identification	Velocity ft/sec	Shear Rate sec^{-1}	CIN Average μ-inch/hr	Ash wt %	Viscosity @ 20 C mPa-s	pH	Temp °F	Run Time hr
SD5.7C	8.23	1097	11.8	5.7	1277	8.7	93	5
SD5.7C	7.57	1009	10.1	5.7	1277	8.7	83	5
SD5.7C	6.81	908	9.0	5.7	1277	8.7	87	5
UF13.7A	8.16	1088	22.3	13.7	944	9.2	87	5
UF6.8A	8.32	1109	12.8	6.8	513	9.3	79	5
CG7.1A	8.25	1100	2.5	7.1	1755	9.5	89	5
CG4.8A	8.22	1096	0.0	4.8	1064	9.5	84	5
SD2.6C	8.29	1105	9.8	2.6	612	8.5	86	5
SD6.7F	8.18	1091	10.7	6.7	1660	6.5	83	5

combustion characteristics can be separated into two categories: atomization properties and coal reactivity. 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. Since the combustion properties of coal can vary widely, it is necessary to carefully consider these characteristics in predicting combustion behavior.

The ignition and turndown characteristics of the CWF feed coals were assessed by determining volatile matter content, volatile matter calorific value, and Flammability Index. Volatile matter content has been traditionally used to predict coal combustion properties. The calorific value of the volatile matter further defines the quality of these volatiles. Since the volatiles in the coal represent the bulk of material which first ignites and burns, they obviously play a major role influencing flame stability and turndown limits. The volatiles would be expected to have an even greater impact during CWF firing than conventional pulverized coal firing since a lower concentration of very fine particles are present during CWF combustion to assist in flame stabilization.

Typical fuel analyses of the CWF feed coals on a moisture free basis are shown in Table 3-4. The volatile matter content and volatile matter calorific values were fairly similar and relatively high for these coals. The fuel ratio (i.e., fixed carbon/volatile matter) was less than 2.4 for each coal. These results are indicative of good combustion characteristics from a conventional pulverized-coal firing standpoint.

A relative measurement of the coal's 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. Typical ranges in Flammability Indices for different coal ranks are summarized below:

TABLE 3-4

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	6.0	5.7	2.6	13.7	6.8	7.1	4.8	5.9
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	6.0	5.7	2.6	13.7	6.8	7.1	4.8	5.9
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_2O_3	24.1	27.0	30.8	24.9	24.7	28.9	28.2	22.8
Fe_2O_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_2O	0.7	1.1	1.9	0.3	0.4	0.4	0.5	0.7
K_2O	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	0.6	0.5	1.4	1.7	0.6	1.9	2.1	1.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Quartz in Ash (Wt.%)	28.7	19.9	7.0	13.6	11.7	18.5	15.1	18.5

Coal Rank	Flammability Index (°F)
Anthracites	1400 - 1700
Bituminous	1000 - 1200
Subbituminous	900 - 1000
Lignites	800 - 900

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 turndown 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. Typical char surface area ranges for different coal ranks are summarized below:

Coal Rank	Char Surface Area (m^2/g, Dry-Ash Free)
Anthracite	1 - 5
Medium Volatile Bituminous	5 - 20
High Volatile Bituminous	15 - 50
Subbituminous	50 - 100
Lignites	75 - 200

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 (15 to 23 m^2/g) and should have comparable reactivity.

TGA results are consistent with surface area data, also indicating very similar char reactivity. Figure 3-3 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 (1). 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.

The CWF feed coals were additionally tested in the DTFS to provide more insight on the pyrolysis and combustion characteristics of these fuels. Pyrolysis tests were conducted on a 200 x 400 mesh size cut fraction in nitrogen gas medium while combustion tests were conducted using a 100 x 200 size fractions in 5% O_2 gas medium. The close control of particle size distributions were necessary to ensure that any differences in reactivities between the chars of interest are not due to differences in particle sizes.

Results on the effect of temperature and time on pyrolysis weight loss are plotted in Figure 3-4. The high temperature (2650°F) pyrolysis results indicate each test coal yielded ~100% pyrolysis efficiency within 0.3 sec. The DTFS volatile matter yields in high temperature are very similar to those determined by standard ASTM volatile matter method; no enhancement in volatile matter yield at this higher temperature was found for the coals investigated. The absence of volatile matter enhancement under high temperature, suspension firing conditions encountered here is consistent with results for most eastern bituminous coals previously studied in this laboratory.

The low temperature (1900°F) pyrolysis results show that pyrolysis efficiencies are about 15% lower than those of high temperature ones. The reduction in volatile matter yields at the lower DTFS temperature indicates that the heavy fractions of the volatiles in these coals present a constraint on temperature requirement for high pyrolysis yield. This implies potential ignition delay at low furnace temperatures and more severe turndown limitations for many smaller industrial furnaces operated at low temperatures.

