

CWS Rheology: The Role of the Coal Particle

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Introduction

The rheological properties of concentrated suspensions are important in a number of industries, particularly paints and coatings. The work of Chang et al (1) mentions some of the early experimental work in this area, but theoretical work on concentrated systems is quite limited(1-5). The reason for this is clear--the assumption of independent particles interacting only with fluid surroundings is not valid under these conditions, and the coupled motions of particles can be treated only empirically. The current research activity in coal slurry fuels has caused a renewed interest in this problem because the rheological properties of these fuels are of primary importance. Typically, one desires a liquid fuel with 65-70 weight percent solids, viscosity on the order of 10^3 centipoise, and resistance to sedimentation and shear degradation. These properties can be manipulated by the use of different particle size distributions of the powdered coal, surfactants or wetting agents, and water soluble polymers which act as stabilizers.

However, the wide variety of choices for these three compounding variables makes the task of finding the optimal formulation quite tedious and unsure. For this reason the work described below was undertaken. It represents an attempt to isolate the effect of particle size distribution (PSD) on the resulting slurry viscosity given that all other variables, i.e., the additive package, remain fixed. Comparison of theoretical predictions of relative viscosities of slurries with different PSD with experimental results show that the theory can be useful in optimizing the PSD.

Theory

There are two steps in the development of a model for predicting relative viscosity for particle size distribution. The first is to compute the maximum packing efficiency (volume fraction) ϕ_p possible for a given PSD. At this loading the viscosity of a slurry at realistic shear rates is assumed to be infinite, since it represents a random dense packing. Another way of viewing this limit is to consider the flow of a slurry as motion of the larger particles over one another as being "lubricated" by the motion of the smaller particles in the interstices. At ϕ_p no motion of these smaller particles is possible and hence the viscosity becomes very high. Thus it is expected that the viscosity of a slurry will increase rapidly as the actual particle loading ϕ approaches the value ϕ_p . The second step of the model is to quantify this behavior.

In order to calculate ϕ_p for a given PSD the method of Lee (7) has been used. A brief description of this procedure will be given here, but for a detailed discussion the reader is referred to the original work. Consider a binary PSD, that is one which consists of only two sizes of spherical particles, and ask how the maximum packing fraction can be determined. One procedure is to fill a volume with the dense random packed larger spheres giving a packing fraction $\phi_{max,L}$ and then filling the remaining volume with the smaller spheres. The final packing fraction is

$$\phi_{\max} = \phi_{\max,L} + (1 - \phi_{\max,L}) \cdot \phi_{\max,S}$$

It is assumed that $\phi_{\max,L} = \phi_{\max,S}$, that is that monodisperse spheres all pack with the same efficiency in dense random packings. The value assigned is determined by experiment to be .639. The composition of this mixture is $X_{\max,L} = \phi_{\max,L} / \phi_{\max} = .735$. An assumption which is implicit in the above is that the large and small particles are sufficiently different in diameter ($D_L/D_S > 100$) that the interstitial volumes between the large spheres can be summed and treated as a bulk void for purposes of packing the smaller spheres. The experimental work of McGeary (8) is used to determine the ϕ_{\max} for diameter ratios $1 < D_L/D_S < 20$. Thus far this process gives the ϕ_{\max} for binary mixtures of arbitrary sized spheres. The next extension is to compute the packing fraction ϕ_p for binary mixtures with a specified composition. Lee has given an analytical procedure for doing this under the assumption that the $X_{\max,L}$ is independent of the diameter ratio of the spheres. This reasonable assumption is based on the premise that any optimal packing will contain a dense, random packing of the largest spheres in the system, which is then filled in with any available smaller spheres. Clearly the replacement of a large sphere in such a packing arrangement with the maximum number of inscribed smaller spheres will produce a less efficient packing. Finally, Lee has given an algorithm for computing the packing fraction ϕ_p for mixtures which contain an arbitrary distribution of spherical particles. The algorithm, which is based on a geometrical construction, is given below.

$$(\phi_p)_i = \sum_{j=1}^N \phi_{ij} X_j \quad 1 = \sum_{j=1}^N X_j$$

where $\phi_{ij} = .639$

$$\phi_{ij} = .639 + (\phi_{\max}(D_i/D_j) - .639) / .265$$

$$\phi_{ji} = .639 + (\phi_{\max}(D_i/D_j) - .639) / .735$$

$$D_i/D_j > 1 \text{ or } i > j$$

$$X_j = \text{volume fraction of particles of diameter } D_j$$

$$N = \text{number of discrete diameters present in mixture}$$

$$\phi_{\max}(D_i/D_j) = \text{maximum packing fraction of binary mixture consisting of spheres of diameter } D_i \text{ and } D_j.$$

The set of (ϕ_p) values has N members and the smallest one is chosen as the packing fraction ϕ_p . The algorithm is not easily understood by inspection because it is graphical in nature, but is developed in a straightforward way in Reference 7. In order to use this technique to predict ϕ_p for a coal grind, one simply performs a particle size analysis, discretizes the distribution into N bins, and then computes ϕ_p .

There are several equations available for obtaining the relative viscosity of concentrated slurries from a knowledge of the packing fraction ϕ_p and the actual volume fraction solids ϕ . The Mooney equation (9)

$$\eta = \eta_0 \exp[2.5\phi / (1 - \phi/\phi_p)] \quad (1)$$

expresses the hydrodynamic viscosity of the suspension in the limit of high shear rate, relative to the viscosity of the pure suspending medium η_0 . This expression is valid in the range where $\phi \approx \phi_p$, and where the double layer thickness surrounding particles in aqueous solution is small compared to the particle diameter. Both of these criteria are satisfied by the coal slurries described here.

However, the justification for this form is clear only for monodisperse or slightly polydisperse systems. An alternative is the empirical equation (1,10)

$$\eta = \eta_0 \left[1 + .75 \frac{\phi/\phi_p}{1-\phi/\phi_p} \right]^2 \quad (2)$$

which has been successful in describing results obtained with suspensions of glass beads in polyisobutylene.

Experiments

The theory presented above has been used in two different ways to predict the viscosity of coal water slurries. One application involved mixing a fine grind of coal with a coarse grind in varying proportions to produce bimodal particle size distributions. It was found by experiment that there always existed an optimum blending proportion which produced a slurry of minimum viscosity (with the additive package remaining fixed). The theory was tested to see if it could successfully predict this optimum blend given the PSD for the two starting grinds and the total weight fraction of coal to be used. The procedure was simply to compute the packing fraction ϕ_p using the above algorithm, convert the weight fraction coal to a volume fraction ϕ in the slurry, and use equation (1) or (2) to evaluate the relative viscosity η/η_0 . The value of η_0 was then selected to scale the data at one point (usually the minimum viscosity). The results of this procedure are shown in Figures 1 and 2. The data in the former utilized two different grinds of the same coal which had median diameters of 5μ and 35μ . Although the viscosities are not predicted quantitatively, the shapes of the curves are similar and the location of the minimum is given correctly. In Figure 2 the data was obtained from mixtures of two different coals with median sizes 15μ and 40μ . Again the blend composition giving the minimum viscosity is given correctly. Both of these coal slurries were 65% coal by weight. Also equation (2) was used to compute the theory points in both cases but equation (1) was equally suitable, the difference being in the width of the curves rather than in the location of the minima.

A second application was to predict the change in viscosity with coal loading in coal water slurries. Figure 3 shows viscosity data for a coal subjected to different grinding conditions which resulted in different size distributions, A and B. The volume median (or equivalently, weight) sizes were 50μ and 25μ , respectively. The ϕ_p corresponding to each of these PSD's were computed, and theoretical curves drawn using equation (2) with ϕ being the independent variable. Note that the x axis in the figure is the more familiar weight percent coal while the ϕ_p in equation (2) is the volume fraction coal (conversion was made assuming a coal density of 1.34 g/cm^3). The theory is quite successful in fitting these results, but substantially less so when equation (1) is used.

Conclusion

The effect of coal particle size distribution on the viscosity of coal water slurries has been analyzed using a particle packing model due to Lee in conjunction with an empirical relationship between packing efficiency and viscosity. The technique is able to predict the optimum PSD when one degree of freedom is present, such as the blending ratio between a coarse and a fine grind of coal. The results presented here illustrate this for the cases where the two grinds are the same coal and where they are different coals. In addition data has been presented which shows that one can predict the behavior of viscosity vs. coal loading curves as the PSD of the coal is varied. Both of these achievements are quite useful in the development of coal water slurry formulations in that they allow the value of specific coal

grinds to be assessed without extensive slurry preparation and measurement. The method can also be used to assess the relative merits of unimodal and bimodal size distributions.

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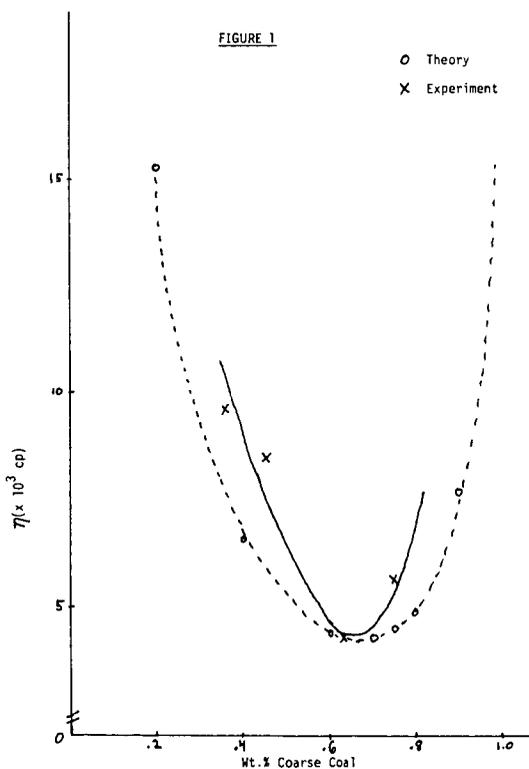


FIGURE 2

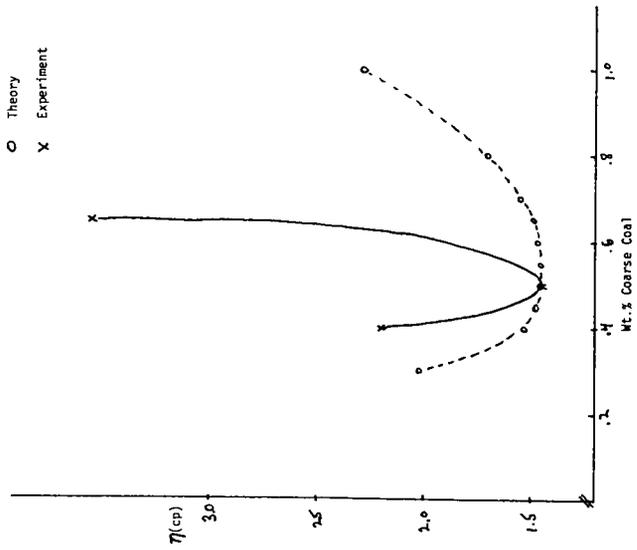
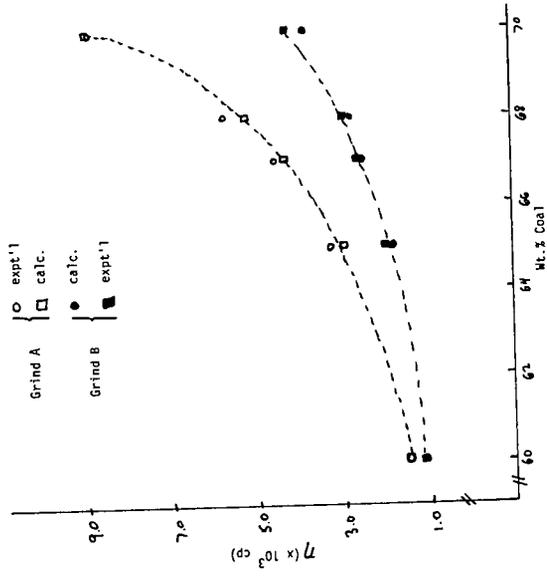


FIGURE 3



BENEFITS OF COAL CLEANING UPON THE PERFORMANCE OF COAL-WATER SLURRIES

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Introduction

Coal preparation as described in "days gone-by" functioned around the one word - "TIPPLE". This word, tipple, is rapidly losing its identification within the coal industry except for those we admire so much who have devoted their entire industrial life to this coal industry. Now, through the modern coal industry, we hear such terms as coal washing, coal preparation, coal cleaning, coal beneficiation, which also in themselves create confusion about what is meant.

As you drive along the Appalachian roads today, remnants of the tipples of "days gone-by" can be seen. Long chutes can be seen coming down the mountainside to the loading truck ramps. These wooden structures remind us of the technology of that day and they are now left only to the imagination of the artist to describe those days.

Today's coal preparation facility looks more like a massive industrial complex with long belt lines coming in and out of a preparation facility and ancillary facilities such as dewatering and refuse handling systems. An aerial view of one of our preparation plants is shown in Figure 1. This plant, located at one of our operations near Grundy, Virginia, processes in excess of 700 TPH of feed coal in both coarse and fine coal cleaning circuits. It is true that the coal industry is now directed more by the characteristics and quality of coal than if it were just a black versus gray color used years ago. Even in a few years from now, this preparation plant will be obsolete. One will see a complex which looks similar to an oil refinery. Various grades of coal products will be produced and tank cars will be used to carry the liquid coal product away from the plant. The coal industry is becoming more concerned with the needs of the customer than ever before. Oil has replaced coal in many markets because it is a liquid that can be pumped, stored and burned much easier and cleaner than coal. With the development of new technology to convert coal into a liquid fuel form through coal-oil mixing, coal-water mixing and even with some new technology still on the horizon, coal can be placed into a converted liquid form similar to oil. However, one major technology gap remains and that is the need to remove the non-carbon products of ash and sulfur from the coal to a level equivalent to that required for burning oil. Now I did not say the same ash and sulfur levels must be achieved. No, one must look at the burning, off-gas systems, and regulations and then decide what the ash and sulfur levels of any liquid coal product must be.

Coal Preparation & Impact on Utilization

The steel industry has generally benefitted from coal preparation from production of metallurgical grade coal with desirable coking coal through optimum blending of seams of coals and reduced ash, sulfur, and moisture of coal. Today, almost 100% of metallurgical coal is processed in preparation plants. Whereas, less than 25% of the coal burned by industry for utility generation is cleaned before combustion.

What coal preparation can do.

- Reduce ash - and sulfur oxide - forming components from coal before combustion.
- Produce consistent quality fuel.
- Upgrade the heat value of fuel.
- Optimize the size consist of fuel.
- Produce multigrade fuel with varied levels of ash, sulfur, and heat content.

The coal producer benefits from the coal preparation through production of improved and premium fuel with broad market acceptability. With our recent emphasis to utilize the low ash and low sulfur coal, the premium quality coal in the ground is depleting. Coal preparation is the only technology available to producers to increase the utilization of low-grade coals. The continuous mining operations are producing more fine size and higher ash coal which can only be upgraded through proper coal preparation. However, dewatering of the fine size coal is still problematic which not only affects the fuel value but also is a major problem in handling and transportation due to freezing in winter months.

