CHEMICAL AND PHYSICAL PROPERTIES OF HIGHLY-LOADED COAL-WATER FUELS AND THEIR EFFECT ON BOILER PERFORMANCE

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ABSTRACT

Coal-water fuels (CWF) are being developed as substitute fuels for industrial and utility boilers presently burning oil. The chemical and physical properties of CWF vary widely depending on the coal and preparation process used. Also, the traditional methods for characterizing fuels and existing correlations between boiler performance and fuel properties may not be applicable to CWF. Babcock & Wilcox is working under contract to the Electric Power Research Institute to determine the range of properties a CWF should have to qualify as a boiler fuel. Laboratory fuels characterization methods are being developed for use as standard procedures for measuring the key properties related to storage, atomization, combustion, handling in various transport systems, and deposition tendencies on boiler heat transfer surfaces. The relationship between laboratory-measured rheological characteristics of CWF's and their pipe flow and combustion performance is being determined. Atomization studies are being performed in a newly constructed atomization facility having the capability of testing atomizers at fuel flows equivalent to 5-50 million Btu/hr. Atomization quality is assessed using laser diagnostics to determine droplet size and velocity distributions. Flame stability and combustion efficiency are being correlated with atomization quality through combustion testing at 5×10^6 Btu/hr. The status of these studies is reported.

INTRODUCTION

Background

The use of residual fuel oil as a utility boiler fuel is coming to an end. Its price has increased by more than a factor of 5 since 1973. Its availability has become a matter of uncertainty. Federal policy prohibits its use in new baseload utility boilers, and the Congress has been considering mandatory conversion of existing oil-fired units to coal. Not surprisingly, then, utilities are aggressively searching for alternative fuels.

One such alternative may be coal-water fuel (CWF). Comprised of finely pulverized coal particles suspended in water, CWF may contain 65 to 80 percent dry coal by weight. The important and somewhat surprising characteristic of these highly loaded slurries is that they are quite fluid. They are also stable suspensions: the coal particles do not settle during storage for several weeks or even several months. Although producers differ in their methods, these properties are generally obtained by using a particular coal particle size distribution for efficient particle packing coupled with the use of certain chemical additives to provide good fluidity and stability.

One of the first applications of these fuels in the utility industry may be in boilers which were originally designed for coal firing, but because of the price, availability, and convenience of fuel oil, have been firing oil instead. In many cases these utilities never purchased, or have removed coal handling equipment, and many no longer have room for coal storage piles. If these utilities could be offered a coal-water fuel which could be fired with only minor modifications to their fuel oil handling systems, their conversion to coal firing would be greatly simplified and less costly. The environmental problems associated with coal storage piles would also be avoided.

Another possible short-term application for coal-water fuels is in utility boilers which were designed for oil firing. However, since coal-water fuel firing is similar to firing a moist pulverized coal, a number of problems arise.

The coal particle residence time in the boiler may not be long enough, at full load, to permit good carbon burnout. The boiler may not have an adequate ash removal system. Finally, there are problems associated with slagging, fouling, deposition, and erosion which must be addressed. All of these factors, which are strongly boiler-dependent, must be used to determine whether and by how much a boiler must be derated when firing coal-water fuel. Use of coal beneficiated to circa 1% ash may lessen the derating penalty enough to make slurries more viable for this application.

In the future CWF could fuel new utility boilers. Such factors as land availability, coal transportation costs, and relative capital costs of fuel handling and combustion systems will dictate the fuel choice.

Before coal-water fuels can fulfill this potential role, large-scale combustion tests must be performed. Also, large-scale fuel preparation facilities that can produce fuels of consistent quality and uniformity for a variety of coals must be designed and built.

To Babcock & Wilcox's (B&W's) knowledge, there are at least seven vendors of coal-water fuels who intend to market this product and who have subscale production facilities. It is suspected that many other organizations are currently pursuing the technology and could enter the marketplace in the near future. Prior to the work reported herein, B&W had performed preliminary fuel characterization, pumping, and combustion tests on CWF's from two of these vendors. The purpose of these feasibility studies was to determine whether these fuels, containing 67-72% dry solids, could be handled and burned in a manner similar to residual fuel oil. An existing 8-million Btu/hr oil burner fired at 4-million Btu/hr was used during these combustion tests. This burner is similar in design to burners provided in recent utility boiler offerings.

Results of these tests were encouraging. It was concluded that stable ignition of CWF could be obtained without the necessity of support fuel. The range of stable conditions, however, was more limited for the CWF tests than it was during combustion of the parent coals in the conventional pulverized form.

CWF properties had a profound influence on these combustion tests. For instance, large particles tended to plug the atomizer, and high CWF viscosities limited atomizer effectiveness. The ability to produce finely atomized droplets containing very few coal particles seemed to be the most important factor in achieving stable ignition. The effectiveness of atomization was greatly influenced by CWF viscosity, which could be decreased by preheating or diluting the fuel. Interestingly, while the viscosity of some CWF fuels decreases with increasing temperature, viscosity increases with increasing temperature for others. Clearly, more had to be learned about the effects of CWF properties on the combustion process prior to the eventual full-scale demonstrations of this new fuel.

Objectives

The Electric Power Research Institute (EPRI), concerned about fuel procurement for its planned industrial and utility boiler CWF demonstrations, awarded B&W a contract to resolve some of these issues. The prime objective of the program is to provide EPRI with a standard coal-water fuel specification with which it can procure fuels for future tests. Since such a specification would be useless without standard fuel characterization test procedures, B&W will also recommend testing procedures for use with CWF's. B&W's work on this contract is in progress, and this paper presents some preliminary experimental results.