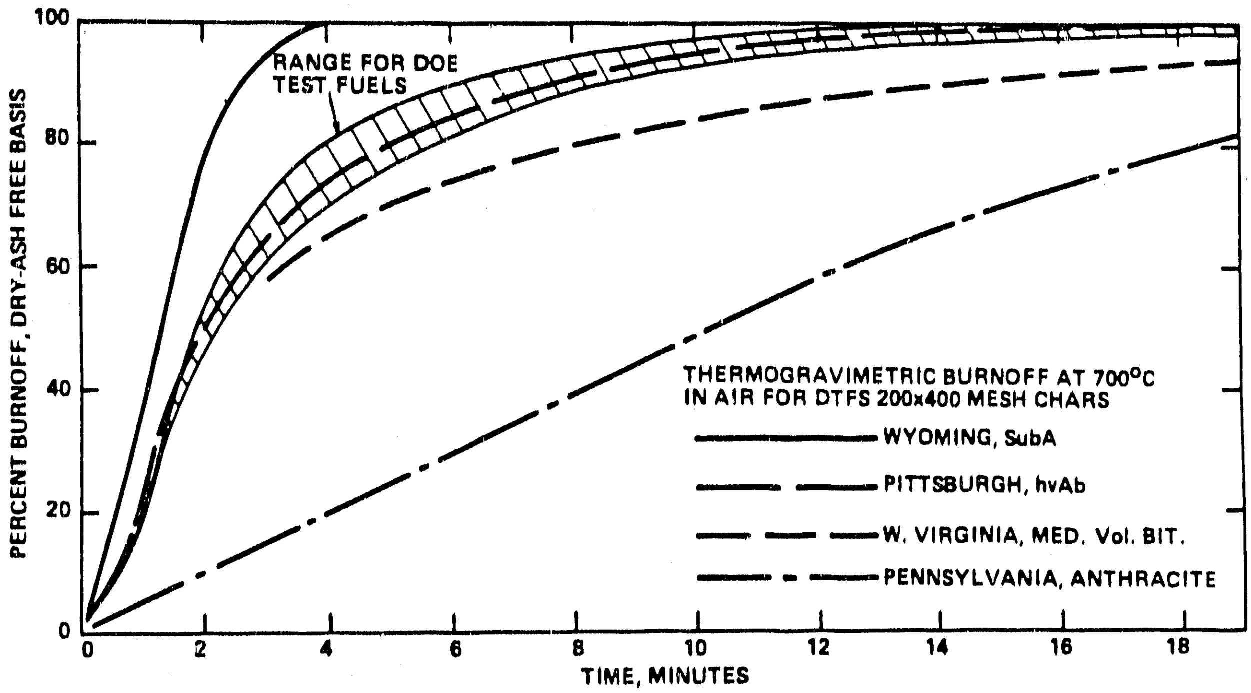

FIGURE 3-3 RELATIVE TGA CHAR BURN-OFF RATES FOR 200x400 MESH DTFS CHARS

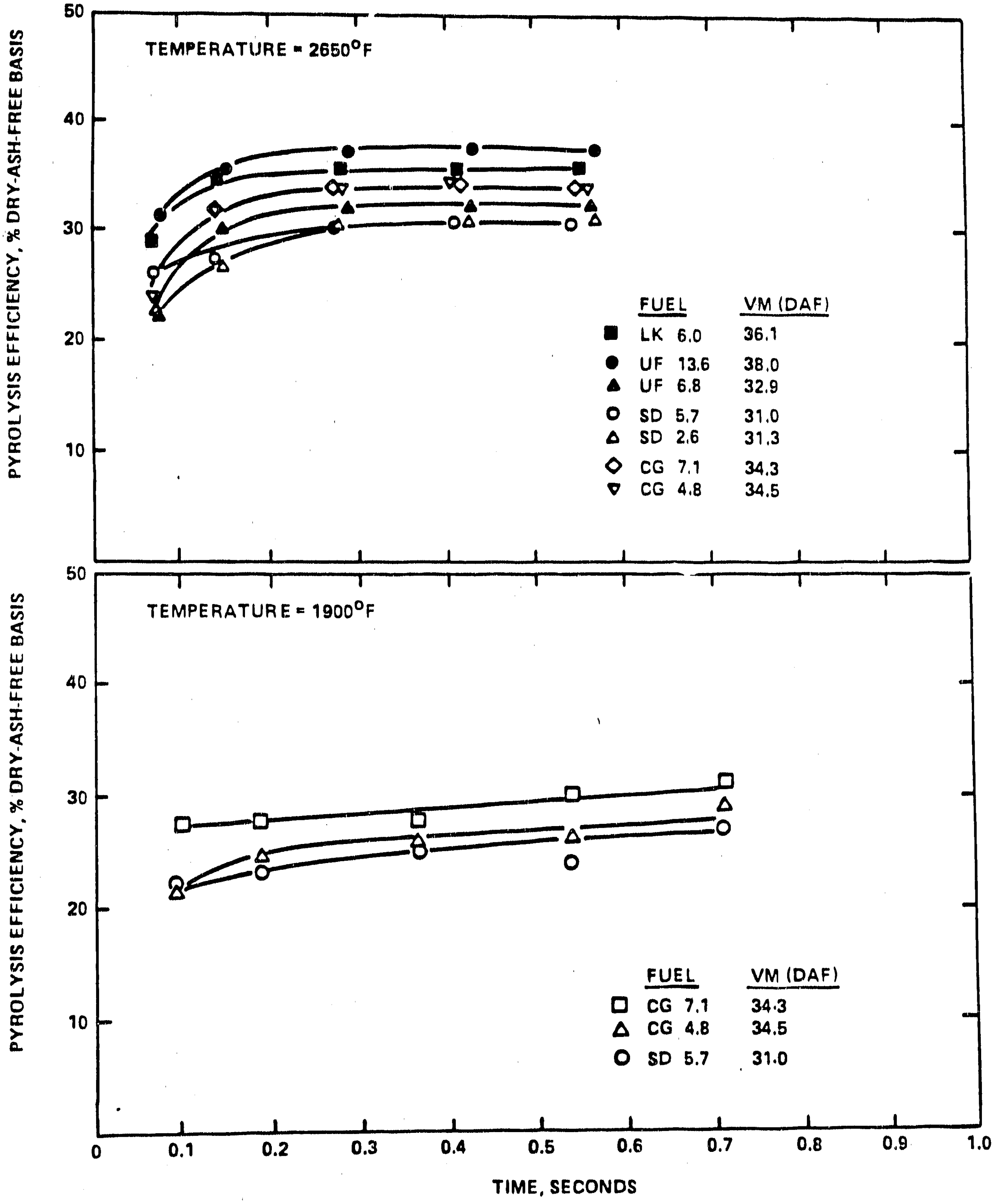

FIGURE 3-4 DTFS PYROLYSIS EFFICIENCIES OF 200 x 400 MESH COALS IN NITROGEN ATMOSHPERE

The swelling characteristics of three CWF feed coals (SD5.7, UF6.8 and CG7.1) were also determined during the DTFS pyrolysis tests at 2650°F furnace temperatures. Results indicate that the average swelling factors were 1.35, 1.28 and 1.04 for SD5.8, UF6.8 and CG7.1, respectively. Judged by their close similarities in chemical characteristics, the differences in swelling tendency of the three coals are quite significant but not unusual for coals of this rank. It should be noted that the higher swelling coals do not necessarily have a greater tendency for coal/char agglomeration in CWF firing as each coal would be expected to go through a sticky, plastic state. Difference in CWF atomization/combustion behavior is expected to have a much greater impact on agglomerate formation.

The DTFS combustion test results indicate that under the prevailing testing conditions at 1900°F and 2650°F, respectively, all test coals had similar burnout characteristics (Figure 3-5). The "High Ash" and corresponding "Low Ash" of these coals had very similar reactivity, which points out that the quantity and quality of mineral matter in these coals had very little influence on fuel burnout characteristics.

CWF COMBUSTION PROCESS MODELING

Combustion process modeling was conducted to examine the effects of operating parameters and CWF properties in boiler performance with respect to carbon loss. A methodology has been developed and successfully applied by C-E to predict carbon heat losses in pulverized coal fired boilers (5). Essentially, it consists of using the fuel char combustion kinetic information generated from the DTFS in conjunction with fuel and boiler information and in-house proprietary mathematical model, known as Lower Furnace Program-Slice Kinetic Model (LFP-SKM), to simulate the combustion of a given fuel under specific boiler operating conditions.

The LFP-SKM mathematical model is based upon the formulation of Field and co-workers (6,7), whereby the following differential equation is solved:

$$du_j/dt = 1S_j q_j \qquad (1)$$

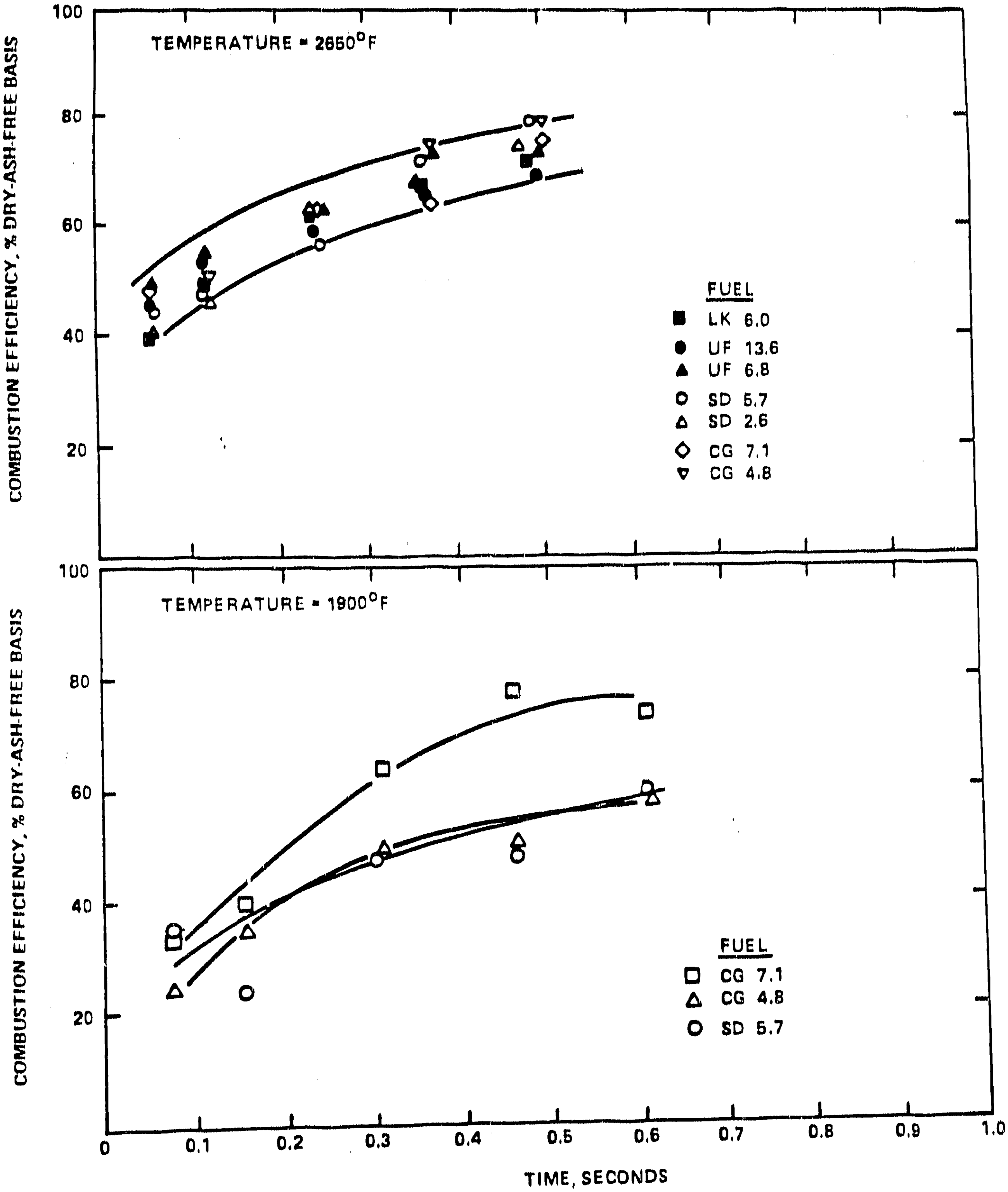

FIGURE 3.5 DTFS COMBUSTION EFFICIENCIES OF 100 x 200 MESH COALS IN 5% O_2/95% N_2 MEDIUM

where

u_j = weight of residual char at any particular time per unit initial weight of char;

S_j = geometric surface area of each particular fraction per unit weight of initial char;

q_j = rate of carbon removal per unit surface area.

Equation (1) assumes that the volatile matter is instantaneously released and burned. As such, the pyrolysis process is not modeled. Assuming spherical particles

$$S_j = (6\ w_j\ \alpha^2)/(C_f\ \rho_f\ Y_j)$$

where

Y_j = initial diameter of fuel particles before devolatilization;

α = fuel swelling factor;

w_j = fraction of unburned char at time t;

C_f = fraction of dry-ash-free fuel after devolatilization

ρ_f = apparent density of dry-ash-free

$$q_j = (P_g(U))/(1/K_D + 1/K_s)$$

where

P_g (U) is oxygen partial pressure in the effluent gas stream at time t, and K_d, and K_s are, respectively, the diffusional reaction rate coefficient and surface rate coefficients.

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:

- Atomizer droplet size distributions were used as model inputs in the form of Rosin-Rammler Parameters.

- Instant water vaporization was assumed, and, therefore, a 30% reduction was applied to CWF 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.

- Char reactivity parameters (activation energy and frequency factor) were selected from C-E data bank based on a bench-scale reactivity comparison between the CWFs chars and the data bank's coal-chars.

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.

The general results from this paramatric study indicate that carbon heat loss is exacerbated the most by coarse droplet size followed by high volumetric heat release rate, and high gas recirculation. Therefore, these parameters should be controlled in concert to minimize carbon heat loss. Carbon in the fly ash is inherently high due mainly to the fact that CWF has very low ash content, and hence, a higher carbon-to-ash ratio than typical pulverized coal at equivalent combustion efficiencies.

The effects of mean weight droplet size and gas recirculation on predicted values of carbon in fly ash and carbon heat loss for SD 5.7 CWF at volumetric heat release rate of 15.1×10^3 Btu/hr-ft^3 are shown in Figure 3-6. Results showed that carbon heat loss was highly dependent on CWF droplet size distribution. An increase in mean weight droplet size from 75 μ to 90 μ

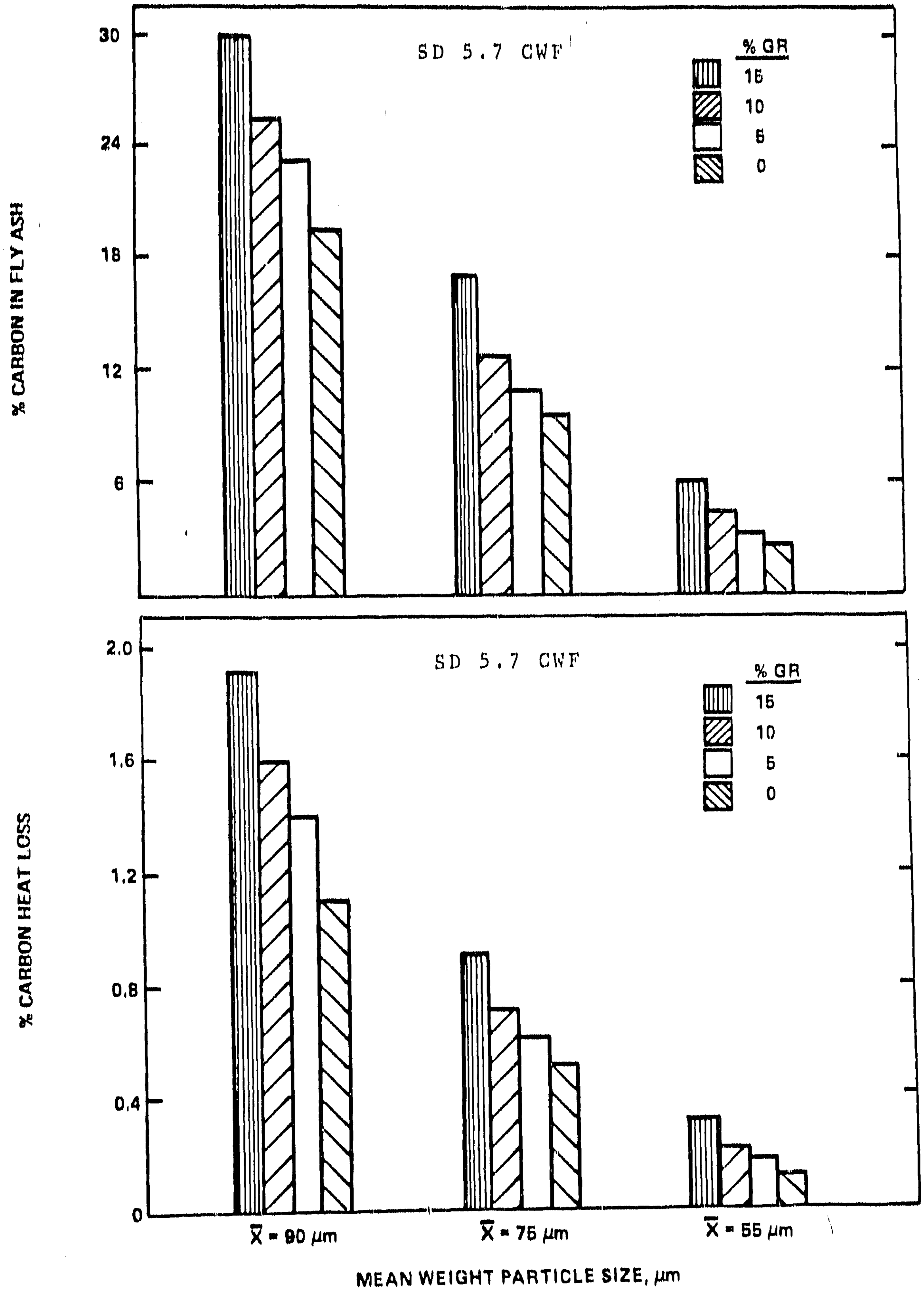

FIGURE 3-6 EFFECTS OF GAS RECIRCULATION AND MEAN WEIGHT DROPLET SIZE ON PREDICTED VALUES OF CARBON IN FLY ASH AND CARBON HEAT LOSS AT 15.1×10^3 $BTU/HR-FT^3$ VOLUMETRIC HEAT RELEASE RATE