Coal users for industrial applications have been motivated in the past primarily by the lowest price coal. Not until the last decade have many of the more modern utility companies started to appreciate that just because coal is black does not mean it is all the same. To date, compliance of air quality standards has been the prime incentive for using beneficiated coal. However, a number of recent studies by the utilities, Electric Power Research Institute and the U. S. Department of Energy have shown the benefits of coal preparation on overall systems and significant reduction on the cost of electricity production. (1,2,3,4,5)

These benefits include:

- Reduced transportation cost through more Btu per ton.
- Improved boiler efficiency and boiler availability due to consistent and high quality fuel.
- Reduced operating costs of pulverization, ash-handling systems, flue-gas clean-up, and ash-disposal systems.
- Reduced capital cost of boiler and flue gas clean-up equipment.

The American Electric Power Company has been one of the prime advocates of benefits of coal preparation of utility application. Mr. Gerald Blackmore, the Vice President of AEP, has spent almost his entire life in the coal industry and advocating the benefits of coal preparation. He has been referred to many times as the "Patron Saint of Coal Washing". To prove his point, he points out that AEP's

average price to all its customers in 1979 was 2.86 cents against an estimated national average of 3.94 cents.(6)

Benefits of Coal Cleaning Upon Performance of Coal-Water Mixtures

One of the major problems that has hampered coal utilization for industrial use is the materials handling problems associated with bulky coal. With the advent of new technologies associated with coal-oil, coal-water, and coal-methanol mixtures, it is becoming possible to put coal into a liquid form where it can be stored in tankers, shipped by pipeline and fed into boilers without the manual labor associated with coal handling as it is today.

This type of developing market encourages coal preparation of fine size coal and mixing of the coal into a stabilized solution even at the preparation plant and shipped directly to boilers through pipeline and fed into boilers without even being touched.

If this market does develop, as it is expected to do, the utilities then will be able to replace oil with liquid coal as well as develop new boilers designed specifically for this liquid coal form. However, much of the development depends upon cleaning the coal to very low ash and sulfur levels. United Coal has been pursuing this development for the past several years. In fact, UCC has now developed and optimized a commercial coal preparation plant to produce up to 300 TPH of 2% ash coal. Currently, no customers are beating our door down for this super-clean coal primarily because the market for replacing oil with a liquid coal has not developed. The prime purpose of developing this super-clean coal is to optimize the coal feed to make a premium coal-water mixture fuel for testing purposes.

To date, United Coal Company has produced 300 tons of this super-clean coal in our commercial plant to optimize our processing conditions, establish economics of the process and prepare test samples for combustion tests by various organizations. A preliminary report on the Department of Energy's tests on our coals is given below. A comprehensive detailed report on these tests is currently under preparation at DOE.

Coal-Water Combustion Tests on Beneficiated Coal

The Department of Energy has conducted several combustion tests on coal-water mixture fuel prepared with beneficiated coals. These tests were conducted at DOE's Pittsburgh Energy Technology Center 700 HP combustion test facility. United Coal Company supplied the beneficiated coals from their commercial process and advanced beneficiation process.

The primary purpose of the tests was to evaluate the particulate emissions and furnace ash deposits as a function of ash content in the coal. The Department of Energy's combustion test conditions were set at excess air of 15 weight %, combustion air temperature of 500°C, with a steam output of about 24,000 lbs/hr. Significant test results are listed in Table I.

TABLE I. TEST RESULTS OF DOE COMBUSTION TESTS
ON COAL-WATER MIXTURE WITH BENEFICIATED COALS

<u>Coal Type</u>	<u>Ash%</u>	<u>Particulate Emission, lb/hr</u>	<u>Furnace Ash Deposit, lb/hr</u>	<u>Carbon Conversion Efficiency</u>
UCC Commercial Coal	~ 8	120	8.9	97.5
UCC Super-Clean Coal	~ 2	79	2.3	97.4

These test results show that even though the carbon conversion efficiency remains about the same, there is significant decrease in particulate emissions and furnace ash deposits. The composition of furnace ash deposits from the low-ash coal was primarily aluminum silicate and is highly friable and non-sticky and thus can be blown off with blower action.

These results indicate that by cleaning the coals to low levels of ash, the most serious problem of furnace ash deposits can be solved thus making coal-water mixture fuel compatible with boilers designed for firing low-ash fuel oil.

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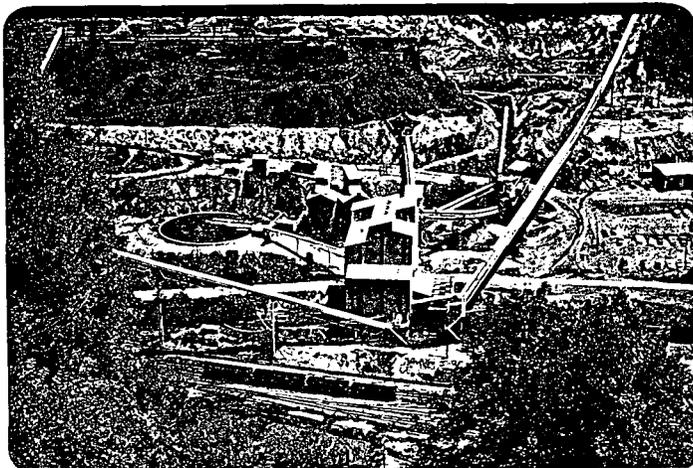


FIG. 1: COAL PREPARATION PLANT (WELLMORE NO. 7)
OF UNITED COAL COMPANY AT
GRUNDY, VIRGINIA

COAL AQUEOUS MIXTURES

SEYMOUR MARK

ADVANCED FUELS TECHNOLOGY

A Gulf+Western Company

Zerbe Research Center

Bethlehem, PA 18017

Coal aqueous mixtures can be prepared by simply mixing pulverized coal with water. Table 1 shows the formulation for such a slurry and compares it to one for a modern slurry.

Simple Slurry Versus Modern Slurry

A visual inspection of slurries made with these formulations would show them to be quite similar. Both would appear to be black fluids with comparable viscosities. A closer examination would reveal that the simple slurry had a considerable degree of settling while the modern slurry was uniform. Another difference between the two slurries is their concentration of coal.

Table 1 shows that the simple slurry contains 518.5 pounds of coal per hundred gallons and that the modern slurry has 725.9 pounds. Expressed another way, simple slurry contains 53% coal and modern slurry 70% coal. A comparison of the volume relationships of the ingredients in these slurries shows that simple slurry contains about 45% coal and 55% water. In the modern slurry formulation we see that the volume of coal is considerably greater than that of the water; 62.6% coal, 36.9% water. This higher ratio of coal to water is achieved in part with the use of additives. These additives, which can total only 0.5% of the weight of the slurry in some cases, not only allows a greater concentration of coal to be incorporated into the mixture; but they also disperse the particles, keep them apart and

suspended in the medium, and provide the type of flow properties necessary to pump and atomize this fuel.

What are these additives, and how did they come to be used in preparing coal aqueous mixtures? The additives are primarily surface active compounds. The technology is guided by the sciences of colloid and surface chemistry, and of rheology.

Preparing Coal Aqueous Mixtures

The first challenge in preparing coal aqueous slurry is to disperse the coal particles into the medium. When coal has been ground into a powder, the coal particles can adhere to each other in aggregates. A dispersion of the particles must be accomplished. The process involves separating the particles in an aggregate until they are dispersed. Figure 1 shows different aspects of wetting and dispersion, as now viewed. The cluster of coal particles shown as "aggregated" has various degrees of air and moisture on the surface of the particles and in the spaces between them. Work and surfactants are used to break up these aggregates, by replacing the air with water. The separated particles are shown as "wetted." They are covered with a layer of water, that has displaced the air. They also contain adsorbed surface active agents and protective colloids on their surface. Coal will occupy less space when it is wetted by a liquid, than when it is mixed with air and moisture. The volume of air displaced is considerable, it demonstrated by weighing the amount of powdered coal that can fit into a gallon container. This is generally about 4 pounds. Yet we know from our examination of a modern slurry formulation that it contains over 7.25 pounds of coal per gallon, and still has room in the

container for over 3 pounds of water.

It is believed that after the coal particles are wetted-out, they disperse uniformly throughout the medium into individual pieces shown as "dispersed." The dispersed state is achieved if the particles in the suspension are separated sufficiently for the repulsive force to exceed the attractive force⁽¹⁾. If the attractive force is stronger, the particles are believed to re-combine as flocculates. The cluster shown as "Flocculated" differs from the aggregated cluster in that the surface of the particles and the space between them contain water rather than air. As a result they are easier to redisperse. Nevertheless, they act as if they are single large particles, and tend to settle more rapidly.

The Interaction Forces Between Particles

There are three major types of interaction forces between colloidal particles: 1. London - van der Waals, 2. Coulombic forces (DLVO), 3. Solvation, adsorbed layers⁽²⁾. The effect of these forces is shown graphically in Table 2.

London - van der Waals forces are due to the influence of the dipoles within the particles acting on each other. They are attractive forces which are electromagnetic in nature. It is conventional to assign a negative value to an attraction potential and a positive value to a repulsion potential.

Coulombic forces may be either attractive or repulsive, but are almost always repulsive when dealing with coal particles dispersed

in water. They are electrostatic in nature and arise from the unequal distribution of ions in solution around the particle and at its surface. This unequal distribution causes one side of the interface to acquire a net charge of a particular sign and the other side to acquire a net charge of the opposite sign, giving rise to a potential across the interface and the so-called electrical double layer⁽³⁾. The stability of a dispersion can depend upon the degree of electrostatic repulsion. The degree of which is related to the thickness of the electrical double layer.

The interplay of the electromagnetic and electrostatic forces forms the substance of the DLVO theory, which deals in a fundamental manner with the kinetics of flocculation and the stabilization of particle dispersions. Although the DLVO theory is very useful in predicting the effect of ionic surfactants as electrical barriers to flocculation, other factors must be considered to explain the effect of surfactants on dispersion stability.

Surfactants that are polymers or that have long polyoxyethylene chains may form non-electrical barriers to flocculation in aqueous media. An adsorbed layer of non-ionic surfactant on the surface of a particle can provide a steric hindrance to close particle approach by interposing a mechanical barrier. When particles collide, the distance between the surfaces is increased by twice the thickness of the adsorbed layer. When the attractive force at this distance is still sufficiently large that interaction of the adsorbed layers occurs, there is a decrease in the entropy of the system. The term "entropic repulsion" was introduced by Mackor and van der Waals in reference to the loss of movement in the tails of the adsorbed molecules when two adsorbed layers interpenetrate⁽⁴⁾.

Properties of Coal

The water requirement of coal aqueous mixtures is a function of the properties of the constituents in the slurry. These are the coal, the water, and the additives. The chemical and physical properties of the coal have a major influence on the amount of water needed to achieve a slurry with desired flow characteristics. Coal is a heterogeneous substance that is a mixture of combustible metamorphosed plant remains that vary in physical and chemical composition⁽⁵⁾.

Coal may be classified by rank according to fixed carbon content and heating values. Higher carbon content generally correlate with higher BTU values that designate the coals that usually make better fuels. Coals with higher volatile matter improve the combustion properties of aqueous slurries.

Coals also differ considerably in physical structure. The structure of coal can be so intricate and extensive as to make them something like a solid sponge⁽⁶⁾.

The mineral matter and sulfur content of coal show large variations. Of course, coals that are low in these materials produce slurries that are lower in pollutants and cause less ash deposits in furnace. Another way to make slurries that are low in pollutants and less prone to furnace fouling, is to beneficiate the coal prior to its incorporation into slurry. Beneficiation processes have been developed that remove a substantial part of the ash content of a coal and lower its sulfur concentration. This can now be accomplished at very high rates of recovery and excellent slurries are being prepared with this beneficiated coal.

Coal Size Consist

Another property of coal to be studied that may influence its water requirement in aqueous mixtures is size consist. Coal with a coarse size consist has a relatively small surface area per unit weight and requires less water to coat the coal particles. Consequently, a lower amount of water is needed to fluidize the particles, and slurry of higher solids content can be produced. Coal with a fine size consist has a relatively large surface area per unit weight which requires more water to coat the coal particles. However, the finer particles may fit into the interstices between the larger particles thereby reducing the void volume.

Predictions of the packing patterns of coal particles are complicated by many factors among which are size, size distribution, and particle shape. The Rosin-Rammler relationship was developed for representing the size distribution of powdered coal⁽⁷⁾. This formula, as well as empirical methods, have been employed to determine coal size consists that have the lowest water requirement. However, the type of particle size distribution likely to give the lowest water requirement would include sizes that might be too large for good combustion and suspension properties, and the procedures needed to produce this type of size distribution would be expensive. Certainly, economic considerations as well as fuel properties are influential in determining the size consist of coal to be used in aqueous slurry.

Slurry Formulation

Coal aqueous mixtures have been prepared containing coal, water, a nonionic surfactant, and also defoaming agents, gums and salts. Nonionic surfactants containing polyoxyethylene can be used. It is believed that they lower the surface tension of the water, keep the coal particle from flocculating, promote suspension, and provide good flow properties. While playing a major role in producing coal aqueous mixtures, nonionics can be employed at concentrations of less than 0.4%.

Anti-foam agents can be used to lower the amount of foam in the slurry. Also, gums such as water soluble resins can be used to increase the viscosity of the medium. The quality of the water can also influence the stability of the slurry and its solid concentration. Water can contain soluble minerals which become electrolytes in the slurry, that can have an effect on the electrical balance of the system. Slurries stabilized with non-ionic surfactants are less susceptible to their influence.

NonIonic Surfactants

Some nonionic surfactants that contain long chains of polyoxyethylene are shown in Figure 2. Figure 2a shows a surfactant having an ethylene diamine backbone, which is a block polymer containing chains of propylene oxide and ethylene oxide of various lengths. Another compound of this type containing chains of propylene oxide and ethylene oxide is shown in Figure 2b. This surfactant has a propylene glycol base. The formula shown in Figure 2c contains a single chain of ethylene oxide attached to a nonylphenoxy group. It has no propylene oxide.

Each of the formulas shown in Figure 2 represent a different series. The individual surfactants in each series differ from each other primarily by the length of the ethylene oxide chain. The moles of ethylene oxide on these molecules range from 4 to over 300.

The nonionic compounds are polar and have hydrophobic and hydrophilic portions. In coal aqueous mixtures, the hydrophobic end of the surfactant is believed oriented toward the coal particle and the hydrophilic end toward the aqueous medium. In Figure 2a, the hydrophobic portion encompasses the ethylene diamine and propylene oxide part of the molecule. For the molecule shown in Figure 2b, it is the propylene glycol portion together with the propylene oxide chain that comprises the hydrophobic segment of the surfactant, and in Figure 2c, the nonyl hydrocarbon chain and benzene ring are the hydrophobic end of the compound. For all these molecules, it is the ethylene oxide portion that is hydrophilic. For each of the compounds, those with the highest molecular weight in the series have the longest polyoxyethylene chains. The longer the chain of ethylene oxide, the further they extend into the solution.