EXPERIMENTAL APPROACH

In attempting to meet these goals, B&W is conducting an extensive experimental program consisting of work in four major areas:

- Laboratory fuel characterization tests
- Rheology testing
- Atomization characterization
- Combustion testing

EPRI has procured CWF's from five vendors to provide a range of physical properties representative of the expected commercial product. The vendors are each providing a CWF produced from a coal of their own choice. In addition, one vendor is producing a CWF from a coal provided by EPRI from its Homer City Coal Cleaning Plant. This "clean" coal was also supplied to B&W to be fired in the conventional pulverized form to provide a basis of comparison of combustion performance.

Experimental results in the four major areas of investigation will be correlated to link CWF combustion performance with CWF physical properties. This information will be used to determine the properties a CWF must have for use as a boiler fuel, and a standard CWF specification will then be generated.

Fuels Characterization

The fuel analysis procedures listed in Table 1 were used to characterize the parent coals and CWF's. These tests provide a basis for comparing different CWF's and a basis for assessing the effects of coal properties on CWF properties. The results of these tests aid combustion tests and in interpreting handling and combustion test results.

The test procedures consist of standard ASTM methods, special methods developed by B&W for routine evaluation of fuels, and additional test methods specific for CWF's. The CWF viscosities were measured by a Haake Rotoviscometer, Model RV-100. The particle size distributions of the CWF's were measured by two Leeds & Northrup Microtrac Particle Size Analyzers covering a range of 0.3 to 300 microns.

The Laboratory Ashing Furnace (LAF), shown schematically in Figure 1, was used to study factors pertaining to ash deposit formation in boiler tube banks. Properties of fly ash produced in this unit are comparable to those of fly ashes obtained from commercial installations when similar combustion conditions are maintained. The LAF is designed to fire liquid, solid, slurry, and gaseous fuels. The LAF has a nominal heat input of 200,000 Btu/hr. The LAF consists of pulverized coal and liquid/slurry feed systems, an appropriate burner for specific fuel type, a refractory combustion chamber with a three-zone electric guard heater, a water-cooled heat exchanger, and a fly ash collection system. The CWF feed system includes a heated 55-gallon storage tank with an air powered mixer, a Moyno pump with variable-speed drive, feed lines, and a water-cooled burner with internal-mix atomizers.

The CWF dynamic stability test equipment consists of CWF sample containers, a Ling shaker table, a G-force generator, and a random frequency generator. The simulated transportation modes and test conditions included ship (5-20 HZ and 0.6 G's), rail (5-20 HZ and 0.6 G's), truck under normal road conditions (20-100 HZ and 0.6 G's), and truck under severe road conditions (100-200 HZ and 0.6 G's). The dynamic and static test results provide information on the storage and transportation properties of CWF's.

Rheology

Many of the key physical properties of a CWF are associated with its flow properties. Not only do they determine its handling characteristics during transport and pumping, but the quality of atomization is also expected to be controlled by these properties. Since atomization quality has been shown to have a tremendous influence on the combustion performance of CWF's, the link between rheological properties and atomization quality must be established.

Since it is expected that the combustion characteristics of CWF fuels will be strongly dependent on the quality of atomization, and atomization quality will depend on the CWF flow properties, a support activity has been included to investigate the rheology of CWF's. In the development of a CWF working specification, it will be important to understand how slurry rheology affects the other phenomena of interest in this study. To facilitate this analysis it is important to verify that the rheological behavior of coal-water fuels can be understood in terms of the available theoretical models of non-Newtonian fluids. In particular, it is important to show that the flow properties of these slurries in process pipelines, etc., can be predicted well enough for design purposes using theory and certain key laboratory physical property measurements.

It is believed that the time-independent rheology of coal-water fuels can be modeled in the following way:

$$\tau - \tau_y = k\dot{\gamma}^n$$

where:

τ = shear stress

τ_y = yield stress (empirical constant)

k = empirical constant

$\dot{\gamma}$ = shear rate

n = empirical constant

It is known, for example, that most CWF's exhibit a yield stress (will not flow until the applied shear stress reaches some critical value) and show decreasing viscosity with increasing shear rate ($n<1$). Both of these characteristics can be handled in a straightforward manner using this model.

There are complicating factors, however. All of the empirical constants in the model are functions of temperature and quite possibly functions of time as well. Slurry fuels are known to exhibit thixotropy (viscosity decreases with increasing time at constant shear rate) meaning that the constants in the rheological model change as the slurry flows down the length of the pipeline.

The approach taken in this study was to use extensive laboratory viscometer measurements to determine the effect of temperature, shear rate, and time at constant shear rate on the apparent viscosity of the various coal-water fuels tested. This information will be used to determine the appropriate values for the constants in the rheological model corresponding to various flow conditions. Eventually, these results will be correlated with pipe flow results and results from the other areas of investigation.

Atomization

Atomization characterization tests are performed in B&W's recently completed Atomization Facility (Figure 2). This facility is equipped with state-of-the-art laser diagnostics, and permits local droplet velocity, size distribution, and relative number density measurements to be made in large-scale sprays. The inside dimensions of the spray chamber are 8 feet x 8 feet x 10 feet. Mounted on opposing walls are two 4-foot x 8-foot plate glass windows which provide optical access to the spray for laser measurements, visual observation, and still and motion picture photography.

A uniform, axial flow of air continually sweeps through the chamber to prevent the build-up of a "fog" of very fine droplets. This air flow is provided by a large, forced draft fan, and is straightened and uniformly distributed by the windbox. The atomizer barrel is inserted through the windbox as shown. A gas cleanup system attached to the downstream end of the chamber removes most of the spray droplets from the air stream before it is exhausted back into the atmosphere. In the case of CWF, the fuel collected in the gas cleanup system is pumped into a large holding tank for subsequent disposal.

A 2000-gallon storage tank holds the CWF to be tested. The tank is equipped with a low-rpm stirrer. A variable speed, progressing cavity pump is used to supply CWF to the atomizer, and is capable of delivering 2-20 gallons/minute of CWF at a discharge pressure of 400 psig. The system is also equipped with an electric CWF heater which has a 100 KW capacity. With this heater the CWF can be heated to temperatures in excess of 250°F.