can increase the carbon heat loss by a factor of two with no gas recirculation. For a given droplet size distribution, the carbon content in fly ash and the corresponding carbon heat loss also increased with increasing gas recirculation. The adverse impact of gas recirculation is due to the fact that this parameter is a diluent in the combustion system.

Figure 3-7 illustrates the effects of volumetric heat release rates and reactivity parameters on predicted values of carbon in fly ash and carbon heat loss for CWF. The values of carbon in fly ash and the corresponding carbon heat loss increased with increasing volumetric heat release rate when using either lower or higher reactivity fuel parameters. The increase in carbon heat loss with increasing volumetric heat release rate is most likely attributed to the change in temperature/time history. The beneficial effect of the small temperature increase due to increasing heat release rate is more than offset by the negative impact of increased residence time.

Overall, bench-scale ignition and TGA char burnoff characteristics of each CWF feed coal were similar and comparable to those of typical high volatile bituminous coals. Combustion process modeling firing the CWFs showed that the carbon heat loss was exacerbated the most by coarse droplet size followed by high volumetric heat release rate and high gas recirculation.

ASH PROPERTIES

The ash qualities of the feed coals were evaluated by bench-scale techniques to assess their slagging and fouling potentials. Behavior of the mineral matter 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 maximum capacity the unit run at without operational problems and necessary equipment modifications. Both ash deposition and fly ash erosion are primary areas of concern. 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

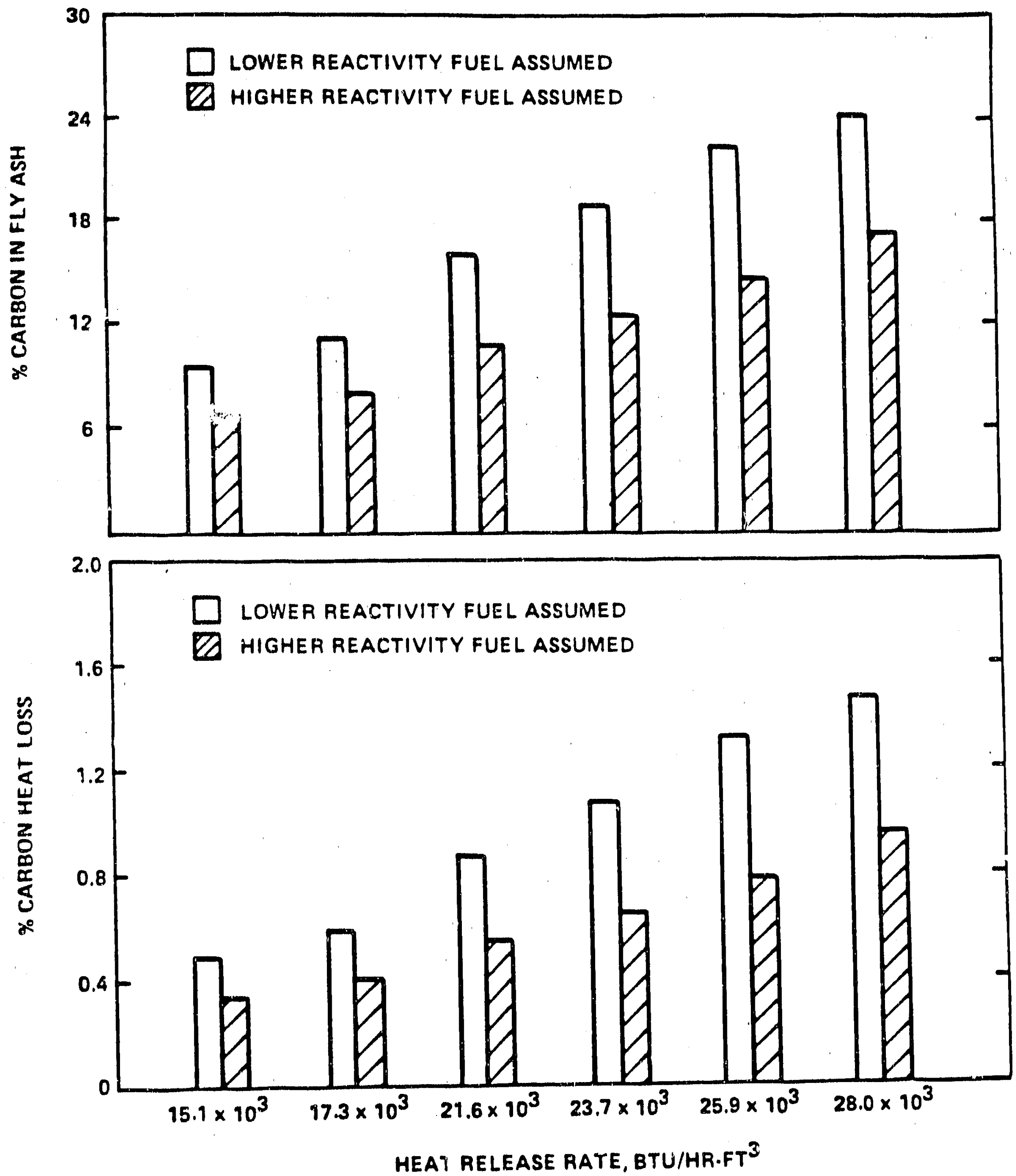

FIGURE 3-7 EFFECTS OF VOLUMETRIC HEAT RELEASE RATE AND REACTIVITY PARAMETERS ON PREDICTED VALUES OF CARBON IN FLY ASH AND CARBON HEAT LOSS

temperature furnace radiant sections, and fouling, which is associated with deposit formation in convection sections at somewhat lower gas temperatures. Ash erosion can greatly reduce convection tube life and unit availability, forcing derating to minimize erosion.

Bench-scale evaluation of the ash properties of the CWF feed coals were determined to assess differences in CWF behaviors compared to those which could be expected if fired as pulverized coal. The bench-scale data were also used to help interpret the performance results from the pilot-scale ash deposition and performance testing conducted under Task 5. Slagging, fouling and erosion characteristics of each CWF were extensively evaluated during the pilot-scale testing as discussed in Volume 5.

Ash Slagging Potential

Commonly used bench-scale slagging indicies of each test fuel are summarized in Table 3-5. The Lower Kittanning (LK 6.0), Splash Dam (SD 5.7 and SD 2.6) and Cedar Grove (CG7.1 and CG4.8) fuels can be characterized by their high fusibility ashes (softening temperatures $\geq$2600°F), and the Upper Freeport (UF 13.6 and UF 6.8) and Alma (AL 5.9) by their moderate to low ash fusibility temperatures (softening temperatures $\geq$2240°F).