Experiments

Experimental work done with these surfactants in coal aqueous slurry was revealing. A comparison of the compounds that were effective in producing a 70% solids slurry, with those that were not, showed that between the primary difference between them was in the ethylene oxide content. The surfactants that were found effective contained 100 or more moles of ethylene oxide, while all

that were not, contained less. Molecular weight did not appear to be as influential because two of the compounds deemed not effective had higher molecular weights than the one that was.

Slurry Properties

Coal aqueous mixtures are designed to conform to two major categories of properties: fuel and rheological. Fuel properties relate to the BTU content of the slurry, its level of ash, sulfur, and volatile matter, and sieve analysis. Rheological properties are concerned with the flow and handling characteristics of the slurry, and its stability to settling and shear.

A viscosity profile of a coal aqueous slurry is shown in Figure 3. This slurry exhibits desired rheological properties; its viscosity is well above 10,000 centipoise at low shear rates of 0.3 sec^{-1} and below, and it is lower than 2000 cP at shear rates above 100 sec^{-1} . The high viscosity at low shear rates indicates that this slurry will resist settling when it is at rest. The lower viscosity at 100 sec^{-1} indicates that it will pump readily. Shear rates during atomization are estimated to be at least $10,000 \text{ sec}^{-1}$. The curve in Figure 3 suggests that the viscosity of this slurry at that shear rate will be low, and that it will atomize well.

Slurries that decrease in viscosity with increased shear stress are described as pseudoplastic, and the curve in Figure 3 shows a material with this property. If this slurry was measured at even lower shear rates, and the data showed that flow did not begin until a certain minimum shear stress was exceeded, then the slurry could be described as a Bingham plastic. The point at which flow starts in such a system

is called yield value, which is often manifested in materials with high concentrations of powder dispersed in liquids.

Summary

Coal aqueous mixtures can be prepared that have high coal content, are stable to settling, and can be pumped and atomized. The concentration of coal in a slurry depends upon the water requirement of the system. This requirement is effected by the grade of coal used, its size consist, and upon the additives in the formulation. Of particular importance is the type of surfactant used. Surfactants lower the surface tension of water and adsorb at the solid/solution interface to hinder close particle approach, ionic surfactants do so primarily by electrostatic repulsion. Nonionic surfactants do so primarily by steric hindrance.

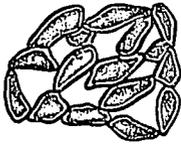
Coal aqueous slurry can be made at a cost that is lower than that of No. 6 fuel oil by over \$1.00 per million BTU. This differential has provided the economic incentive to develop aqueous slurry as a replacement fuel. The findings presented in this study, and in work done by others in the industry, indicate that the research in this field has succeeded in developing a new fuel.

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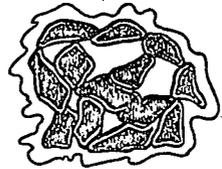
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Figure 1

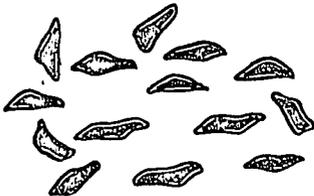
ASPECTS OF WETTING AND DISPERSION



AGGREGATED



FLOCCULATED



DISPERSED



WETTED

FIGURE 2 MONIOMIC SURFACTANTS

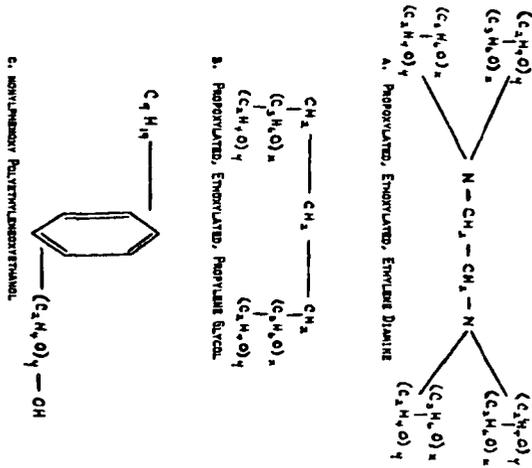


Figure 3

VISCOSITY PROFILE

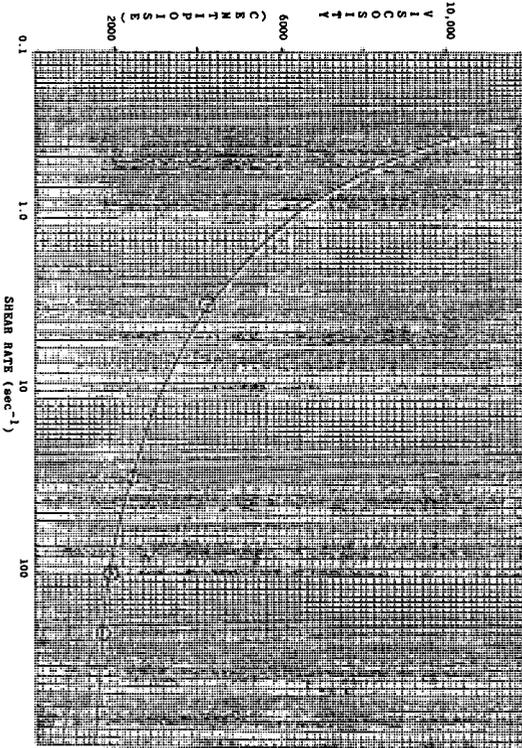


Table 1

Coal Aqueous Mixture Formulations

(per 100 gallons slurry)

	<u>Simple Slurry</u>		<u>Modern Slurry</u>	
	<u>Weight</u>	<u>Volume</u>	<u>Weight</u>	<u>Volume</u>
	<u>Lb.</u>	<u>(Gal.)</u>	<u>Lb.</u>	<u>(Gal.)</u>
Coal (MF)	518.5 (53.0)	44.7	725.9 (70.0)	62.6
Water	460.1 (47.0)	55.3	306.6 (29.5)	36.9
Additives			5.0 (0.5)	0.5
	978.6	100.0	1037.5	100.0

Table 2

Interaction Forces Between Particles

	<u>Forces</u>		<u>Nature</u>
	<u>+</u>	<u>-</u>	
DLVO THEORY	1. London	Attraction	Electromagnetic
	2. Coulombic	Primarily Repulsion	Electrostatic (Electrical Double Layer)
STERIC HINDRANCE THEORY	3. Solvation	Repulsion	Adsorbed Layers Entropic

CURRENT PROGRESS IN
COAL-WATER SLURRY BURNER DEVELOPMENT

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CURRENT PROGRESS IN COAL-WATER SLURRY BURNER DEVELOPMENT

INTRODUCTION

There has been significant interest in recent years in development of domestic fuels which could displace those presently imported by U.S. industry. Because of the large quantity of fuel consumed by the electric power generation industry, much of this interest has been focused on fuels to replace oil and gas combusted in existing utility boilers. Many of these efforts have focused on the use of coal as the replacement fuel since it is the United States' most abundant fossil fuel.

Unlike oil, coal cannot be easily nor inexpensively refined into a consistent definable fuel. Every coal type is different in combustible properties as well as mineral matter content and composition. Unfortunately, these are two key parameters which significantly influence the determination of a particular coal's successful application as a replacement fuel in an existing utility boiler. Successful application also depends on several other key economic factors as well; boiler derating, differential fuel savings between the presently used fuel and the candidate alternate fuel, and lastly, the resulting payback period over which the utility must amortize the cost of converting to the new fuel.

Figure 1 shows the relationship of these economic parameters. If one considers seven (7) years a reasonable payback period, Figure 1 illustrates that, with realistic unit deratings of up to 25%, a differential fuel cost of between \$1.00 and \$2.00 per million BTU's must be achieved to make conversion economic. This delicate economic balance is the very reason utilities have been slow to accept coal/oil slurries as a viable alternative to oil alone. With the nominal cost of oil at approximately \$6.00/MMBTU and the nominal coal price at \$2.00/MMBTU, and the practical amount of coal that can be mixed with oil limited to about 50% on a mass basis, the raw products alone are about \$4.00/MMBTU without any allowance for slurry preparation. With this narrow differential in cost, many utilities are unwilling to risk conversion of operating units to this new fuel.

Because of the marginal economic incentive of coal/oil slurries, interest has shifted to a relatively new potential conversion fuel-coal/water slurry (CWS). Coal/water slurries have the distinct advantage of requiring no oil and therefore the potential differential in fuel cost over operation on oil alone can be much greater than that with coal/oil slurries. Coal/water slurries have several possible technical limitations, however, which must be reconciled before they can be considered as a viable replacement for oil or gas in utility boilers.

One of the concerns which must be addressed is the development of an atomizer that will properly atomize this new fuel. A problem that the atomizer development engineer faces is that most CWS fuels under development today have been designed to maximize coal content and fuel stability (i.e., minimization of settling). From an economics and transportation standpoint this approach makes sense but results in a fuel which maybe viscous, and therefore difficult to effectively atomize. If a slurry cannot be economically atomized it will not be a viable commercial fuel. Therefore, the successful CWS fuels will have to have both acceptable storage stability and rheological properties to permit good atomization with realistic levels of atomizing assist fluid.

Other concerns, in addition to rheological fuel properties, are fuel ignition and warm-up requirements, burner stability and turn-down, and carbon conversion and thermal efficiencies. Most CWS testing to date has been in small laboratory facilities of 1 to 4 MMBTU/hr and, in general, results have been poor, compared to that which must be achieved if CWS fuels are to be accepted as a viable replacement fuel by utilities. Test furnaces have required extensive preheat, burner turn-down has been extremely limited and carbon conversion efficiencies have, at best, been in the high 80% to mid 90% range(1,2,3).

In addition to these potential problems with CWS combustion, Figure 1 indicates that unit derating can play a significant role in dictating the success of a fuel conversion. For this reason coals to be used for CWS's must either be carefully selected on the basis of their original ash characteristics or they must be beneficiated (i.e., cleaned of mineral matter) to minimize furnace slagging/fouling and erosion such that significant boiler deratings will not be encountered.

CWS BURNER DEVELOPMENT

This paper is a progress report on a joint program between Combustion Engineering (C-E) and the Electric Power Research Institute (EPRI) to develop and demonstrate a commercial scale CWS burner which meets reasonable commercial success criteria. As such, a burner is presently being developed which meets the following constraints:

1. Permits ignition in a cold furnace with conventional ignition equipment.
2. Operates stably over a 4 to 1 turndown range without supplemental ignition fuel.
3. Employs fuel and atomizing media pressures that are obtainable with commercially available equipment.
4. Requires atomizing media to fuel mass flow ratios similar to those used for oil.
5. Produces carbon conversion efficiencies comparable with oil (i.e., high 90% range) at acceptable excess air levels (i.e., 20-30%) and reasonable air preheat temperatures (i.e., 250 to 400°F) over the full load range of the burner.

To achieve these goals C-E is using a proven three step firing system development approach.

1. Development of a CWS atomizer using C-E's Atomization Test Facility.
2. Development of an aerodynamically sound burner register using C-E's Burner Modeling Facility.
3. Integration of the developed atomizer and burner register, and optimization of the CWS firing system's combustion performance at a commercial firing scale of 80/MMBTU/hr in C-E's Full Scale Burner Test Facility.

This paper does not contain all combustion data which was still being analyzed at the time this paper was prepared; the combustion data is, therefore, preliminary.

FUEL PREPARATION AND CHARACTERIZATION

The fuel required for this development program was donated by Advanced Fuels Technology (AFT), a Gulf and Western Company. The coal used was a Clearfield County, Pennsylvania bituminous, selected by EPRI. The required coal was cleaned, prior to testing and slurry preparation, at EPRI's Coal Cleaning Test Facility in Homer City, Pennsylvania. A simplified flow schematic of the cleaning process used is shown in Figure 2, and the analysis of the cleaned coal is shown in Table 1.

Coal to be cleaned by EPRI's test facility is initially crushed to a nominal 3/4" x 0 size and then processed through a multistage "desliming screen". The first screening stage removes oversized material (+3/4") from the process stream. The second stage removes coal which is of a 3/4" x 28 mesh size. This is the main process stream. Separated material (+3/4" and -28 mesh) is collected in a refuse pile for future independent treatment. The main coal stream is then processed through two stages of "heavy media cyclones" followed by a "sieve bend & screen" to separate the clean coal from the refuse portion. The separation principle is based on the mass density differences between the coal (which is relatively light) and the high mineral matter

fractions (which are relatively heavy). After passing through these steps the coal is passed through a "basket centrifuge" to be partially dewatered. At this point the coal is considered "cleaned". It is metered by a weigh belt and is passed to a storage pile.

The high ash refuse obtained from the separation processes is collected in a refuse pile for disposal and/or future reprocessing. Process fluids are separated from the refuse and cleaned coal streams, and collected for reuse. For the special purpose of generating a very low ash coal for this testing program, refuse material was not reprocessed and combined with the initially cleaned main coal stream as would be the normal procedure.

In all, approximately 150 tons of cleaned coal were prepared for this program. Approximately 40 tons of the cleaned coal was reserved for base coal testing to establish a meaningful reference base for comparison to CWS combustion performance. The balance of the coal (approximately 110 tons) was processed, by AFT, into a nominal 70% solids CWS of predetermined specifications. These specifications were developed jointly by C-E and AFT to assure the maximum probability for combustion success through careful attention to oversized particles and minimization of fuel viscosity. The developed fuel specifications are presented in Table 2 with an analysis of the produced CWS. A schematic of AFT's CWS preparation system is shown in Figure 3.

Figure 4 shows a typical viscosity profile of the CWS which was obtained using a Haake Rotovisco viscometer. As can be seen in Figure 4, the CWS exhibited Newtonian to slightly pseudoplastic behavior (i.e., viscosity remains constant or decreases slightly with increasing shear rate). From an atomization standpoint, pseudoplasticity is desirable since the viscosity decreases at the high shear rates encountered within the atomizer. A Newtonian behavior is also acceptable since the viscosity remains constant with increasing shear rate. Dilatent behavior is not acceptable since the viscosity increases with increasing shear rate and would lead to poor atomization.

It is important to note that in order for CWS to attain commercial acceptance, a balance must be achieved between the high static viscosity required for transport and storage stability and the rheological properties required for atomization and combustion. Also, rigid control of particle top size and stringent quality control by the slurry manufacturers is necessary to insure a consistent supply of usable CWS.

FUEL SHIPPING, STORAGE AND HANDLING

The CWS prepared by AFT was shipped to C-E's Kreisinger Development Laboratory (KDL) at Windsor, Connecticut in conventional pressurizable tanker trucks. Although the tankers used had volumetric capacities of approximately 6500 gallons, five tankers were needed to transport the required 21,000 gallons of slurry because each was limited to a capacity of only about 4,200 gallons due to the legal over-the-road weight limit of 45,000 lbs. Photographs 1 and 2 show a tanker truck arriving at C-E and being unloaded, respectively.