Local droplet velocity, size distribution, and relative number density can be obtained from the laser diagnostics using particle sizing interferometry (commonly referred to as the visibility technique). The method requires the same basic optical equipment as the dual-beam Laser Doppler Velocimeter (LDV) technique. The visibility and LDV techniques can provide non-intrusive local measurements of individual droplet size and velocity.

A schematic of a dual-beam LDV is shown in Figure 3. It consists of a laser, beam splitter, focusing lens, collection optics, photodetector, and signal processor. At the intersection of the two beams, which defines the measurement volume, a fringe pattern is formed by the interference of the two coherent beams. As a droplet moves across the measurement volume, it scatters light which is collected and processed by the signal processor. A typical signal is also shown in Figure 3, and is know as a Doppler burst.

The Doppler burst is made up of two components - an AC signal superimposed on a Gaussian "pedestal". The period of the AC signal and the fringe spacing can be used to determine the droplet's velocity. Droplet size can be determined from the "visibility" defined as

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

where I_{max} and I_{min} are defined as shown on the figure. It turns out that visibility is a simple function of (D/S) (where D = droplet diameter and S = fringe spacing) over a droplet diameter range of about 10:1. By changing the fringe spacing, a different range of droplet diameters can be measured.

The Atomization Facility is used to characterize the droplet size distribution obtained from the same atomizer being used for the combustion tests for each of the CWF's. A variety of atomization conditions (fuel flow rate, air/fuel ratio, fuel temperature) is investigated. Again, these results will be correlated with the results from the other areas of investigation.

Combustion

Combustion tests are performed in B&W's Basic Combustion Test Unit (BCTU) shown in Figure 4. It is a water-cooled horizontal furnace with a nominal firing rate of about 5 million Btu/hr when firing pulverized coal. The combustion chamber is cylindrical with a diameter of 4-1/2 feet, and is 8 feet long. It is partially lined with refractory brick to bring flame temperatures more in line with larger units. Two separately-fired air heaters are capable of supplying 800°F combustion air. A number of viewports mounted on the furnace permit visual observations, and provide access for various probes for detailed in-flame measurements.

Coal-water fuel is supplied to the furnace with a system consisting of a 500-gallon storage tank equipped with a stirrer, a variable-speed progressing-cavity pump, and a mass flow meter. An electric heater is also available for heated CWF tests. A dual-fluid, internal-mix atomizer is used to inject the CWF into the furnace in the form of a fine spray. Compressed air is used as the atomizing fluid.

The burner being used is a research burner having four concentric air zones which provide flexibility in how the air enters the furnace. Two of the zones are equipped with devices for imparting swirl to the flow, and another is equipped with a natural gas burner for firing the furnace at full load on natural gas. The burner is also equipped with a bluff body stabilizer for improved ignition stability.

The combustion characteristics of coal-water fuels must be comprehensively studied in order to achieve EPRI's principle objective -- the establishment of specifications for such fuels with which EPRI can confidently procure the large quantities of CWF that will be needed for future large-scale demonstrations. For B&W, determining combustion characteristics of CWF means performing a standard fuel characterization program similar to many such programs the company has performed in the past to determine the characteristics of other potential boiler fuels. Of course, each program must be tailored to fit the peculiarities of the fuel being tested.

In the case of CWF, there are a number of important areas in which further information is needed before these fuels can be demonstrated on a utility boiler. Ignition stability, the excess air and residence time needed for good carbon utilization, ash handling and deposition characteristics, flame temperature, and pollutant formation must all be addressed. And for the purpose of determining the specifications of a CWF boiler fuel, the way these factors are affected by changes in the various CWF properties such as, moisture content, particle size distribution, chemical additives, slurry rheology, and parent coal characteristics must be delineated. It is the purpose of the combustion test program to address all of these factors and provide a maximum amount of the needed information.

Using the BCTU, B&W will relate combustion performance in terms of ignition stability, turndown, excess air requirements, NO_x emissions, and carbon burnout, to slurry characteristics such as solids loading, particle size distribution, viscosity vs. shear rate, viscosity vs. time, viscosity vs. temperature, and coal type. This information will be combined with an evaluation of slurry pressure drop, slurry storage and handling characteristics, and qualitative characterization of atomizer wear to provide the basis for recommending an acceptable range of slurry properties to guide future development work.

PRELIMINARY RESULTS

At the time of writing much of the testing has been completed, but only a small fraction of the data has been analyzed. A detailed presentation of the results of the entire program is therefore not possible. Rather, it is our intention to present in this section some examples of the type of results being obtained, and to indicate some of the trends that have been noted thus far.

Fuels Characterization

ASTM and B&W fuel analysis procedures were applied to samples of the parent coals and coal-water mixtures as show in Table 1. The results of selected procedures for the CWF's are shown in Table 2. All the CWF's were prepared from high volatile eastern bituminous coals. Based on the volatile content and burning profile of the CWF's, ignition and a stable flame would be expected in a burner and furnace designed for similar coals. Other things being equal, ignition and flame stability of CWF's are strongly dependent on both volatile content and atomization quality. It is safe to state that CWF should be made from high volatile bituminous coals with volatile contents as high as possible.

The five CWF's had a wide range of solids contents from 69.3 to 75.3% and viscosities from 510 to 1955 cp @ 100 sec^{-1} shear rate. Examples of viscosity curves (viscosity versus shear rate) will be presented in the discussion of the CWF rheology. All the CWF's tested were thixotropic (decreasing viscosity with time at constant shear), but some appeared dilatant (increasing viscosity with increasing shear), while others appeared pseudoplastic (decreasing viscosity with increasing shear). A slurry which is both thixotropic and pseudoplastic is more desirable from a handling and atomizing standpoint. The fuels exhibited different responses as a function of temperature. The viscosity of several CWF's decreased with increasing temperature, while several did the opposite.