The base-to-acid ratio is based on the tendency of coal ash constituents to combine, according to their acidic and basic properties, to form salts with low melting temperatures. Values of this ratio between 0.4 and 0.7 have been correlated to ashes with low melting temperatures (8). The Lower Kittanning and Splash Dam coal ashes showed low base-to-acid ratios. These values are indicative of a low slagging tendency. The values for Upper Freeport indicate moderate slagging potential, and values for Cedar Grove and Alma indicate low to moderate slagging potential. The base-to-acid ratios for all these coals are consistent with their fluid temperatures.

The iron-to-calcium ratio is primarily used as a slagging indicator to account for the fluxing effect of calcium upon iron. This fluxing effect is usually most pronounced for ratios between 3 and 0.3 (8). Results for all subject fuels fall in the 4.2-13.4 range, indicating their low slagging potential.

Gravity fractionation results showed 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 (9). 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 minimal.

Overall, based on these bench-scale analyses, the Upper Freeport fuels should exhibit moderate slagging potential, the Cedar Grove and Alma fuels low to moderate slagging potentials, and the Lower Kittanning and Splash Dam fuels low slagging potentials. These bench-scale predictive results were generally in good agreement with the pilot-scale test results (Volume 5). Waterwall deposit characteristics observed during the pilot-scale tests indicated low slagging for Lower Kittanning and Splash Dam, moderate for Cedar Grove and Alma, and high for Upper Freeport fuels. The higher slagging characteristics of Upper Freeport fuels are mostly attributed to the lower ash fusibility temperatures.

Ash Fouling Potential

The bench-scale indicators characterize the fouling potentials of the Lower Kittanning, Splash Dam and Cedar Grove fuels as low, whereas the Upper Freeport and Alma fuels would expect to exhibit low to moderate fouling potentials (Table 3-6). The higher fouling characteristics of the Upper Freeport and Alma 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

TABLE 3-5

BENCH-SCALE ASH SLAGGING CHARACTERISTICS

COAL TYPE	ST (°F)	FT (°F)	B/A RATIO	Fe_2O_3/CaO RATIO	Fe_2O_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	2460	0.4	13.4	96.0	0.8	Moderate
CG7.1	2600	>2700	0.2	5.1	82.0	0.1	Low/Moderate
CG4.8	2650	>2700	0.2	4.2	80.6	0.8	Low/Moderate
AL5.9	2240	2510	0.3	4.6	89.0	0.2	Low/Moderate

TABLE 3-6

BENCH-SCALE FOULING CHARACTERISTICS

COAL TYPE	IDT (°F)	ST (°F)	TOTAL ALKALIES (%)	SOL. Na_2O (%)	SOL. K_2O (%)	SOL. TO TOTAL FRACTION	FOULING POTENTIAL
LK6.0	2320	>2700	2.0	0.4	<0.1	0.2	Low
SD5.7	2440	2610	2.8	0.2	0.1	0.1	Low
SD2.6	2270	>2700	3.0	0.7	0.1	0.3	Low
UF13.6	1990	2260	3.1	0.1	<0.1	<0.1	Moderate
UF6.8	1980	2270	2.9	0.4	<0.1	0.1	Low/Moderate
CG7.1	2510	2600	2.6	0.4	0.1	0.2	Low
CG4.8	2290	2650	2.3	0.7	0.1	0.3	Low
AL5.9	1920	2240	2.0	0.5	<0.1	0.3	Low/Moderate

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 the observed pilot-scale fouling performance (Volume 5) as well as results typically obtained for low fouling Eastern U.S. bituminous coals (10).

Fly Ash Erosion

Convection tube erosion resulting from fly ash generated during combustion can be the load limiting factor associated with CWF utilization. Units designed for oil or gas typically have considerably higher convection pass gas velocities and tighter tube spacings than coal-designed units. The high gas velocities accelerate erosion rates and reduce tube life. Fly ash erosion rates are believed to be exponentially related to ash impact velocity and linearly proportional to ash loading. Other significant factors include the size distribution of the ash and the relative erosiveness of the ash (11). 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 ash samples determined by quantitative x-ray diffraction are shown in Table 3-4. Both ash contents and the concentration of quartz in the CWF beneficiated 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.

Overall, the bench-scale ash characteristics were in good agreement with the pilot-scale ash deposition and performance test results (Volume 5). The slagging and fouling characteristics of the CWFs were mainly determined by the ash quality of the feed coals. CWF prepared from coal beneficiated at deeper level showed improvement in overall ash deposition and fly ash erosion characteristics.

Section 4
CONCLUSIONS

Several representative 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. Specific conclusions drawn from the test results are as follows.

1. 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.

2. Cross-country shipping of CWFs by truck over 2700 miles 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 effect on CWF stability.

3. 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 atomizer quality could not generally be made from the bench-scale data.

4. Corrosion and erosion in piping varied significantly with coal type, ash content and vendor process. Small scale metal loss rates were sufficiently high to warrant further investigations.

5. Bench-scale ignition and TGA char burnoff characteristics of all CWF feed coals were similar and comparable to those of typical high volatile A bituminous coal.

6. Combustion process modeling firing the CWFs showed that the carbon heat loss was exacerbated the most by coarse droplet size followed by high volumetric heat release rate, and high gas recirculation. Therefore, these parameters should be controlled in concert to minimize carbon heat loss.

7. The ash quality of the CWFs were source coal specific. In general, the ash slagging and fouling characteristics of the test fuels improved with increased level of beneficiation. Fly ash erosion potential should also be reduced with CWF prepared from lower ash feed coals.

Section 5
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APPENDIX A

DROP TUBE FURNACE SYSTEM

Drop Tube Furnace System (DTFS)

The Drop Tube Furnace System (Figure A-1) is comprised of a 1-inch inner diameter horizontal tube gas preheater and a 2-inch inner diameter vertical tube test furnace for providing controlled temperature conditions. Both tubes are electrically heated with silicon carbide elements (SiC) and are rated at 2800°F. The DTFS was used to study pyrolysis and combustion of coals and/or chars.

The principle of operation of the DTFS is as follows: Size graded fuel is introduced with a small amount of carrier gas into the hot reaction zone of the test furnace through a water-cooled fuel injector. A preheated secondary gas stream is introduced around the primary stream. Injection of fuel particles into the hot gas stream results in a rapid heating of the particles to the prevailing gas temperature (at a rate of the order of 10^4°C/sec). Following the rapid heating period, pyrolysis and/or combustion of particles occur for a specific time. Then all reactions are rapidly quenched. Solid products are separated from the gaseous products in a small filter housing, and an aliquot of the effluent gas sample is sent to a pre-calibrated Gas Analysis System.

The solid products collected at various locations along the axis of the DTFS reaction zone can be analyzed to determine solid conversion efficiencies. An ash tracer method, which is based on the assumption that ash remains inert during either pyrolysis or combustion, is used to calculate the fuels' pyrolysis or combustion efficiencies. The aliquot of the effluent gas sample is analyzed on-line to determine NO_x, O_2, CO, and CO_2 concentrations.