C-E's Alternate Fuels Handling Facility (AFHF) is shown schematically in Figure 5. This facility is comprised of a 15,000 gallon storage tank, a 2500 gallon day tank, an homogenizer and several pumps, filters and heaters configured to handle slurry-type fuels. Figure 6 shows the arrangement of those components of the AFHF specifically utilized for the CWS testing program.

Preliminary testing indicated that the tanker trucks could be effectively unloaded two ways. One manner was by pumping the CWS from the tanker in an unpressurized state. A Tuthill model 120A pump was used and permitted unloading to the AFHF 15,000 gallon storage tank at a rate of 12-15 gpm. The second procedure, which was used for the balance of the required unloading, was to by-pass the pump and unload the fuel by pressurizing the tanker to 30 psig. At this pressure, the tankers were unloaded at an average rate of 50-70 gpm, or 1-1½ hours per 4,200 gallon tanker load.

As was previously mentioned, a total of five tanker truck loads of CWS were received for the test program. The initial two tankers received contained CWS of proper specification (see Table 2) and appeared to maintain storage stability and slurry uniformity over a period of several weeks with only occasional recirculation using the Tuthill pump. A portion of the fuel from these initial two tankers was used for the atomizer development phase which will be discussed later.

These were some off-spec. changes in the third tanker shipment of fuel which affected rheological properties of previously shipped fuel as well as the fourth tanker load of CWS fuel. On-site adjustments by G&W personnel combined with increased fuel circulation at C-E permitted testing to continue. The last tanker of fuel was significantly higher in viscosity than the previous fuel batches; this required higher fuel supply pressures to achieve the same mass flow rates as the previous fuel shipments.

CWS ATOMIZER DEVELOPMENT

The development of an atomizer for CWS was essential to the developmental success of the C-E/EPRI CWS burner. The purpose of the atomizer is to fragment the CWS fuel stream into readily combustible droplets. The size, velocity and trajectory of these fuel droplets is a function of both the atomizer's design and the burner's near-stream aerodynamics, and directly affects burner performance in terms of flame length, stability and carbon burnout.

In the course of development, careful consideration was given to both the CWS atomizer's generic design as well as its specific geometric dimensions. Of generic atomizer designs reviewed by C-E, the "Y" jet configuration (Figure 7) appeared to have the greatest potential for success with CWS. Two properties of CWS were identified as potentially problematic to effective atomization. These were its erosive nature and high viscosity (Figure 4). "Y" jet type atomizers utilize pressurized atomizing media (superheated steam or compressed air) to initiate fuel stream breakup through high shear turbulent mixing of the atomizing media and fuel streams. This "Y" jet atomization principle has been shown(4) to be effective for the atomization of viscous fuels and thus would be potentially successful with CWS. Secondly, because of the atomizer design's simple geometry, with no tortuous paths, it permits fabrication with erosion resistant materials (Figure 8).

Combustion Engineering has extensive experience in "Y" jet atomizer design and has developed a computer design code and a full scale Atomization Test Facility (ATF) to assist in "Y" jet atomizer design development. These were utilized in a three step approach which resulted in the successful development of a CWS atomizer. These steps were:

1. Theoretical identification of critical atomizer geometric dimensions based on fuel properties and atomizing media considerations.
2. Preliminary ATF testing and performance optimization of the theoretical atomizer design.
3. Detailed ATF performance characterization of an optimum atomizer design over a matrix of operation.

ATOMIZER TEST FACILITY

C-E's Atomizer Test Facility (ATF) is designed to quantitatively characterize the atomization quality of full scale (10 gpm) burner atomizers. The facility is uniquely configured to obtain droplet size distribution and droplet ballistics (velocity and trajectory) information from fuel sprays.

The facility operates in a cold flow (non-combustion) mode and has provisions for studying both conventional liquid and slurry fuels. Provisions for slurry fuels include

a 700 gallon transportable fuel tank for storing and heating fuels prior to ATF testing. The tank is equipped with a mixer and recirculation system to minimize potential slurry solids stratification.

A schematic of the Atomization Test Facility is shown in Figure 9. The actual facility is presented in Photo 3.

Test atomizers are centrally located in the spray chamber and spray vertically down, thus minimizing the effect of gravity in atomization droplet ballistics measurements. Also, a constant velocity profile (10 ft/sec) airflow passes by the atomizer during testing to prevent potential droplet recirculation which would otherwise bias droplet trajectory information. Large windows in the spray chamber permit optical access across the atomized sprays. Optical spray diagnostic equipment is located on the two benches as shown. Once data is obtained from the spray, the fuel droplet-laden air flow is demisted and exhausted from the facility. The collected fuel is then removed for reuse or disposal.

OPTICAL DIAGNOSTIC TECHNIQUES

Two optically-based techniques are utilized by C-E in the ATF to quantify spray quality. A laser diffraction technique is used to determine the spray droplet size distribution and a high speed double spark photographic technique is utilized to define droplet velocity and trajectory.

The laser diffraction technique is based on the Fraunhofer diffraction of a parallel beam of mono-chromatic light by moving of stationary droplets or particles(5). A Fourier Transform lens yields a stationary light pattern from the light diffracted by the particles. A multi-element photo-electric detector located at the focal plane of the Fourier Transform lens produces an electrical signal analogous to the diffracted light. A mini-computer compares this signal with the derived signal based on a Rosin-Rammler model which continuously modifies the mean diameter and exponent parameters until a best fit is obtained(5). Percentage weight fraction and normalized percentage number density are then calculated from the best fit model.

Figure 10 shows a schematic of the laser diffraction apparatus. The laser is the monochromatic light transmission source and the diffracted light is received and analyzed by a Fourier Transform lens, a photoelectric detector, and a mini-computer. Note, the optical probe included in the schematic is used to alleviate measurement errors in dense fuel sprays.

The optical arrangement for the high speed double spark photographic technique is depicted schematically in Figure 11. Two spark-gap light sources are located on one side of the facility. Each source produces one intense, short duration (1 microsecond) flash of light. These flashes of light are directed through the atomizer spray by a lens system and into a camera lens located on the opposite side of the facility. The camera lens is focused on a specified plane within the spray field (object plane). Silhouette images of the droplets located in the camera's object plane and field of view are recorded on film.

The two flashes produce a double exposure silhouette photograph of the droplets. Accurate droplet velocity information is then obtained by measuring the distance traveled by an individual droplet between exposures with knowledge of the time interval between flashes. Similarly, droplet trajectory is determined by observing the direction of travel for individual droplets.

INITIAL CWS ATOMIZER DESIGN

The CWS atomizer was designed in part by the application of a computer code previously developed by C-E to predict "Y" jet atomizer atomization quality (in terms of spray droplet mass median diameter) with heavy fuel oils. This program code estimates atomizer performance as a function of critical fuel properties and atomizing media

constraints. These include, fuel viscosity, atomizing media density, and atomizing media to fuel mass flow. C-E utilized this code to predict CWS atomization quality. The predictions, in conjunction with pressure drop calculations, fluid momentum considerations, and geometric correlations obtained in previous atomizer development efforts, resulted in the identification of specific atomizer dimensions; these are shown in Figure 7. The target CWS atomization quality was that which is typical for firing residual fuel oil using a "Y" jet atomizer. Based on previous tests conducted in the ATF(6), a spray mass median diameter of 120 microns or less is characteristic of effective residual oil atomization. Note, that this droplet diameter is significantly larger than that of the individual coal particles of conventionally ground coal for P.C. firing.

This phase of CWS atomizer design actually yielded two distinctly different "Y" jet atomizer geometries with similar performance, given identical fuel and atomizing media conditions.

PRELIMINARY ATF TESTING

Preliminary ATF testing involved a comparative performance evaluation of the two "Y" jet atomizer geometries identified during initial CWS atomizer development. The laser diffraction system was utilized for this effort. Each atomizer nozzle design was tested at 100%, 50%, and 25% of maximum firing rate over a wide range of atomizing media to fuel mass flow ratios ($.06 < A/F < 1.1$). Compressed air was used as the atomizing media. For these tests, CWS and atomization air were maintained at ambient temperature. Data obtained from these comparative tests is presented in Figures 12, 13, and 14.

At 100% load, nozzle design 5A produced finer sprays than nozzle 5B at A/F ratios greater than 0.17. Operation with such high atomizing media consumption is undesirable, however, because it is a parasitic energy loss, and thus negatively impacts boiler economics. Nozzle design 5B consistently produced a finer spray than design 5A at more favorable A/F ratios of 0.17 and below.

At both 50% and 25% load, nozzle design 5B produced equivalent or finer CWS sprays than nozzle design 5A at given A/F ratio settings. Based on these tests, nozzle design 5B was chosen for further detailed atomization quality optimization and characterization.

DETAILED CWS ATOMIZER TESTING

Detailed parametric testing of the optimum atomizer (design 5B) provided insight into the key operating parameters which influence atomizer performance. Parameters studied included:

- Atomizing media to fuel mass flow ratio
- Fuel mass flow rate
- Fuel temperature
- Atomizing media temperature

Atomizing Media to Fuel (A/F) Mass Flow Ratio

The ratio of atomizing media to fuel mass flow was found to have a significant effect on the performance of the CWS atomizer. Data depicted in Figure 15, taken at 100% load, indicates that above an A/F ratio of 0.17, the spray mass median diameter remains constant. A gradual degradation in atomizer performance occurred between A/F ratios of 0.17 and 0.06, and rapidly degraded below an A/F ratio of 0.06. Similar trends were noted at 50% and 25% load.

The spray droplet size distribution obtained on CWS at full load was similar to that obtained through previous testing of "Y" jet atomizers spraying fuel oil. The optimum range of A/F ratios for the CWS atomizer appeared to be between .08 and .14, which are also typical of those required for fuel oil atomization.

Effect of Slurry Temperature

The effect of CWS temperature on atomization quality is presented in Figure 16. Atomizing air temperature was held constant at 95°F during these tests. CWS was tested at 95°F (ambient temperature) and at 150°F over a range of atomizing media to fuel mass flow ratios.

The data indicates that a slight decrease in spray mass median diameter (MMD) of approximately 10% occurred when the particular CWS tested was preheated prior to atomization. The reduction in MMD could possibly be attributed to a reduction in fuel viscosity at elevated temperature.

The slight decrease in MMD did not appear to provide sufficient justification for preheating the fuel in the combustion phase of the testing.

Effect of Atomizing Air Temperature

The effect of atomizing air temperature on atomization quality is presented in Figure 17. CWS temperature was held constant at 95°F during this series of tests.

The data indicates that a reduction in MMD, of approximately 10%, can occur by preheating the atomizing air. Again, however, this reduction would not appear to be significant enough to warrant preheating the atomizing air.

Effect of Slurry and Air Temperature

The combined effect of both elevated CWS and air temperature on atomization quality is shown in Figure 18. It was concluded from ATF testing that heating both slurry and air produced a finer spray yet than either fluid heated individually.

This information would be useful should a particular burner/atomizer combination prove to perform marginally on a specific CWS. Preheating both fuel and air may shift the droplet size distribution down to within a range capable of improving combustion performance. The improvement in performance would have to be evaluated against the increased capital equipment costs and energy costs incurred when preheating these fluids.

Overall, the performance of the developed CWS atomizer, with ambient CWS and air temperature, was quite similar to conventional C-E "Y" jet atomizer performance and fuel oil. For this reason, for the combustion evaluation of CWS, fuel was supplied at ambient temperature and atomization air was not heated beyond the compressor's nominal delivery temperature of 160°F.

Droplet Ballistics

Droplet velocity and trajectory information, obtained through the use of the high speed double spark photographic technique, indicated that CWS droplet velocities were similar to those obtained for conventional fuel oils. Velocities ranged between 2 and 24 meters/second, at an axial downstream distance from the atomizer of 140 nozzle diameters. Droplet trajectories tended to follow predictable streamlines of a freely expanding jet.

Droplet velocity is a strong dependent function of droplet diameter for both oil and CWS.

Since the velocities obtained for both oil and CWS were similar, no droplet ballistics related changes in burner aerodynamic design appeared necessary.

BURNER REGISTER DEVELOPMENT - COLD FLOW MODELING

A full-scale model of the proposed burner register was fabricated and flow model tested under isothermal conditions. The purpose of this work was to confirm that the register design exhibited satisfactory aerodynamic characteristics over the full range of air flows expected to be used during combustion operation. An important and necessary aerodynamic characteristic for good flame stability is the existence of a strong well developed recirculation zone at the burner throat. In the C-E CWS burner, the recirculation zone is established through combustion air swirl and a divergent burner throat. These are well known methods of inducing a recirculating flow and have been used commercially for some time(8,9).

Flow visualization techniques were employed by C-E and confirmed the CWS register design's satisfactory aerodynamics over a range of simulated operation. Figure 19 shows, schematically, the model used and the observed recirculation zone boundary.

BURNER DESCRIPTION

The C-E coal-water slurry burner is a swirl stabilized unit configured for tangential firing and is shown schematically in Figure 20. The basic burner design is adaptable to wall firing with suitable modifications. The principle elements of the burner system are: a refractory-lined divergent throat, a combustion air swirler through which a portion of the combustion air is passed, auxiliary air nozzles, above and below the burner, through which the balance of the combustion air is ducted (unswirled), and a slurry gun with an atomizer.

The purpose of the refractory-lined divergent throat is to increase the mass recirculation ratio and therefore to stabilize the flame both aerodynamically and thermally. The swirled combustion air stabilizes the flame and contributes to high combustion efficiency. The atomizer's production of relatively fine CWS droplets combined with the overall burner aerodynamics has yielded acceptable stability, over a to 1 load turndown range. Acceptable combustion efficiencies have also been demonstrated with this burner/atomizer combination. Preliminary data documenting this performance will be covered in the following section.

COMBUSTION TESTING

The combustion performance of the CWS burner was optimized and extensively evaluated at a commercial load which ranged from 20 to 80 MMBTU/hr. These tests were conducted in C-E's Full Scale Burner Facility (FSBF). The burner's combustion performance was parametrically investigated on both CWS and parent coal so that a meaningful combustion evaluation of CWS could be made via comparison to a known reference fuel. Test condition matrices for each fuel (shown in Tables 3 and 4) were designed to parallel one another so that direct test-by-test comparisons could be made. Test variables were; firing rate, excess air level, combustion air preheat temperatures, and also, for CWS, atomization air/fuel mass ratio. Data were obtained, depending on specific test conditions, of numerous independent parameters. These were gaseous emissions (CO , CO_2 , NO_x , SO_2 , and O_2), heat flux profile, calculated combustion efficiency, flame quality, fuel flowrate/temperature/pressure, combustion air flowrates/temperatures/pressures, atomization media flowrate/temperature/pressure, and at selected test points in-stack fly-ash sampling, which included dust loading, carbon content, particle size distribution and in-situ resistivity.