The particle size distribution (PSD) of the CWF's were not drastically different. All the fuels had at least 98.5% passing 50 mesh (300 microns). All the fuels, in general, were coarser than normal pulverized coal (PC) which has a mass mean diameter of approximately 40 microns. Four of the slurries contained more fine material than normal PC, which has an average Sauter mean diameter of 15 microns. Four CWF's had at least 70% of the material less than 200 mesh (75 microns). In general, the CWF's had a wider particle size distribution than PC. Example particle size distributions are presented in a later section.

All the CWF's had sulfur contents less than 1%, ash contents varied from 1.8 to 7.9%. Some of the coals used to prepare the slurries were beneficiated to decrease ash and sulfur levels. The CWF's had almost identical densities. Four of the slurries had a pH in the range of 7.3 to 8.6, and the fifth had a pH of 6.0.

The fuels were subjected to several tests in order to predict the deposition potential of each. Deposition potential and ash chemistry is particularly important because of the effect on the size of industrial and utility boilers, furnace heat release rates, the design of heat transfer surface, and the number and placement of boiler cleaning equipment for ash and slag deposit removal. The deposition potential of the parent coals and CWF's is shown in Table 3.

Slagging potential is indicated by R_s values (based on elemental ash analysis) and R_{vs} values (based on actual slag viscosity/temperature relationship). These slagging indexes indicate that full-scale slagging behavior of these fuels would be low or medium. Some important observations, however, can be noted. Slurries A and D showed a substantial increase in sodium content as compared to the parent coal. The softening temperature of the CWF's were 230 and 350°F lower than the parent coal.

Fouling potential is indicated by R_f values (based on elemental ash analysis) and sintering strength values (based on crushing strength of simulated full-scale boiler fly ash produced in the LAF). The most important observation from Table 3 is the increase in fouling potential of the CWF's A and D compared to that of their parent coals. Since it has been well documented that the sodium content of a fuel plays a major role in its fouling behavior, the severe fouling classification of the two CWF's is probably due to the increased sodium content. The CWF of vendor E also had a high fouling potential based on elemental analysis.

The increased deposition potential of two of the CWF's and the higher deposition potential of the CWF made from a highly beneficiated coal are important from a utilization point of view. The type and quantity of chemical additivies used in the preparation of the coal-water fuel can have a significant influence on the deposition characteristics. While the total quantity of mineral matter in the coal can be reduced by beneficiation, the relative quantities of chemical elements in the remaining minerals may be altered. This may increase the potential for formations of troublesome, difficult-to-remove boiler deposits in spite of the lower ash loading during utilization.

An important CWF property is that related to the settling of coal particles under storage (static) and transportation (dynamic) conditions. Figures 5 and 6 show typical static and dynamic test results for three CWF's (A, B, and D). Several general trends can be stated based on these figures and other test results. All the fuels exhibited little settling (based on solids content) of the liquid portion of the sample, but all contained settled material on the bottom of the container. This material was approximately 2 to 4% of the total weight of slurry.

The settled material ranged from a soft-pack in which the slurry could be easily resuspended to a hard-pack which required significant effort to resuspend. The dynamic stability of the CWF's appear independent of frequency (up to 200 HZ) and acceleration (up to 0.6 G's). The dynamic test results for simulated truck transportation agreed with the condition of the as-received slurries subjected to actual truck transport. The static and dynamic test results for times of 1, 2, and 3 days were almost identical. This would suggest that the stability of CWF's is not dependent on the transportation mode, but can be predicted from static test conditions. Stability was shown to be dependent on storage time because the amount of settled material increased during a test period of 6 weeks. There was essentially no difference in the particle size distribution of the slurry throughout the sample container including the settled material on the bottom.

Rheology

A first step in the analysis of the rheological properties of the various CWF's is to verify that the pipe flow characteristics of these fuels are predictable from laboratory viscometer measurements. A viscometer generates a "flow curve" relating the rate of shear ($\dot{\gamma}$) to the shear stress (τ) applied, or alternatively, to the apparent viscosity $\mu_a(=\tau/\dot{\gamma})$. Generally, such a curve can be used with the equations of motion and continuity to predict pressure losses for pipe flow. The procedure can be reversed, however, to generate a flow curve from pipe line pressure drop measurements which can then be compared with the viscometer-generated curve.

The results of such an analysis for CWF - D are shown in Figure 7. The solid line represents the flow curve generated with a rotational viscometer. It indicates a complicated, non-Newtonian, time-dependent rheology. The time dependence, as evidenced by histeresis, is typical of a thixotropic fluid (its apparent viscosity drops with time at shear). The data points shown in the figure are generated from pipeline pressure drop data. It can be seen that the two sets of results are in reasonably good agreement. Over the common range of shear rates they indicate a fluid whose viscosity increases with increasing shear rate (a dilatant fluid). The small difference in apparent viscosity between the two results is probably due to a slight difference in water content of the two samples, although it may be a result of the time-dependent behavior (thixotropy). A difference in water content of as little as 0.1 percent could account for the difference.

It can be concluded from these results that the flow behavior (pipeline pressure losses, etc.) of this CWF can be predicted from laboratory viscometer measurements and existing non-Newtonian flow models. Rheology test results such as these will be used extensively to understand atomization and combustion results.

Atomization and Combustion

Unfortunately, few results from the atomization and combustion tasks are available at the time of writing. It is partly for this reason that the two have been combined into a single section. Beyond this reason, however, the combination is a natural consequence of the inseparable nature of the two phenomena. It has become apparent that the quality of atomization has a tremendous influence on the combustion performance of a CWF. Production of very fine droplets is essential if stable, unassisted ignition of the fuel is to be obtained. Production of large droplets (in excess of 300 microns) which will not completely burn, means a lower carbon utilization efficiency.