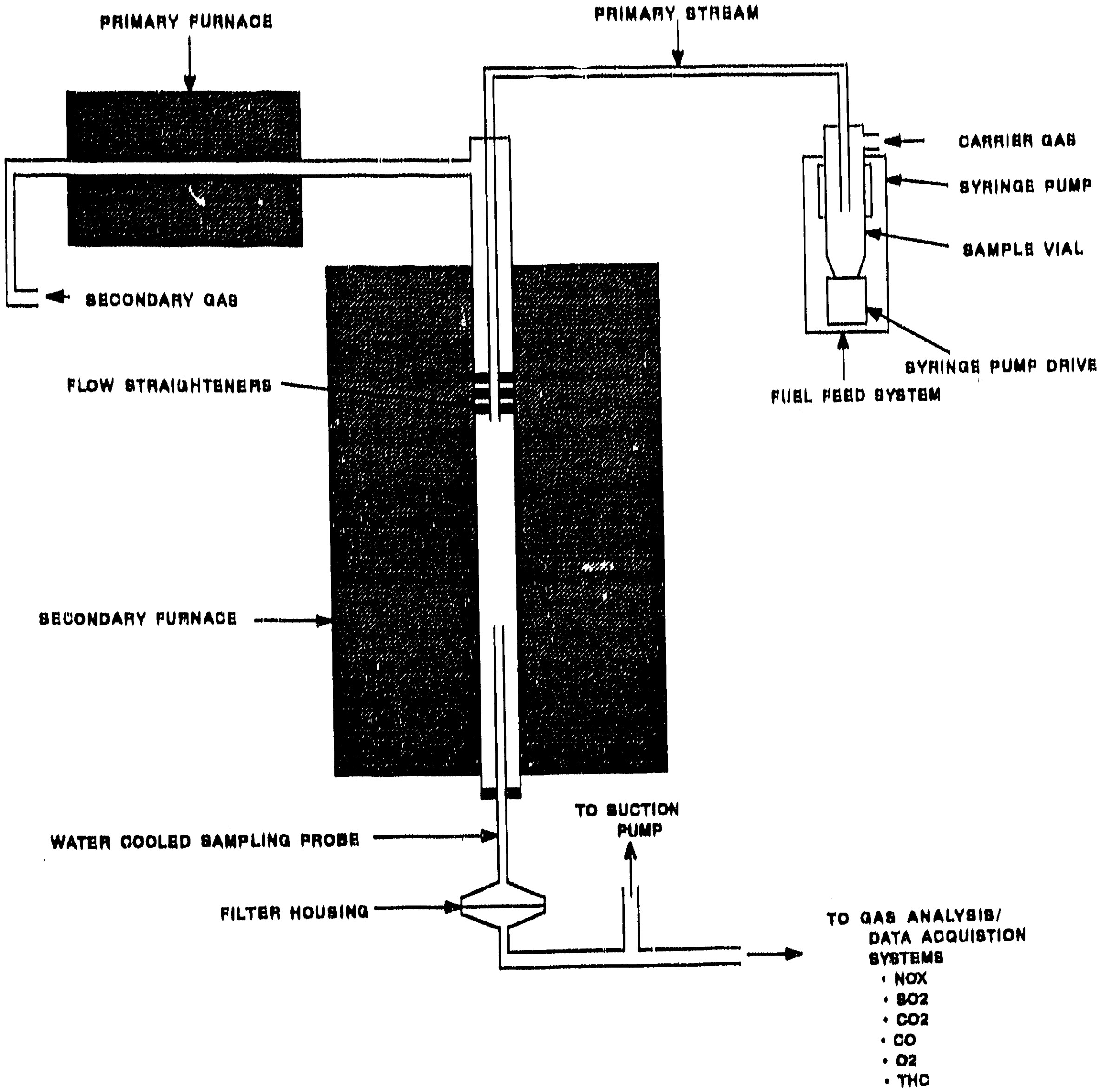


Figure A-1 Schematic of Drop Tube Furnace System (DTFS)

APPENDIX B

ATOMIZER TEST DATA

Figure B-1

COLD FLOW ATOMIZATION TEST RESULTS FOR LOWER KITTANING CWF IN THE ATF

(AT EQUIVALENT 4.1 x 10**6 BTU/HR FIRING RATE)

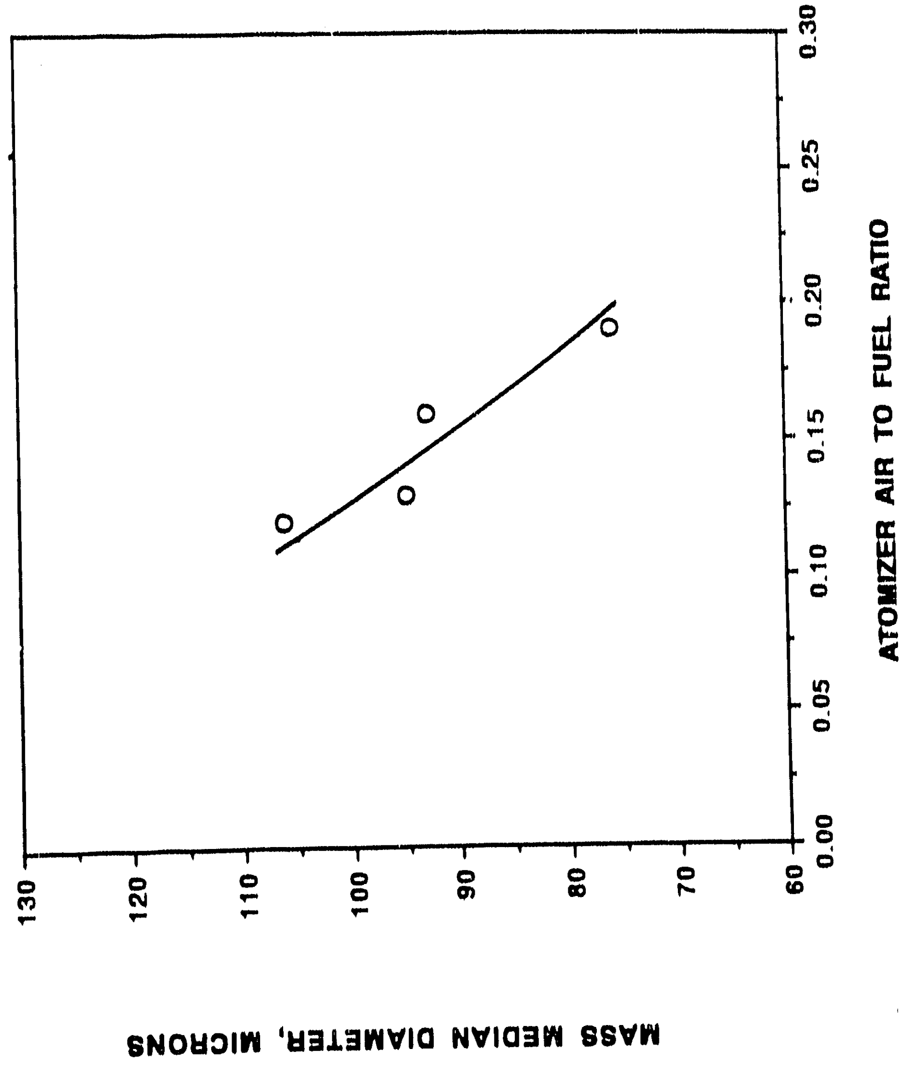


Figure B-2

COLD FLOW ATOMIZATION TEST RESULTS FOR SPLASHDAM CWFS IN THE ATF

(AT EQUIVALENT 4.1 x 10**6 BTU/HR FIRNG RATE)