Prior to conducting these detailed combustion tests, prematrix and shakedown tests were performed to qualitatively define burner performance and to establish the probable ranges of operability. During these tests burner performance was optimized through combustion airflow distribution adjustments. Detailed parametric performance testing was then initiated once these preliminary tests indicated acceptable burner performance on CWS.

As stated previously, this paper is a progress report on C-E's CWS burner development program with EPRI. As of the date of writing (November 1982) combustion testing is complete, but detailed data analysis is still in progress. The data presented must be considered preliminary.

CWS Combustion Testing

Observed CWS flame stability and appearance was acceptable over the range of burner operation tested. In general the flame was "attached" or nearly "attached" to the burner. No major burner operability problems were noted during testing, although several items warrant mention. Because of the CWS storage tank settling problems previously discussed, fuel quality varied appreciably from test to test. Solids content varied from 67.1 to 70.0%. Some degree of combustion data scatter may be attributable to this, although data presented here was well within measurement confidence limits.

Secondly, the CWS was ignited satisfactorily in a cold, unheated test furnace using the facility's standard 5 MMBTU/hr natural gas side pilot ignitor. There was only one unusual requirement identified for ignition. This was the necessity of "prewetting" (with water) the atomizer and slurry gun prior to CWS introduction to prevent the absorption of a small but apparently critical amount of the slurry's water component. This was accomplished by inclusion of a water supply line to the fuel piping at the slurry gun. Failure to follow this procedure significantly increased the potential for nozzle pluggage during ignition.

The ignition procedure was as follows. First, a 5 MMBTU/hr natural gas side pilot ignitor was turned-on. Second, a small amount of water was passed through the slurry gun and atomizer. Next, the water was turned-off and simultaneously the CWS and compressed atomization air were turned-on, resulting in satisfactory CWS ignition. The side pilot was normally shut-off after about fifteen minutes of operation. Nominal burner firing rate for light-off was 25 MMBTU/hr and combustion air preheat of 250°F was utilized. Note, ignition was consistently achieved in the test furnace while in a cold and unpreheated state. However, because the furnace was lined with a thin layer of refractory blanket to simulate normal furnace heat losses and hence actual furnace outlet temperature, the furnace wall temperature may have risen at a somewhat higher rate than would be seen in an actual clean cold boiler. Thus the time that the ignitor is required to be on for a field application may be somewhat longer than the period discussed here.

Lastly, all tests were conducted with the 70° spray angle, tungsten carbide sleeved, "Y"-jet atomizer described under atomizer development. Approximately 20 hours and 100,000 lbs of slurry throughput were logged on this atomizer. The atomizer port diameters were precision measured before and after testing and indicated no measurable wear in the critical zones protected by the tungsten carbide sleeve. By comparison a carbon steel atomizer was used for prematrix testing, and while no meaningful erosion rate data could be obtained because of the intermittent and variable operation, significantly greater wear was noted in this atomizer over a much shorter period (i.e. 4 hours and 25,000 lbs. of slurry).

Parent Coal Combustion Tests

Parent coal combustion tests were conducted to provide baseline data to which the CWS combustion data could be compared. The parent coal was ground, for combustion testing, to a nominal size distribution of 70%-200 mesh which is standard for use as a boiler fuel firing pulverized coal.

Parent coal fuel injection modeled that of CWS so that meaningful fuel performance comparisons could be made. Coal was supplied in "dense phase" through a 1" ID fuel admission port to the center of a 70° diffuser cone. In this way the parent coal was "sprayed" into the furnace at the same 70° angle as that of atomized CWS. Note that the same combustion air register was used for both the parent coal and CWS tests.

Coal was supplied in dense phase with a C-E developed coal pumping, storage and supply system(10). This system permitted dense phase pulverized, parent coal, transport with transport air to fuel mass flow ratios in the range of 9 to 26. The parent coal was pneumatically conveyed from a 30 ton storage silo through an 1½" ID hose to the FSBF firing front. Pressure drop across the transport line varied from 6 to 26 psig.

Qualitatively, the combustion performance of the parent coal was excellent. Observed flame stability and appearance was similar, but slightly better than that noted previously for CWS over the same range of operation. The parent coal burned with a bright flame which was always "attached" to the burner.

Parent coal was readily ignitable in a cold, unpreheated test furnace using the facility's 5 MMBTU/hr natural gas side pilot ignitor. Once the parent coal was ignited in a cold furnace, the side pilot could be turned-off between one and five minutes with maintained flame quality and burner stability. For CWS ignition, 15 to 20 minutes were required before the side pilot could be turned-off. C-E has previously demonstrated that a similar type of dense-phase coal burner could be dependably ignited with an electric arc discharge within 30 seconds with no supplementary ignition or stabilization source, such as the side pilot.

A discussion of the comparative combustion performances of CWS and parent coal follows.

Combustion Performance Comparison of CWS to Parent Coal

To reiterate, both CWS and parent coal burned with bright, stable, "attached" or nearly "attached" flames over the burner load range tested. It was observed that as burner load was increased, from 20 to 80 MMBTU/hr, the axial flame length increased, but stability and attachment to the burner were maintained.

Figure 21 compares the carbon conversion efficiency of parent coal and CWS, as a function of excess air level at full load (80 MMBTU/hr). It can be seen that, at this load, parent coal combusted with 99+% carbon conversion efficiencies, and the CWS combusted with efficiencies about 1% less.

While the trends indicated in this figure are typical of those encountered at the other loads tested, preliminary data analysis indicates differences in carbon conversion efficiency of as much as 4% between parent coal and CWS existed at some test conditions. For most test conditions, however, carbon conversion efficiencies for CWS were diminished no more than 1 to 2 percent below that of the parent coal.

A comparison of carbon conversion efficiency as a function of burner load, between CWS and parent coal, at a constant 30% excess air level is shown in Figure 22. This figure reiterates the efficiencies noted in Figure 21. Parent coal was combusted with 99+% carbon conversion efficiency and again the CWS burned with approximately 1% lower efficiency over the load range presented. Note also that for each fuel, carbon conversion efficiency did not significantly vary as a function of load (40 to 80 MMBTU/hr) at 30 percent excess air.

Figure 23 illustrates the importance of good CWS atomization with regard to carbon conversion efficiency. All other conditions remaining the same, atomizer air to fuel mass ratio (A/F) was varied about an optimum value of 0.11 (identified during cold flow atomization development). Figure 23 indicates that below this optimum value carbon conversion efficiency drops off rapidly, while operation at higher A/F ratios yields no apparent efficiency change. This phenomena is in agreement with cold flow atomization results (Figure 15) which indicated rapid increase in mean atomized droplet size (diminished atomization quality) as A/F decreases from optimum and no improvement in atomization quality as A/F increased from optimum.

The resistivity values of the CWS and parent coal fly ashes, measured in-situ, are given in Table 5. These measurements indicate the fly ashes apparent collectability by electrostatic precipitation. What is important to note from Table 5 data is the lack of

significant difference between the CWS and the parent coal fly ashes. This implies that, at least for this specific case, the slurring process had no significant effect upon fly ash resistivity (i.e., collectability). Fly ash collectability by ESP is also a function of particle size. Fly ash particle size distribution results have not yet been analyzed, however, and are necessary before any final statements can be made with regard to the comparative collectabilities of the CWS and parent coal fly ashes.

In conclusion, although the data obtained indicates satisfactory carbon conversion efficiencies for CWS, other factors influencing overall plant efficiency must be considered in dictating the viability of conversion to CWS. For instance, a latent energy penalty is incurred due to the water component in the CWS. For the CWS tested (30% water by weight) a latent loss of 2.44 percent thermal efficiency would result with stack gas exit temperatures of 212°F; higher stack gas exit temperatures, required above sulfur-related dewpoints, would result in proportionally higher latent thermal losses. Furthermore, based on C-E's experience in handling fuels on a large laboratory scale, coal/water slurries are less efficient than oil from a parasitic power consumption standpoint for storage, transport and atomization (see Table 6). These factors and others must be evaluated in determining the applicability of a given CWS conversion.

SUMMARY

A burner/atomizer combination has been developed by Combustion Engineering which will burn CWS with satisfactory combustion efficiency over a wide load range. This firing system was developed using a three step approach to the problem. These steps included: 1) Atomizer development and optimization using an advanced C-E developed computer program and state-of-the-art spray measurement techniques, 2) Cold flow burner modeling to optimize the burner register's aerodynamic flow field, and 3) Full scale combustion matrix testing firing coal water slurry and its parent coal to characterize combustor performance and gather emissions data.

The preliminary results of this project show that the developed atomizer effectively atomizes high viscosity CWS (up to 2800 CPS). Measured atomization qualities and atomizing media consumption rates were similar to those measured for heavy fuel oil. Spray droplet size distributors were equivalent to those of a pulverized coal grind (with 30% inherent moisture) ranging between 115 and 150 mesh. Measured droplets were still significantly larger than the individual coal particles in the slurry.

Atomizer geometry was found to significantly influence atomization quality. However, preheating CWS prior to atomization (to reduce viscosity) did not have a great influence and yielded little improvement. Preheating the atomizing air also proved to be of limited value. However, because atomization did improve slightly with increased atomizing air temperature, the elimination of air compressor intercoolers would benefit atomization at no additional cost. The combined effects of preheating both slurry and air prior to atomization was found to be greater than either influence alone, however the improvement in atomization quality did not seem significant enough to merit the additional energy penalty. For combustion testing, CWS was not heated and atomizer air was not heated beyond the compressor's delivery temperature.

The preliminary combustion testing results indicate that, with the proper combination of burner and atomizer design, coal-water slurry can be successfully burned with carbon conversion efficiencies in the range of 96 to 99%. This compares with a consistent 99+% carbon conversion efficiency for the base coal fired under similar conditions. Additional improvements in CWS combustion efficiency may be possible through further firing system development and refinement.

This project has also successfully demonstrated that coal-water slurry could be reliably ignited in a cold furnace using conventional ignitors and low air preheat temperatures (250°F).

Although preliminary results have demonstrated satisfactory CWS combustion performance on a large laboratory scale, there are several other boiler-related areas which must be

addressed before CWS can become commercially viable. Furnace slagging, fouling and boiler derating, as well as, differential fuel costs and conversion costs must balance out favorably when compared to continuing operation on heavy oil. Detailed discussion of these factors is beyond the scope of this paper, but will dictate the ultimate viability of CWS as a boiler fuel.

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Figure 1

PAYBACK PERIOD vs FUEL COST AND DERATING
REFERENCE 7

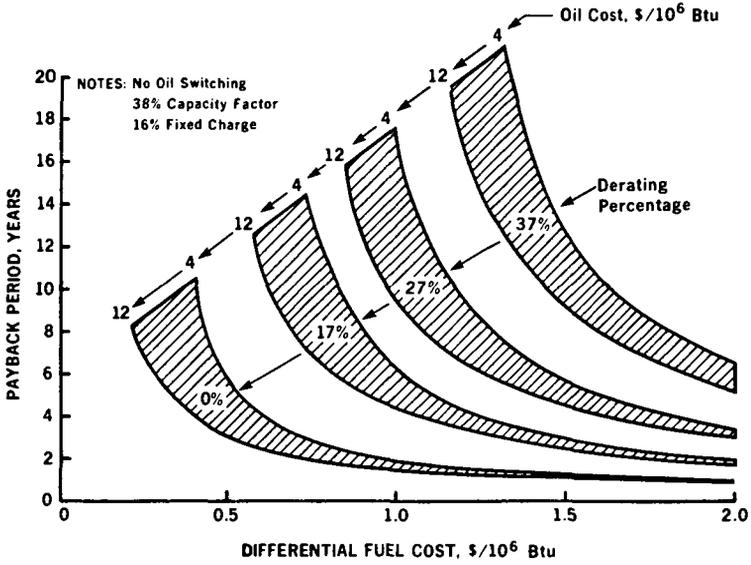


Figure 2

EPRI's HOMER CITY COAL CLEANING TEST FACILITY
SIMPLIFIED SCHEMATIC OF EQUIPMENT CONFIGURATION USED FOR PRODUCING LOW ASH COAL

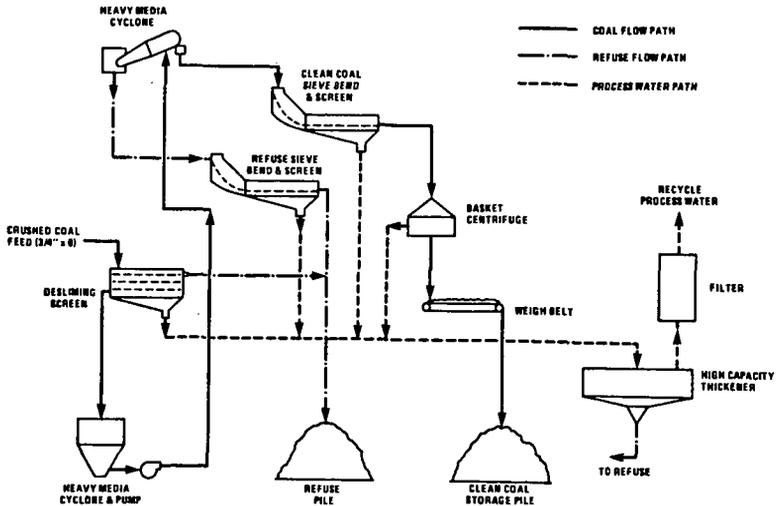


Table 1

Analysis of Parent Coal After Cleaning
at EPRI's Homer City Coal Cleaning Test Facility

	"AS RECEIVED"	"MOISTURE FREE"
<u>PROXIMATE ANALYSIS, %</u>		
Moisture	6.4	--
Volatile Matter	37.6	40.1
Fixed Carbon	53.1	56.8
Ash	2.9	3.1
<u>ULTIMATE ANALYSIS, %</u>		
Moisture	6.4	--
Carbon	74.5	79.6
Hydrogen	5.4	5.8
Nitrogen	1.5	1.6
Sulfur	.9	.9
Ash	2.9	3.1
Oxygen (diff.)	8.4	9.0
<u>GROSS HEATING VALUE</u>		
BTU/lb	13,790	14,730

Table 2

Coal-Water Slurry Properties
CE/AFT CWS Specification

<u>Particle Size</u>	100% minus 100 Mesh
<u>Viscosity</u>	less than 2800 Centipoise at 113 sec ⁻¹ and 25°C (Haake Method) Newtonian or Pseudo Plastic Behavior
<u>Volatile Matter</u>	Greater than 30% by weight (dry)

AFT Coal-Water Slurry Analysis

Total Moisture, %	31.0	
Solids Content, %	69.0	
	"AS RECEIVED"	"MOISTURE FREE"
<u>Proximate Analysis, %</u>		
Moisture	31.0	--
Volatile Matter	27.1	39.3
Fixed Carbon	40.1	58.1
Ash	1.8	2.6
<u>Ultimate Analysis, %</u>		
Moisture	31.0	--
Hydrogen	3.8	5.5
Carbon	56.1	81.3
Sulfur	.6	.9
Nitrogen	1.1	1.6
Oxygen (diff.)	5.6	8.1
Ash	1.8	2.6
<u>Gross Heating Value</u>		
BTU/lb	10,170	14,740