It should be apparent from the last two statements that droplet size, and not coal particle size, determines the size of burning particles in a boiler. We believe that is the case. Even at this early stage in the data analysis, such a conclusion seems unavoidable.

As an example, consider the results shown in Figures 8, 9, and 10. Figure 8 shows droplet size distributions for a CWF generated using the Atomization Facility. Two curves are shown -- one for a CWF flow rate equivalent to full-load conditions at the BCTU (4×10^6 Btu/hr), and the other for approximately one-quarter of that flow. Note that the low-load droplet size distribution is finer than that for full load. This is as expected since the atomizing air flow rate was held constant for the two tests, resulting in a higher air/fuel ratio for the low load condition.

Figure 9 shows fly ash particle size distributions collected during the BCTU combustion tests. Fly ash size for full load conventional pulverized coal firing, full load CWF firing, and lower load CWF firing are shown. Coal particle size distributions for a conventional pulverized coal and CWF-A are shown in Figure 10. By comparing the figures, it can be seen that CWF firing at full load produces a coarser fly ash than conventional pulverized coal firing, while firing at low load produces a finer fly ash. Since carbon conversion in the BCTU is generally poorer at low load than at full load when firing pulverized coal, the finer fly ash at low load must be due to a better quality of atomization -- which is consistent with the atomization results presented above.

This is only one example of the kind of information B&W is generating as part of the EPRI program. A tremendous amount of data is being taken in all four areas of investigation, and on all the CWF's. It is expected that much of this information will be available for presentation at the National Meeting in Seattle.

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TABLE 1

Fuels Characterization Tests

FUEL ANALYSIS PROCEDURE	PARENT COAL	CWF	METHOD
Total Moisture	X	X	ASTM (D3173, D3302)
Solids Content		X	ASTM (D3173, D3302)
Hardgrove Grindability	X		ASTM (D409)
Proximate Analysis	X	X	ASTM (D3172)
Ultimate Analysis	X	X	ASTM (D3176)
Higher Heating Value	X	X	ASTM (D2015, D3177)
Sulfur Forms	X	X	ASTM (D2492)
Ash Fusion Temperatures	X	X	ASTM (D1857)
Elemental Ash Composition	X	X	B&W
Ash Sinering Strength	X	X	B&W
High Temperature Slag Viscosity	X	X	B&W
Burning Profile	X	X	B&W
Volatile Release Profile	X	X	B&W
BET Surface Area	X	X	B&W
Slurry Density		X	B&W
Slurry Viscosity vs. Temperature		X	B&W
Particle Size Distribution			
• Microtrac		X	B&W
pH	X	X	B&W
Slurry Stability			
• Static		X	B&W
• Dynamic		X	B&W

TABLE 2

CWF Properties

FUEL PROPERTY	SLURRY VENDOR A	B	C	D	E
Solids (%)	75.3	69.3	69.4	69.9	74.9
Viscosity (cp @ 100^{-1} sec)	1955	1575	1550	510	520
HHV (Btu/lb, as received)	10730	9910	10180	10180	11380
HHV (Btu/lb, dry)	14250	14300	14670	14560	15190
VM (%, as received)	24.7	26.5	24.8	22.9	28.0
VM (%, dry)	32.8	38.2	35.7	32.7	37.4
Ash (%, dry)	7.9	6.3	5.9	6.9	1.8
Sulfur (%, dry)	0.84	0.87	0.81	0.77	0.91
Particle Size Distribution					
% < 200 Mesh	70	78	63	78	73
Mass Mean Diameter (microns)	59	44	67	48	53
Sauter Mean Diameter (microns)	7	9	15	8	11
pH	8.6	7.6	7.3	8.1	6.0
Density (g/cc)	1.23	1.22	1.20	1.23	1.23

TABLE 3

Deposition Potential of Parent Coals and CWF's

	VENDOR							
	A		B		D		C	E
	Coal	CWF	Coal	CWF	Coal	CWF	CWF	CWF
Slagging Parameter								
R_s (Classification)	.14 (Low)	.12 (Low)	.10 (Low)	.05 (Low)	.11 (Low)	.19 (Low)	.12 (Low)	.79 (Med)
R_{vs} (Classification)	(Low)	.24 (Low)	(Low)	.22 (Low)	(Low)	.81 (Med)	(Low)	.45 (Med)
Fouling Parameter								
R_f (Classification)	.18 (Low)	.61 (High)	.05 (Low)	.03 (Low)	.15 (Low)	.74 (High)	.06 (Low)	.80 (High)
Sintering Strength, psi	2290	17900	500	2072	1052	16200		
@ 1700°F (Classification)	(Med)	(Severe)	(Low)	(Med)	(Low)	(Severe)		
Other Indicators								
Na as Na_2O (%)	0.85	2.56	0.39	0.61	0.92	3.02	0.40	0.92
Fe as Fe_2O_3 (%)	9.02	9.37	5.43	5.93	7.51	9.20	8.20	40.26
Softening Temp. (°F) (reducing atmosphere)	2630	2400	2750+	2750+	2750+	2400	2750+	2140