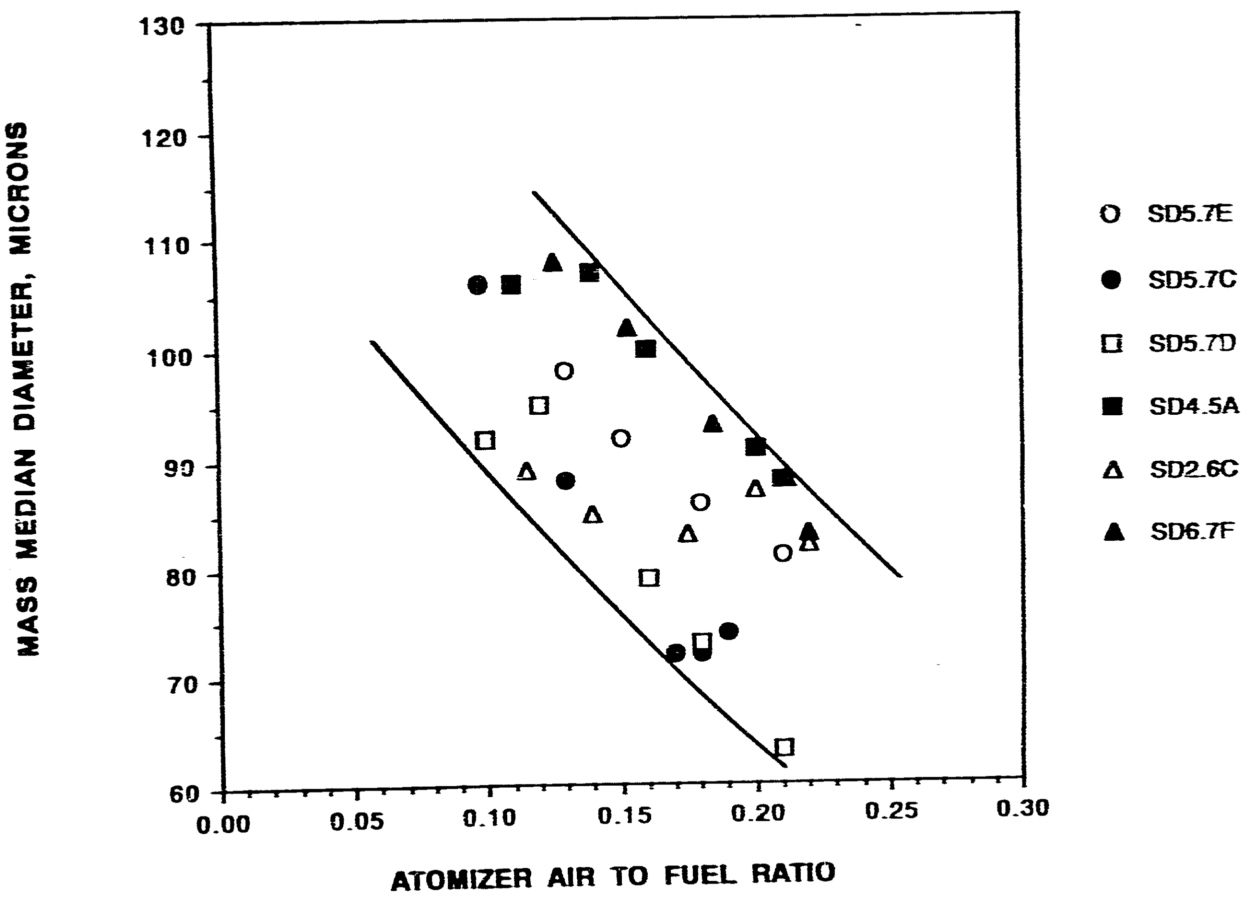


Figure B-3

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

(AT EQUIVALENT 4.1 x 10**6 BTU/HR FIRNG RATE)

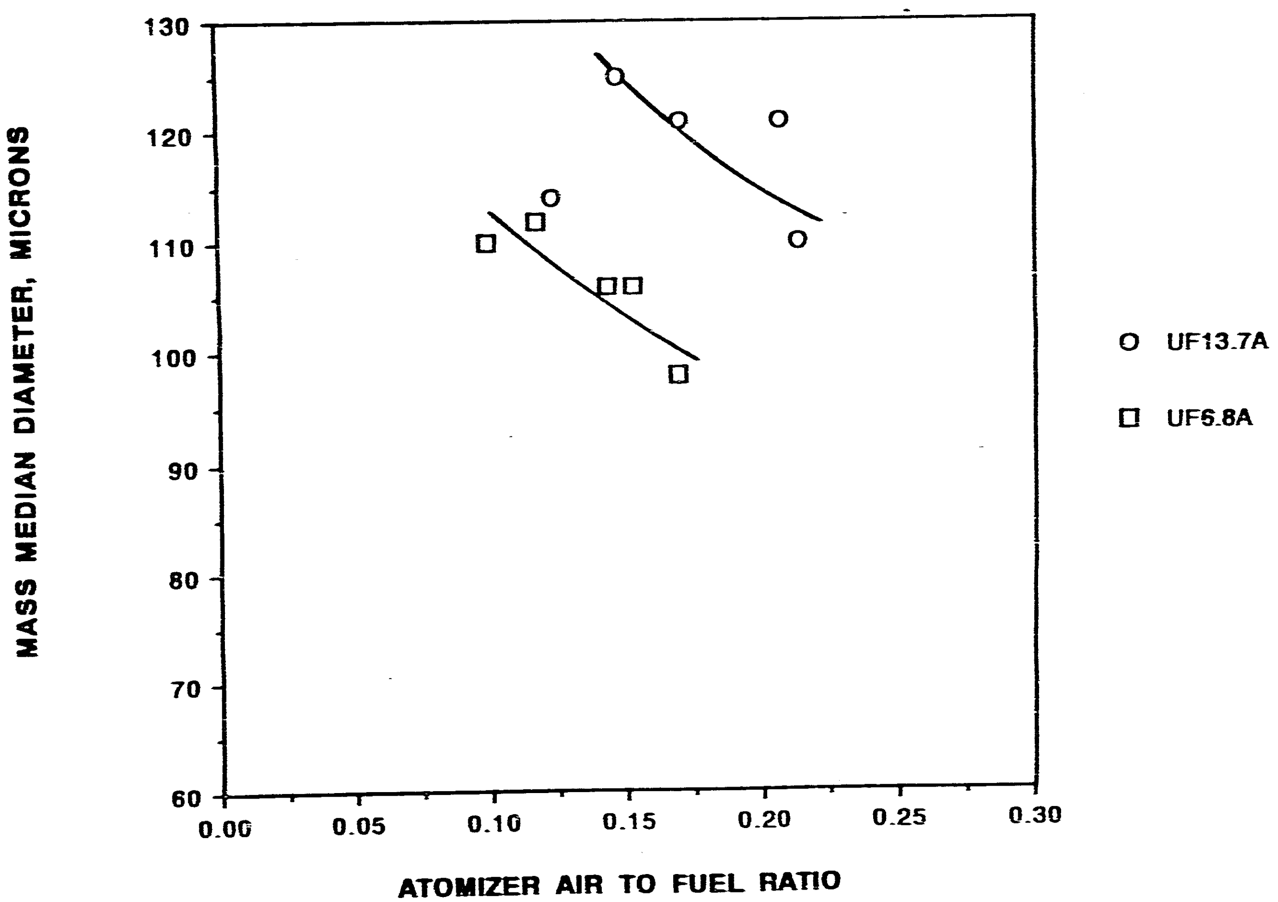


Figure B-4

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

(AT EQUIVALENT 4.1 x 10**6 BTU/HR FIRING RATE)