Photo 1
TANK TRUCK ARRIVING AT ALTERNATE FUELS HANDLING
FACILITY WITH A LOAD OF COAL-WATER-SLURRY

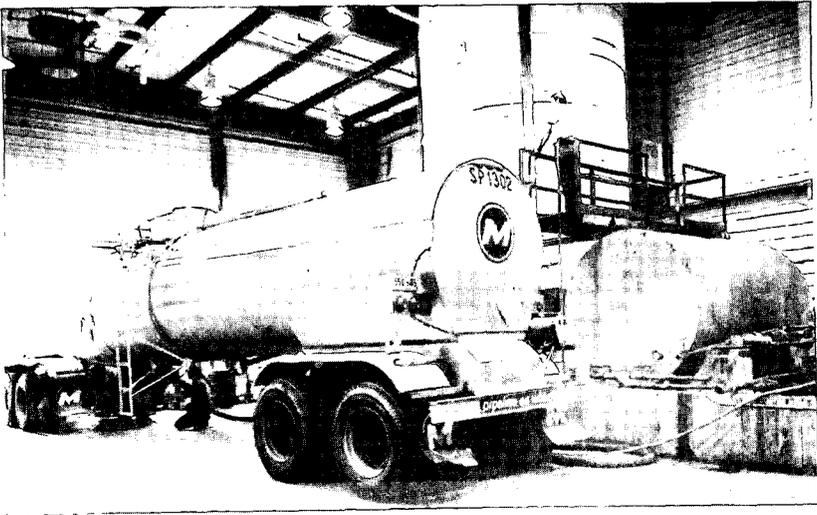


Photo 2
TRANSFERRING COAL-WATER-SLURRY FROM TANKER TO
THE 15,000 GALLON STORAGE TANK

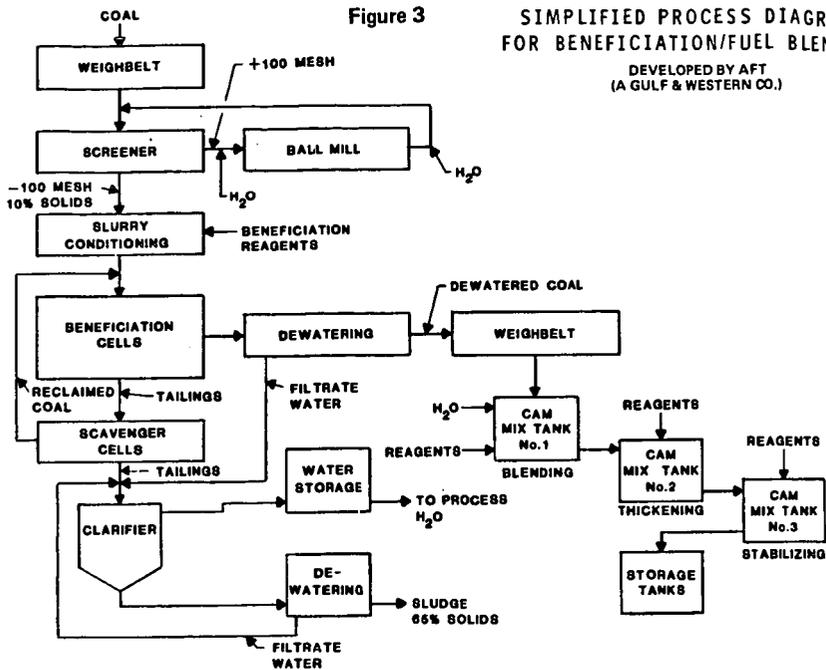


Figure 4

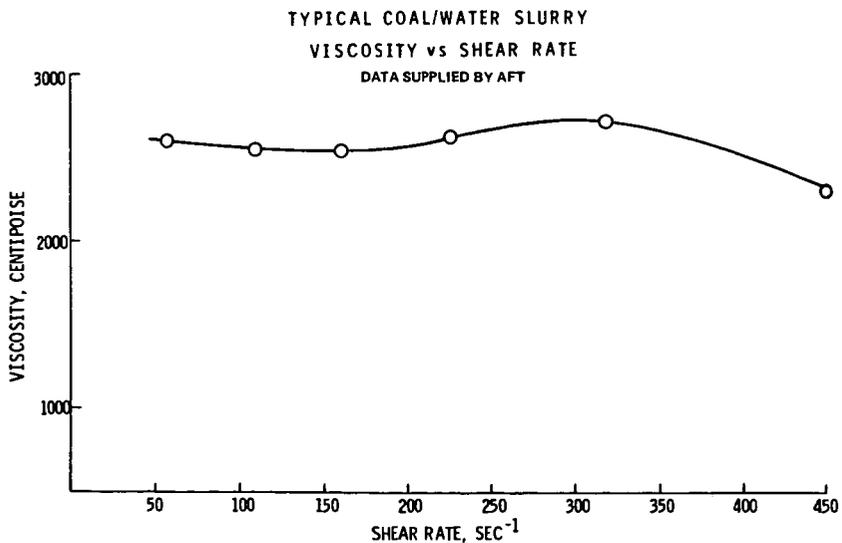


Figure 5

ALTERNATE FUELS HANDLING AND FIRING SYSTEM SCHEMATIC

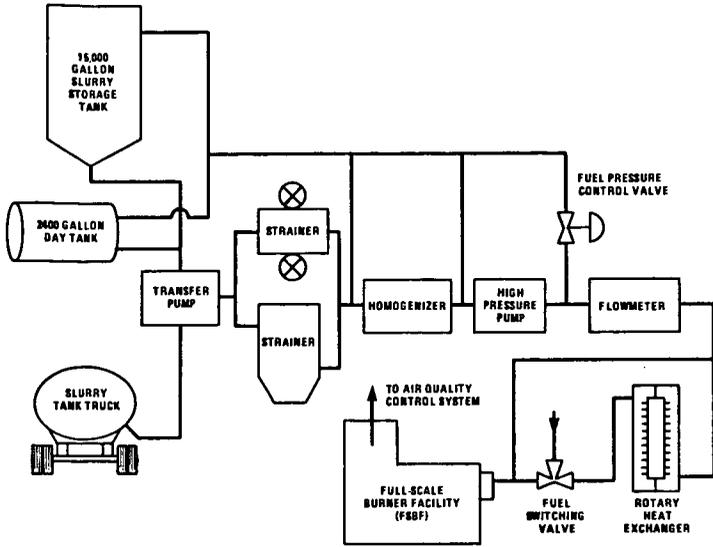


Figure 6

SIMPLIFIED COAL-WATER-SLURRY FIRING SYSTEM SCHEMATIC

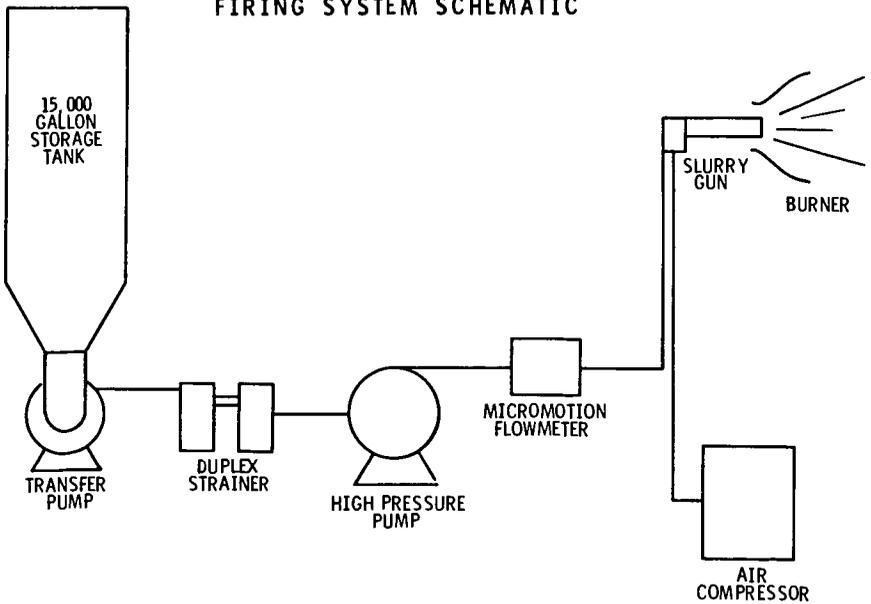


Figure 7

CRITICAL DIMENSIONS "Y" JET ATOMIZER DESIGN
CROSS-SECTIONAL VIEW

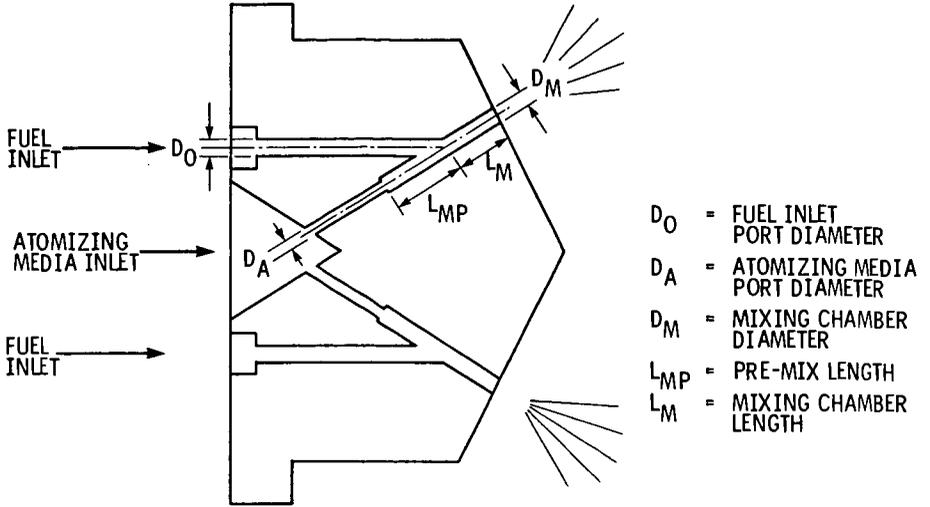
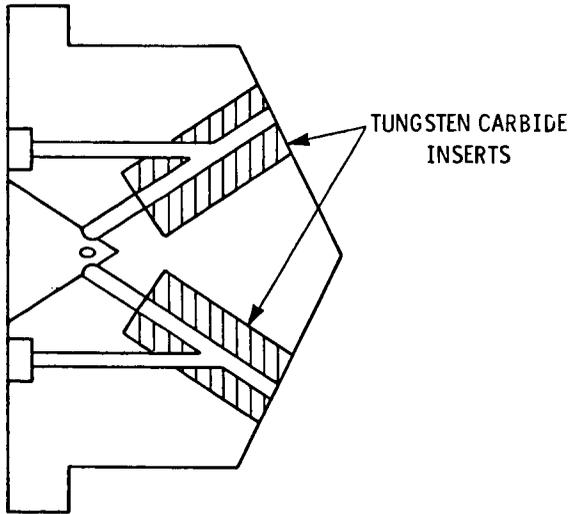


Figure 8

WEAR RESISTANT ATOMIZER DESIGN



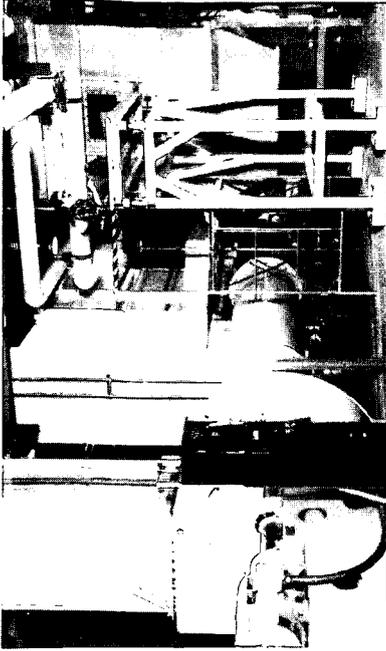


Figure 9

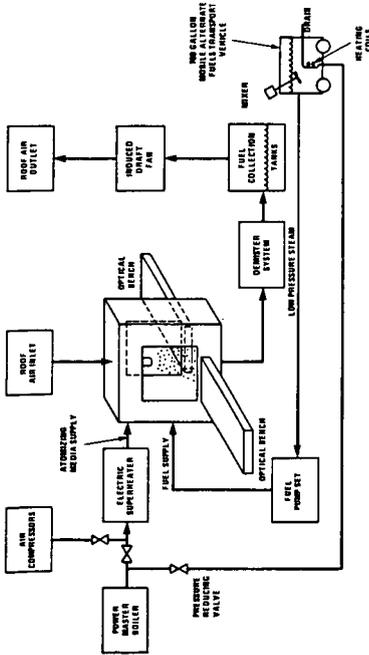
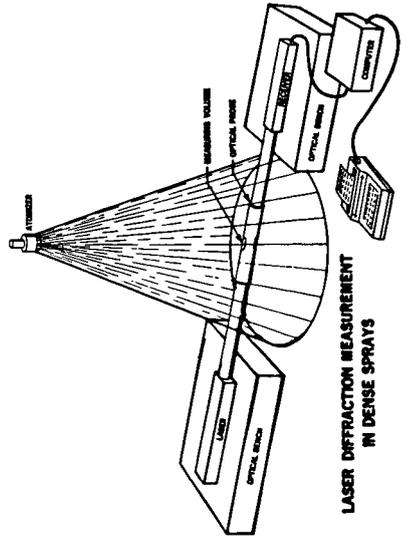
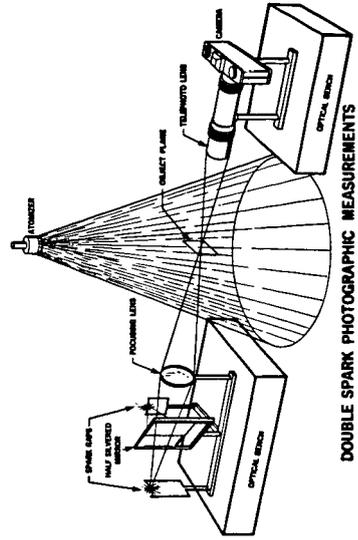