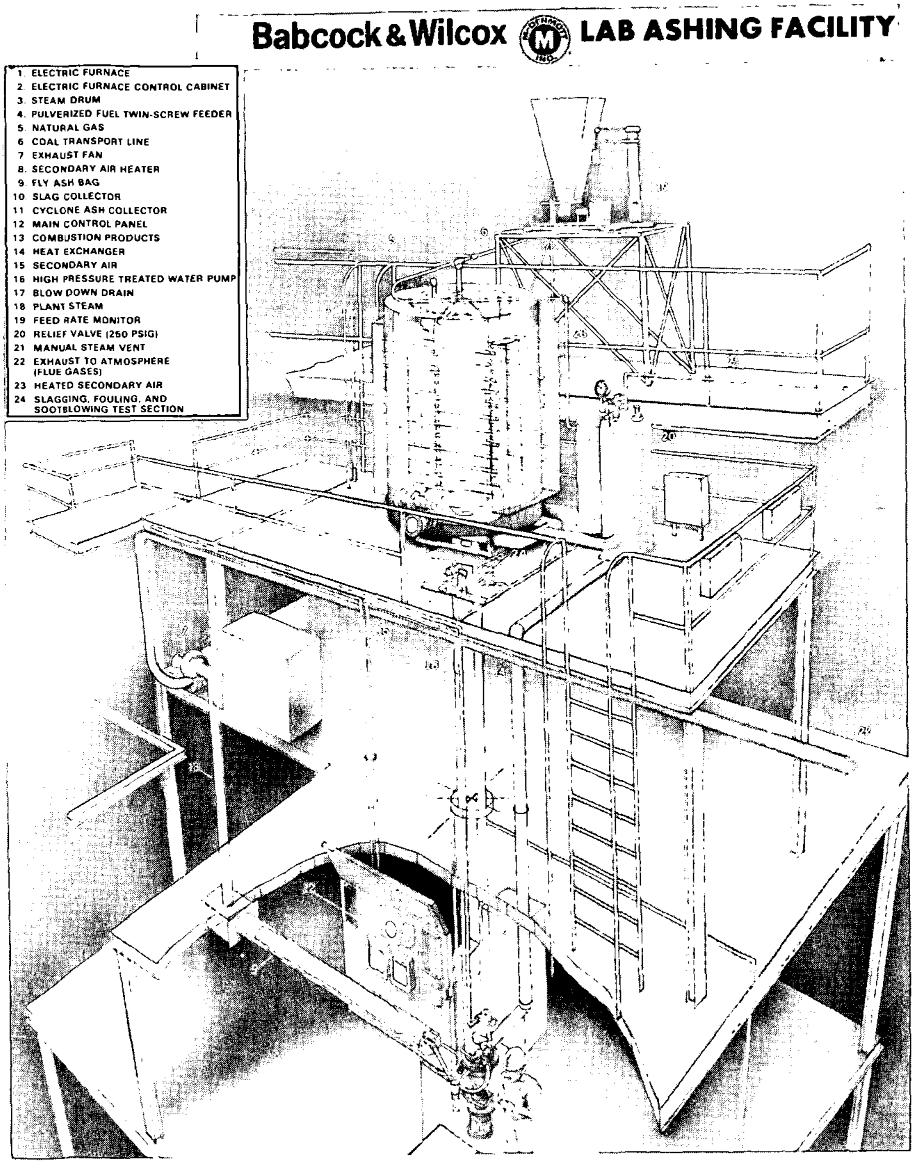

Figure 1. Laboratory Ashing Furnace.

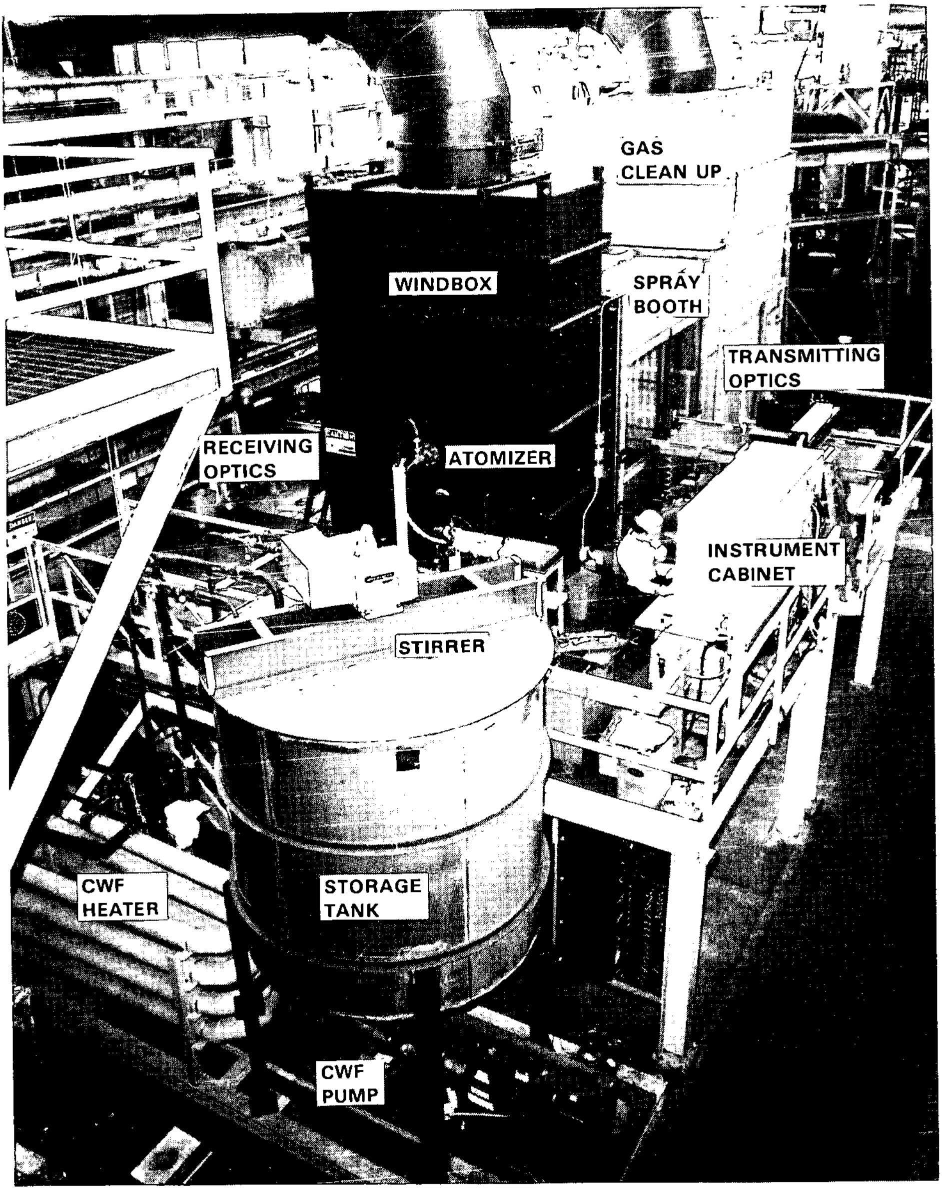

Figure 2. Atomization Facility.