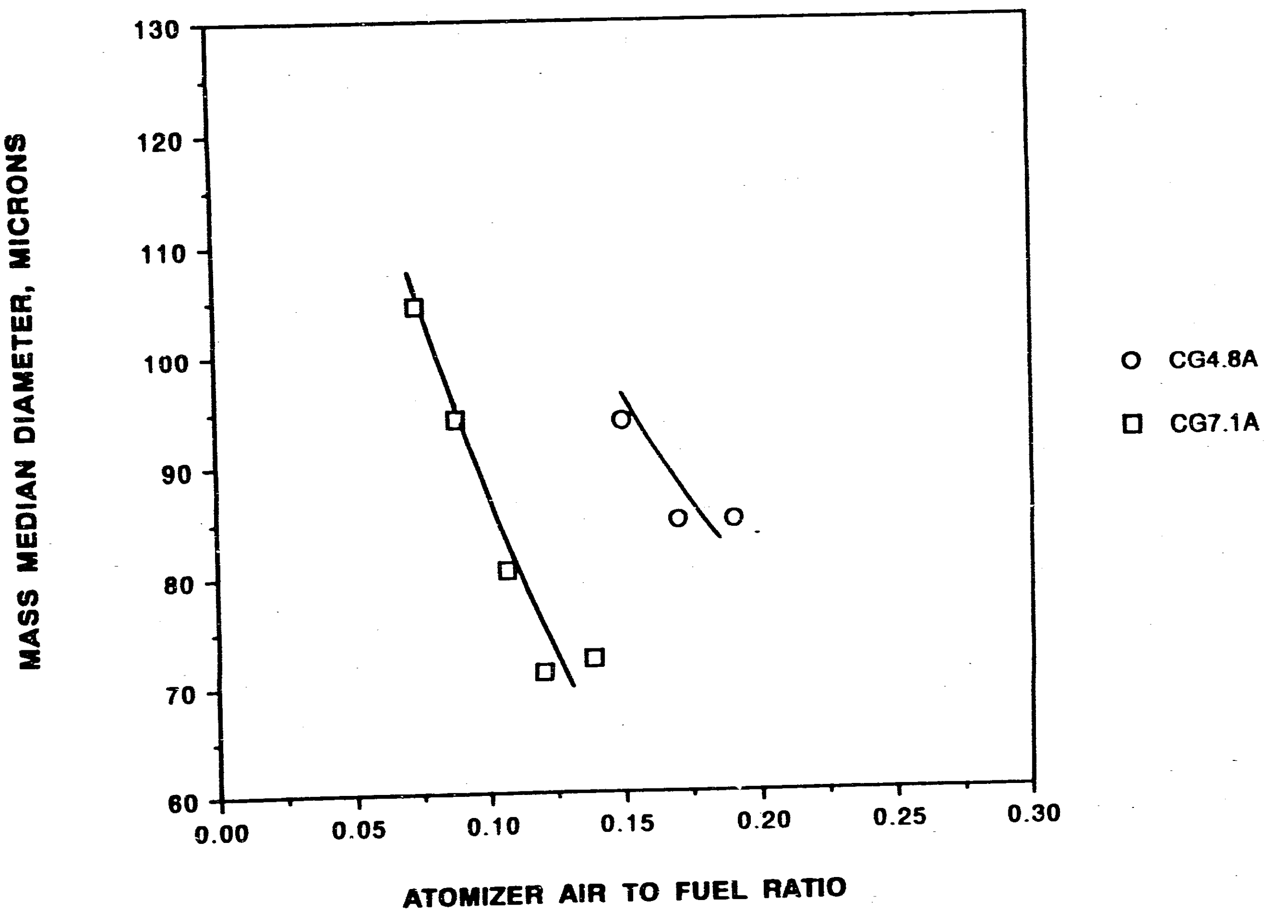
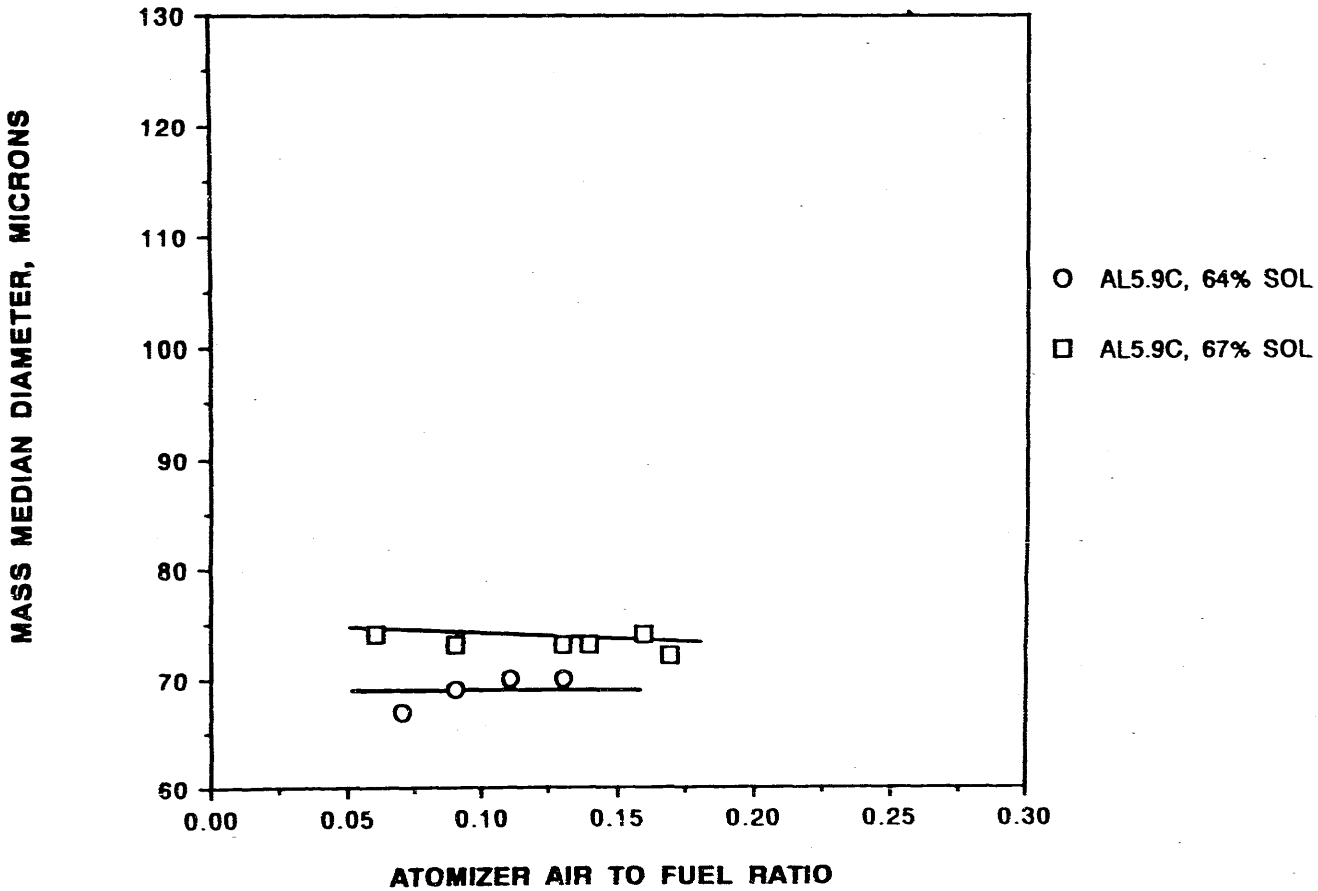


Figure B-5

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

(AT EQUIVALENT 4.1 x 10**6 BTU/HR FIRING RATE)



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