Figure 10



LASER DIFFRACTION MEASUREMENT IN DENSE SPRAYS

Figure 11



DOUBLE SPARK PHOTOGRAPHIC MEASUREMENTS

Figure 12

INFLUENCE OF ATOMIZER GEOMETRY ON
ATOMIZATION QUALITY
100% LOAD

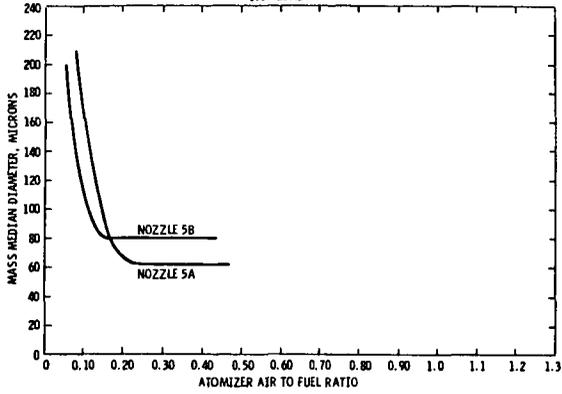


Figure 13

INFLUENCE OF ATOMIZER GEOMETRY ON
ATOMIZATION QUALITY
50% LOAD

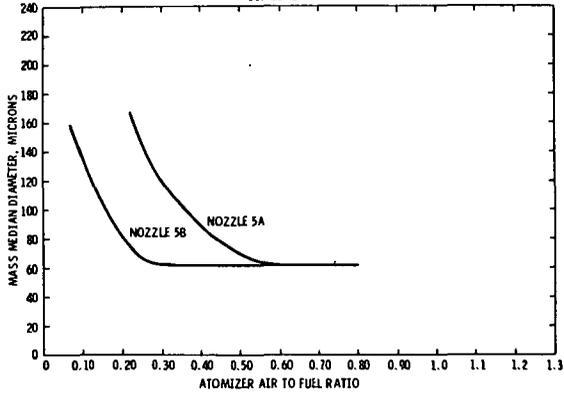


Figure 14

INFLUENCE OF ATOMIZER GEOMETRY ON
ATOMIZATION QUALITY
25% LOAD

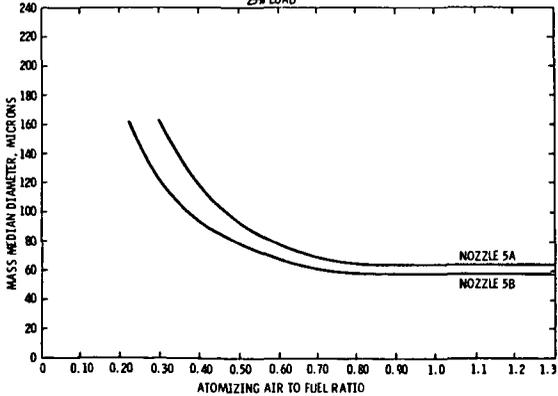


Figure 15
INFLUENCE OF ATOMIZING AND LIQUID MASS
FLOW RATIO ON ATOMIZATION QUALITY
100% LOAD

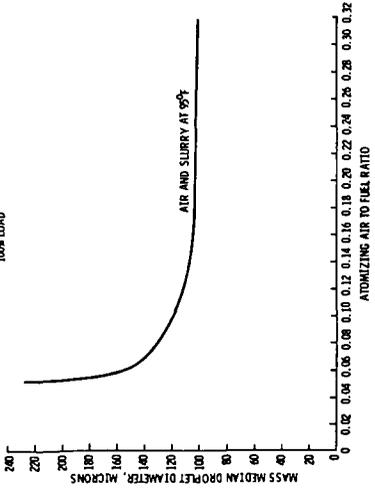


Figure 16
EFFECT OF SLURRY TEMPERATURE

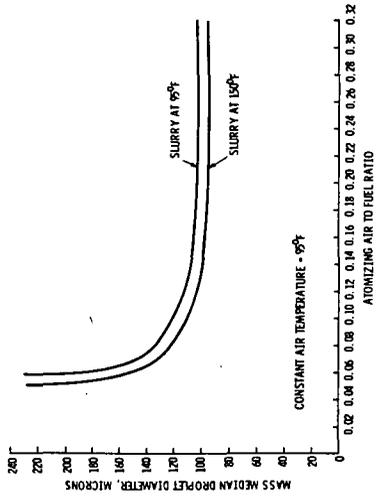


Figure 17

EFFECT OF ATOMIZING AIR TEMPERATURE

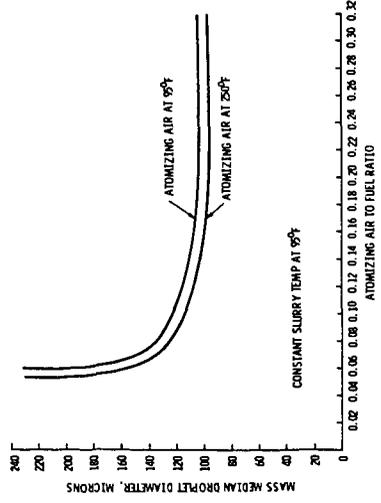


Figure 18

EFFECT OF SLURRY AND AIR TEMPERATURE

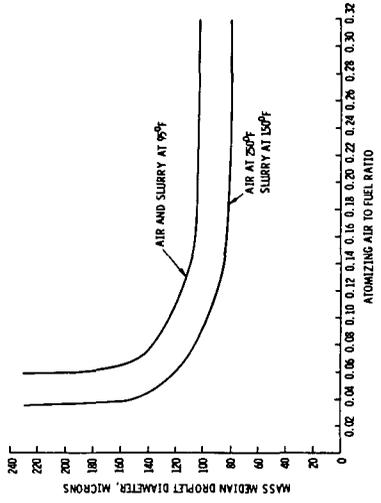


Figure 19

C-E/EPRI CWS BURNER - COLD FLOW MODEL
INDICATED FLAME PATTERN FROM
AERODYNAMICS OBSERVATIONS

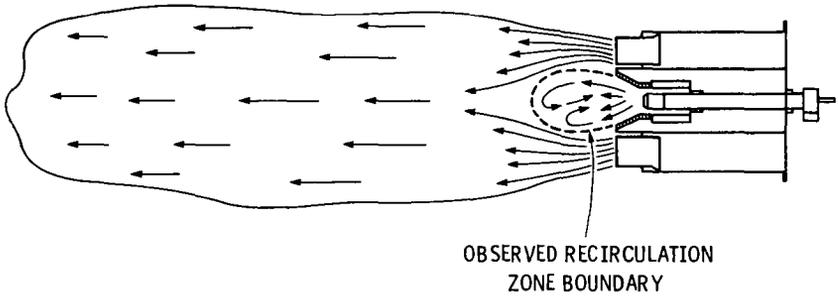


Figure 20

C-E COAL-WATER-SLURRY BURNER SCHEMATIC

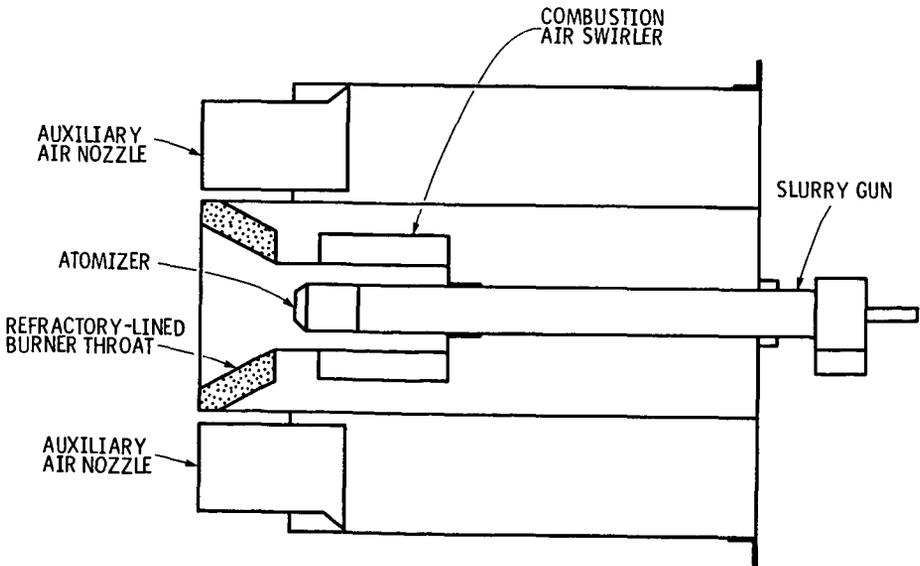


TABLE 3
Coal-Water Slurry Combustion Test Matrix

100% Load = 80×10^6 BTU/HR

TEST NO.	INDEPENDENT VARIABLES			MEASURED DEPENDENT VARIABLES						ATOMIZER AIR			ATOMIZER PRESS							
	EXCESS AIR	CO ₂	CO	CO ₂	CO	NO _x	O ₂	SOLIDS LOADING	CARBON BURNDOUT	FLYASH DISTRIBUTION	STACK FLYASH	INSITU FLYASH	FLAME QUALITY	HEAT CALC. FLUX	HEAT CALC. COMB. FLUX	ATR CORR. FLOW	ATR CORR. FLOW	TEMP	FUEL	AIR
1	100	40	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2	50	40	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3	25	40	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4	100	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
5	50	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
6	25	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7	100	SP	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
8	50	SP	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	25	SP	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
10	75	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11	75	30	400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
12	100	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 4

Parent Coal Combustion Test Matrix

100% Load = 80×10^6 BTU/HR

TEST NO.	INDEPENDENT VARIABLES			MEASURED DEPENDENT VARIABLES						FLAME QUALITY			HEAT CALC. COMB. FLUX			ATR CORR. FLOW				
	EXCESS AIR	CO ₂	CO	CO ₂	CO	NO _x	O ₂	SOLIDS LOADING	CARBON BURNDOUT	FLYASH DISTRIBUTION	INSITU FLYASH RESISTIVITY	FLAME QUALITY	HEAT CALC. COMB. FLUX	HEAT CALC. COMB. FLUX	ATR CORR. FLOW	ATR CORR. FLOW	TEMP	FUEL	AIR	
1	100	40	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
2	50	40	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
3	25	40	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4	100	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
5	50	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
6	25	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7	100	SP	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
8	50	SP	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
9	25	SP	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
10	75	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11	75	30	400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
12	100	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 21

COMPARISON OF CARBON CONVERSION EFFICIENCY OF PARENT COAL vs COAL-WATER-SLURRY AS A FUNCTION OF EXCESS AIR LEVEL AT 80×10^6 BTU/HR

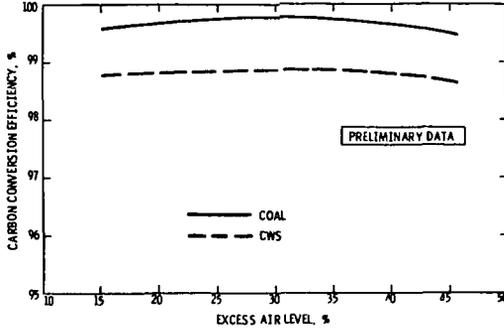


Figure 22

COMPARISON OF CARBON CONVERSION EFFICIENCY OF PARENT COAL vs COAL-WATER-SLURRY AS A FUNCTION OF FIRING RATE AT 30% EXCESS AIR

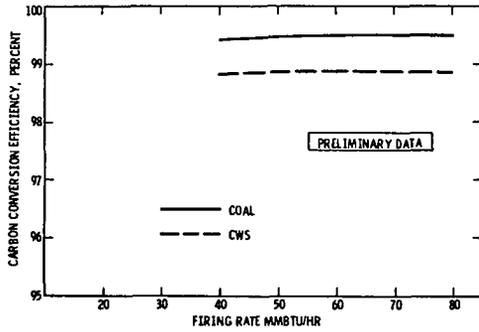


Figure 23

CARBON CONVERSION EFFICIENCY vs ATOMIZING MEDIA RATIO FOR COAL-WATER-SLURRY

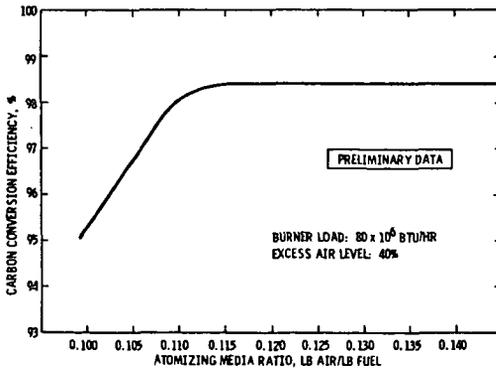


Table 5

FLY ASH RESISTIVITY MEASUREMENTS

<u>FUEL</u>	<u>LOAD</u> (10 ⁶ Btu/hr)	<u>EXCESS AIR</u>	<u>COMBUSTION AIR TEMPERATURE</u> (°F)	<u>FLY ASH RESISTIVITY</u> (OHM-CM)
CWS	40	30%	250	1.8 x 10 ⁸
CWS	60	30%	250	2.1 x 10 ⁸
CWS	60	30%	400	2.9 x 10 ⁸
Parent Coal	40	30%	250	2.0 x 10 ⁸
Parent Coal	60	30%	250	3.7 x 10 ⁸
Parent Coal	60	30%	400	2.4 x 10 ⁸
Parent Coal	80	30%	250	3.0 x 10 ⁸

Table 6

FUEL SYSTEM POWER CONSUMPTION

One Elevation 800 MMBTU/HR Heat Input

(BASED ON LARGE SCALE LABORATORY TESTING)

	<u>Oil</u> (MMBTU/HR)	<u>Coal-Oil</u> (MMBTU/HR)	<u>Coal-Water</u> (MMBTU/HR)
STORAGE	NONE	0.13	0.02
TRANSPORT/FEED	1.71	2.24	2.24
BURNER/ATOMIZER	4.40	5.00	4.60
TOTAL	6.11	7.37	6.86

SMALL (5 MILLION BTU/HR) AND LARGE (300 MILLION BTU/HR) THERMAL TEST RIGS
FOR COAL AND COAL SLURRY BURNER DEVELOPMENT

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1. INTRODUCTION

Thermal test rigs have been used by NEI International Combustion over the past 25 years for the evaluation and development of burner systems for both industrial and utility boilers. Initially, the rigs were little more than open brick containers which have evolved to the water-cooled gas-tight chamber currently in use to enable the development of low excess air combustion systems as demanded by market forces and the need for more effective fuel utilisation. A major step forward in thermal test rig facilities occurred in 1973 with the construction of what is probably the largest and most comprehensively instrumented burner test rig in the Western Hemisphere. The rig design had to meet all of the known oil burner performance requirements at that time, and also be sufficiently flexible to meet the predicted requirements of the succeeding 10 - 12 years. This rig is still in operation today and is currently undergoing the next major step change in conversion to enable pulverised fuel, coal slurries and gas burner systems, sized up to 300 million BTU/Hr, to be developed.

A complementary small scale thermal test rig facility, rated at around 5 million BTU/hr was also provided in 1975 to allow fundamental combustion studies and the development of new ideas in burner design and operation to take place at a more economical level in comparison with the operation of the large test rig.

Both these major step changes in the large scale thermal test rig capabilities have been dictated by market forces. Initially the need was to develop low excess air oil burners utilising the almost continuously deteriorating quality fuel oils supplied to the utility boiler industry. The current need is to meet the renewed interest in coal utilisation now that it is realised that fuel oil supplies are not infinite and consequently will be subject to continual increases in price with little or no guarantee as to quality and availability.