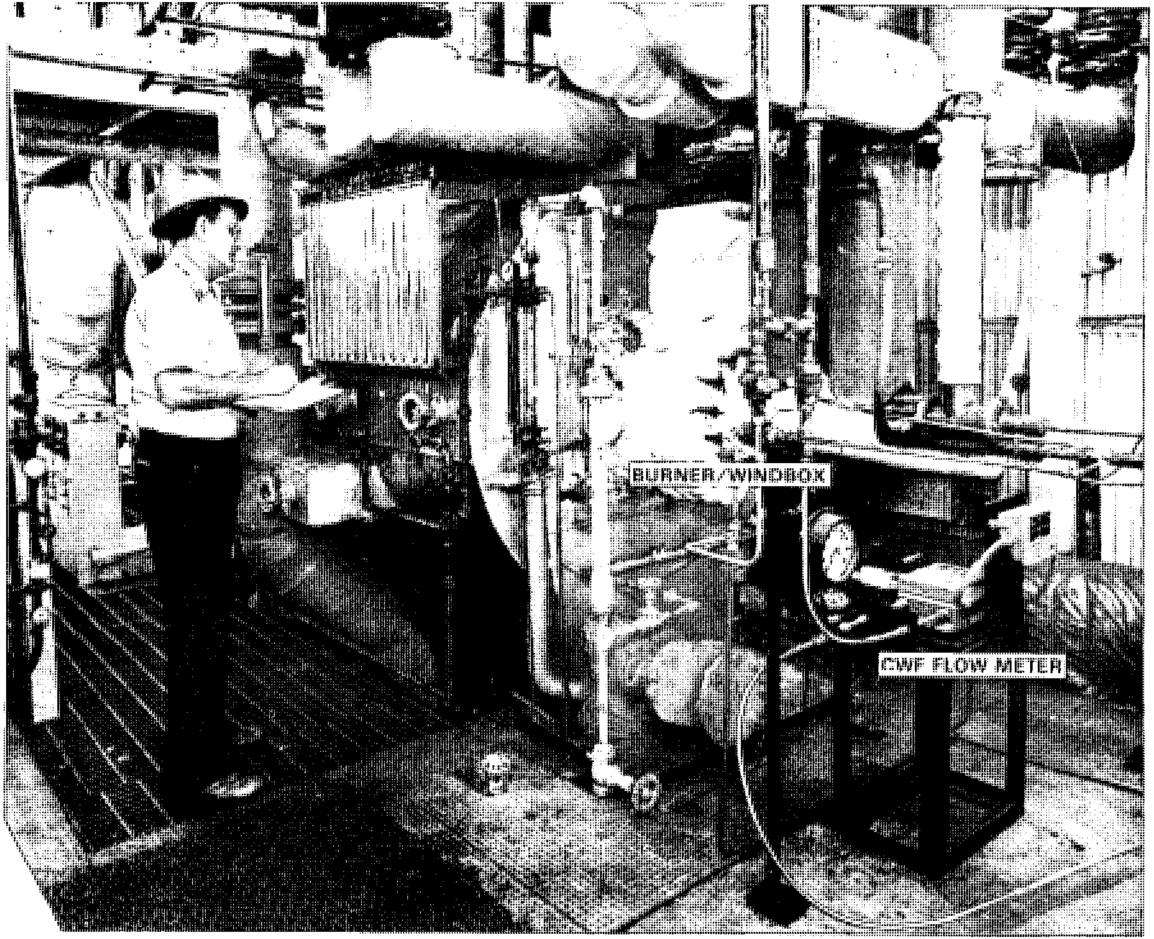

Figure 4. Basic Combustion Test Unit.

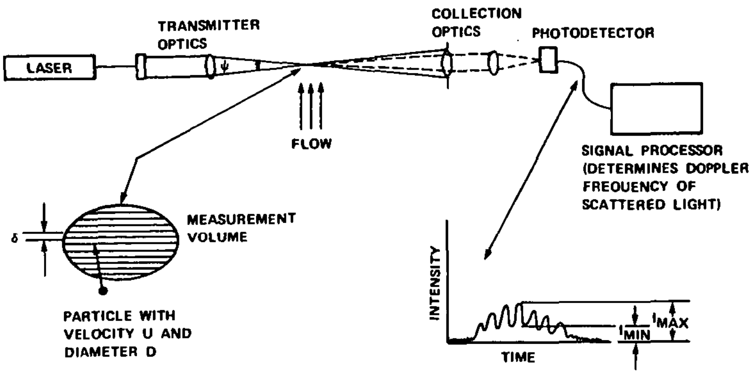

Figure 3. Laser Doppler Velocimeter (LVD) System Used to Size Particles by the Visibility Technique.

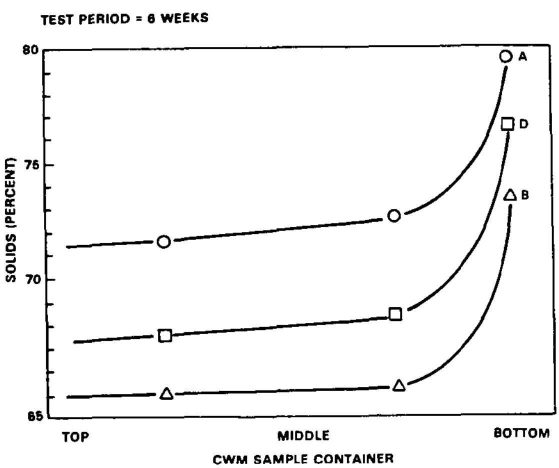

Figure 5. Static Stability Test Results.

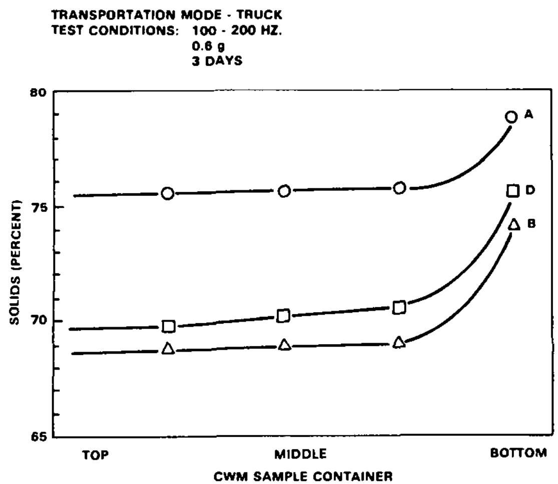

Figure 6. Dynamic Stability Test Results.

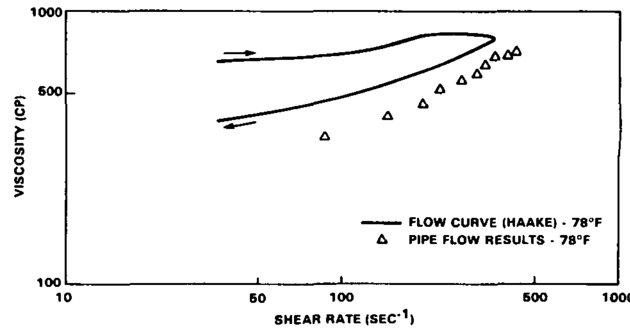

Figure 7. Rheology Test Results – CWF – D

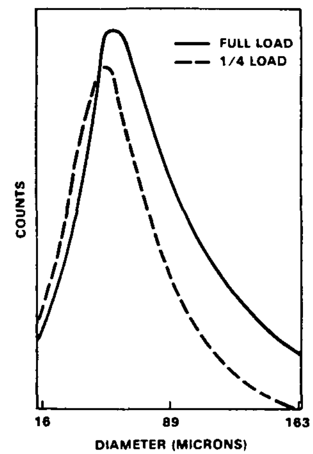

Figure 8. Droplet Size Distributions for CWF Sprays.

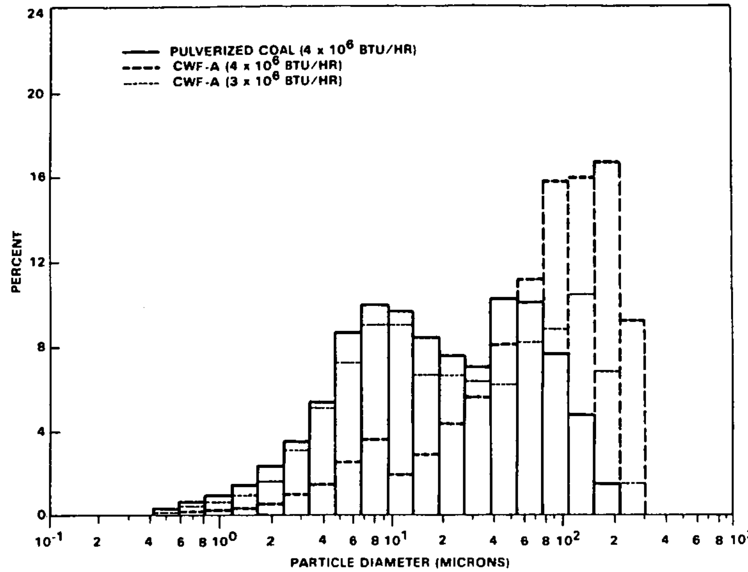

Figure 9. Fly Ash Particle Size Distributions.

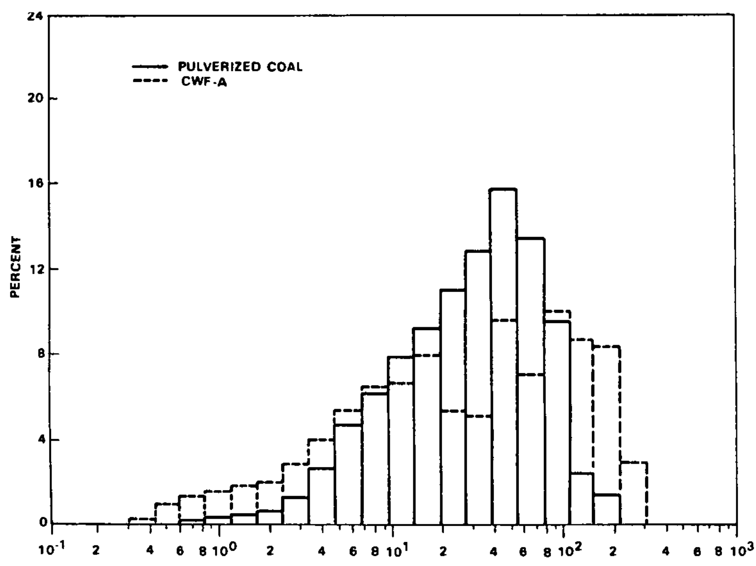

Figure 10. Particle Size Distributions -- Pulverized Coal and CWF -- A.