Although it is not universal practice to test burner systems for large boilers prior to site installation, the availability of a full-scale thermal test rig enables the development of a tailor-made burner system to suit a particular installation. Customers can see a proposed burner system in operation and any changes required, because of alterations in operating procedures or variations in fuel properties, can be accommodated. These investigations, into altered conditions, can be made quickly and economically compared with on site investigations and without interruption to the customers operating schedule. Markets for new fuels, such as coal slurries, can be pursued without relying on potential customers to provide full-scale test facilities. In fact, until the firing of coal-water and coal-oil slurries becomes universally accepted, there should be an increasing demand for off-site demonstrations of the capabilities of these new burner systems. The operation of a full-scale thermal test rig is therefore an essential piece of equipment for any burner manufacturer to achieve and maintain a leading position in the supply of combustion systems to the International utility boiler market.

2. The Large (300 million BTU/Hr) Thermal Test Rig at Derby

2.1 General Description of the Rig and its Capabilities

The original design of the large thermal test rig at Derby was ambitious, as it had to meet the requirement of NEI International Combustion to maintain its leadership in oil burner performance in the Western Hemisphere. A major requirement was that of sheer size. The combustion chamber dimensions had to be such that complete combustion could be obtained, upstream of gas sampling positions, with burner systems (firing up to 9 tonnes/hr of fuel oil) designed to produce long narrow flames typical of burners designed for tangential firing applications and those designed to produce more compact large diameter flames typical of front wall firing applications. These considerations resulted in a combustion chamber of internal dimensions 21.34 m (70 ft) long by 5.49 m (18 ft) square cross section. Cooling of the combustion chamber is achieved by means of static water sandwiched between inner and outer steel skins on the side walls and end wall of the chamber remote from the burner. The centre section of the burner wall is built entirely of refractory to enable easy changing of burner configurations, the roof is also entirely water-cooled and the hearth covered with a layer of refractory pebbles on a bed of sand.

Oil storage is provided by two lagged and steam heated storage tanks, each of 45460 litres (10,000 gallons) capacity. Oil is transferred from the tanks, via a low pressure transfer pump, to a primary pumping and heating circuit capable of delivering oil at a pressure of 44.8 bar (650 lbs/in²) at up to 13640 kg/hr (30,000 lbs) and a viscosity of 70 Redwood No 1 seconds (16 cS, 80 SSU). A second pumping and heating circuit was installed, at a later date, enabling an oil delivery pressure up to 83 bar (1200 lb/in²) and oil temperatures up to 200°C (392°F) to be achieved. This secondary pumping heating system was used particularly in a study of the combustion of fuel oils containing a high percentage (up to 14%) of hard asphaltenes.

Combustion air is supplied to the burner windbox by a four-stage axial flow fan capable of supplying 37.77 m³/sec (80,000 ft³/m) of combustion air at a maximum pressure of 44.8 mbar (18 ins water gauge). Noise levels from the fan are controlled by axial flow silencers immediately upstream and downstream of the fans and air flow rate is indicated by a venturi meter. Coarse air flow control is via the number of fan stages brought into operation and fine control is achieved by a remotely controlled butterfly damper.

All the flows to the rig are controlled from an operating console situated at the end of the combustion chamber remote from the burner. From this position the rig operator can observe an end view of the flame through a glass porthole. A comprehensive gas analysis system is also housed adjacent to the control console.

During the operation of a burner test, gases are sampled from the 2.74 m (9 ft) diameter 18.29 m (60 ft) high refractory lined stack, at a point some 10.67 m (35 ft) above ground level located in the stack. At this same point a platform has been erected to enable the isokinetic sampling of the flue gases for determination of the solids burden. The gas analysis instrumentation provides a continuous record of O₂, CO, CO₂ and NO_x in the flue gases throughout a test. A smoke density meter and facility for determining the Bacharach smoke number is also available. Observation ports are provided along the side wall of the combustion chamber to enable photographs to be taken of the flames as required.

Steam for oil heating and atomisation is available from a package boiler of 4994 kg (10,980 lb) per hour steam capacity at a delivery pressure of 17.24 bar (250 lb/in²).

Most oil burner test work is carried out using cold combustion air. However, combustion air preheat can be achieved by means of duct burners located in the combustion air supply ducting after the axial flow fans. With this system in operation oxygen has to be supplied to the combustion air stream to maintain a 21% O₂ content in the combustion air at the burner windbox.

In order to provide a complete burner test facility, comprehensive laboratory facilities and expertise are available to provide chemical and physical analysis of fuels and particulates and also isothermal test facilities to assess the quality of atomisation of the various atomiser designs under test.

Figure 1 indicates the general layout of the test rig and the ancillary supply and analysis equipment.

2.2 Conversion of the Rig to Provide a Coal and Coal Slurry Firing Capability

The object of the conversion exercise is to maintain the existing oil firing capability and provide the facility for firing pulverised fuel, coal slurries (e.g. coal water or coal oil mixtures) and gas at similar maximum heat input rates of around 300 million BTU/hr. Both light and dense phase systems for the firing of pulverised fuel are incorporated and the coal slurry firing facilities are designed to handle coal water mixtures containing up to 75% coal and coal oil mixtures with up to 50% coal. A typical British East Midlands steam raising coal of 15% ash content (dry basis) and 7220 Kcal/kg (13,000 BTU/lb) calorific value, was used as the basis of design calculations for the conversion exercise.

The problems to be overcome in the conversion exercise were the deposition and collection of ash, both within and outside the test rig (to satisfy Local Authority regulations), the provision of a combustion air pre-heating capability, and the design of conveying systems for dense phase and lean phase pulverised fuel and for coal slurries.

Local Authority environmental requirements restrict solids discharge from the rig stack to 72 kg/hr (158 lb/hr). Therefore, in order to cope with the maximum coal firing rate of 10 tonnes/hr with a 15% ash coal, the waste gases leaving the rig, at about 1000°C (1830°F), must be conditioned and cleaned before being dispersed to the atmosphere. The system decided upon for gas conditioning and cleaning comprised a high pressure hot water waste heat boiler followed by a multi-cyclone dust collector. An induced draught fan after the dust collector conveys the cooled clean gases into the stack and thus to atmosphere. The incorporation of the waste heat recovery system allowed the provision of pre-heat to the combustion air and primary air (conveying lean phase pulverised fuel) via high pressure hot water heat exchangers located in the appropriate air ducts. Surplus heat from the waste heat boiler is dissipated via a series of forced draught dump coolers located remotely from the test rig and operating in the closed circuit mode in line with the waste heat boiler. Water is supplied from the waste heat boiler to the heat exchangers at a temperature of 218°C (425°F) and pressure of 30 bar (440 lbs/in²) providing 121°C (250°F) pre-heat for the primary air lean phase pulverised fuel conveying and 177°C (350°F) preheat for the secondary combustion air. The system of duct burners and oxygen injection is retained in order to provide increased secondary (or combustion) air pre-heat as required.

In addition to collection of ash outside the combustion chamber it is anticipated that up to 50% of the total ash content of the coal could be collected inside the chamber. To facilitate the removal of this ash and any spillages of unburnt pulverised fuel the existing refractory pebble floor is to be replaced by a water-cooled floor of similar design to the side walls as mentioned in section 2.1. As the existing mode of operation for the development of low excess air oil burners is to be maintained a water-cooled door has been provided in the rig back wall enabling combustion gases to be diverted either directly, or via the waste gas conditioning system, to the existing stack

Coal conveying is to be based on a dense phase system either feeding directly to a purpose designed burner system or into a pre-heated primary air system giving the required air dilution to provide a lean phase pulverised fuel firing facility.

The dense phase system comprises a pressurised double-blow tank unit fed from a 20 tonne pulverised coal storage silo. Nitrogen purge facilities and continuous temperature monitoring of the storage silos are provided in order to minimise the explosion risk. The dense phase system will allow pulverised fuel to be conveyed in relatively small diameter pipelines, compared to the more conventional lean phase firing systems, which could be an important consideration when boiler changeovers from oil to coal firing are contemplated and the existing access to the boiler fronts is limited. Fuel flow rates from the dense phase system will be monitored by load cells located in the blow tank system.

The slurry feed system comprises a storage tank which can be stirred and heated continuously, and a mono-pump with facilities for flushing out the complete system after any particular firing exercise. Slurry flow will be monitored by a 'Doppler Effect' flow meter, with the slurry continuously circulated around the pump and storage tank and taken off as required to the burner system.

A facility for continuous data logging of fuel flows, gas flows, gas analysis and temperature is to be provided and this microprocessor controlled unit will also provide a central control over all the operating parameters, giving a continuous visual display of the levels of the parameters throughout a test run. An instant print-out of these parameters can be obtained at any selected point in the test run. Figure 2 shows the general layout of the test rig after the conversion to provide this multi-fuel burner development facility and Figures 3 and 4 show details of the pulverised fuel and coal slurry conveying systems.

The conversion programme is to take place in two phases - the first phase will provide facilities to enable a maximum of 3.5 tonnes/hr of coal to be fired either in dense phase or slurry form. Limiting the firing rate to this level removes the necessity for the provision of gas cleaning to meet the environmental emission levels and enables experience of operating the rig under coal firing conditions to be obtained more quickly. Phase 2 of the conversion involves installation of the gas conditioning dust cleaning plant to allow the operation at the full fuel rating. The conversion work is expected to be completed and the rig fully operational during the first half of 1983.

Attention has also had to be given to the sound levels from equipment to be provided in the conversion work. Firstly, for the protection of operating personnel, the sound pressure level from any individual item of plant will not exceed 90 dBA at 1 metre and secondly, because the rig will operate within the proximity of a local housing estate, the maximum sound power level from the complete plant is limited to 117 dBA, ref. 10^{-12} watts, with a boundary condition of 65 dBA at 200 metres.

3. The Small (5 million BTU/hr) Thermal Test Rig at Derby

Fundamental combustion studies and particular aspects of burner systems development work can be carried out quickly and economically on this small rig. The rig is linked to the same gas analysis system as the large rig and is equipped for oil, gas and coal slurry firing, additionally a combustion air preheater is available capable of delivering combustion air at up to 425°C (800°F).

The combustion chamber comprises a water-cooled mineral wool lined steel cylinder 4 m (13 ft) long by 1.1 m (3.75 ft) diameter, with a 5.2 m (17 ft) refractory lined stack equipped with gas sampling and temperature measurement points. Observation ports are provided on the combustion chamber axis, close to the burner and in the chamber rear wall. Compressed air and steam are available for fuel atomisation purposes as are pumping and circulating trains for oil fuels and coal slurries. At a 5 million BTU/hr rating this rig is capable of burning 125 kg/hr (275 lbs) of gas oil and 205 - 230 kg/hr (450 - 500 lbs) of coal water slurry or their equivalent. Figure 5 shows the general layout of the small scale rig and its ancillary equipment.

4. Work on Coal Slurry Utilisation

4.1 Coal Water Mixtures

Recent work based on the small scale rig has concentrated on investigations into the properties of coal water mixtures and their influence on handling equipment and burner design. In the initial stages of the work considerable problems were encountered with blockages in pipelines and burner heads because of the instability and excessive proportion of over-size coal particles (ca 500µm) in the coal water mixtures.

These early experiences enabled the compilation of a general specification for coal water mixture properties and associated handling equipment to be used as a basis for the successful development of a coal water combustion system. These desirable features can be listed as follows:-

4.1.1 Combustion and Handling Equipment

Atomisers should be based on an external mix air atomiser design avoiding sudden changes in direction and diameter in the coal water mixture conveying system which tends to deposit the coal from the slurry and can be points of excessive wear, particularly in atomiser components. Steam atomisation is to be avoided since the additives used to stabilise the coal water mixture can break down at temperatures above 60°C (140°F).

Coal water mixtures should be fed to the burners via a continuous recirculation system (see Fig. 5) and particularly in the case of intermittent rig work, facilities should be provided for water flushing of all the feed lines and valves after each run. It should also be noted that a coal water mixture can freeze in ambient temperatures of 0°C (32°F) or less and provision should

be made for some form of trace heating, subject to the temperature limitations mentioned above, where these conditions can occur.

4.1.2 Coal Water Mixture Properties

Coal particle size in the coal water mixture should be a maximum of 250µm and the coal volatile matter (dry basis) a minimum of 25%. There should be little or no settling out during transportation and any settling which does occur should be easily overcome by a simple recirculation system as described earlier.

The properties of the coal water mixture used in the small scale test work at Derby are given in Table 1.

TABLE 1

Coal Water Mixture Properties

1.1 Proximate Analysis

	<u>Original Coal</u>	<u>Coal in Slurry</u>
Ash % (dry basis)	3.0	1.8
Volatile Matter (dry basis)	35.5	37.4
Fixed Carbon	61.5	60.8
Sulphur	1.24	1.02

Inherent coal moisture 4%

1.2 Ultimate Analysis

	<u>Original Coal</u>	<u>Coal in Slurry</u>
C	83.4	84.5
H ₂	5.2	5.4
N ₂	1.8	1.8
Ash	3.0	1.8
S (pyritic)	0.55	0.34
S (sulphatic)	0.04	0.05
S (organic)	0.65	0.63
O ₂ (by difference)	5.36	5.48

1.3 Confirmatory Analysis

The above analyses were supplied by the coal water mixture supplier, confirmatory proximate analysis carried out at the Derby laboratories on the coal slurry was as follows:-

	<u>As Received</u>	<u>Dry Basis</u>
Moisture %	26.9	-
Ash %	1.36	1.86
Volatile Matter %	28.85	35.36
Fixed Carbon %	45.89	62.78

1.4 Physical Analyses

<u>Sieve Analysis of Dry Sample</u>	<u>%</u>
+ 30 mesh (570 μ m)	Nil
- 30 mesh + 60 mesh (250 μ m)	0.42
- 60 mesh +100 mesh (150 μ m)	5.02
-100 mesh +200 mesh (75 μ m)	18.55
-200 mesh +300 mesh (45 μ m)	9.93
-300 mesh	66.08

Viscosity Data up to 60°C

Taken by a Contraves RM15 viscometer shear prior to measurement 30 sec⁻¹.

<u>Temperature (°C)</u>	<u>Viscosity (centistokes)</u>
19.5	989
30.0	765
40.5	621
50.0	641
60.0	576

Surface Tension

Liquor extracted from the slurry 57 dyne cm⁻¹.

The coal water slurry is in fact derived from a coal beneficiation process and the properties of the original coal are included in Table 1 for comparison purposes. The coal water mixture meets the desired specification levels with regard to coal particle size, coal volatile matter and stability and has proved very easy to handle through the small scale thermal test rig pumping system described earlier.

4.2 The Influence of Coal Water Mixture Properties on Burner Design

Although, generally speaking, coal water mixtures can, as claimed by the proprietary slurry producers, be handled like a fuel oil there is a significant difference in the viscosity temperature relationship of the fuels which must be taken into consideration in designing a burner to handle a coal water mixture. Normally, to produce good atomisation, heavy fuel oils are heated to around 140°C (280°F), which helps to achieve oil droplet sizes ex - the atomiser in the 60 - 100 μ , mean size range. Equally good atomisation is required for coal water mixture combustion in order to achieve rapid evaporation of the water content and release of the coal volatiles necessary to establish stable ignition conditions.

Typical viscosity/temperature curves for fuel oil and coal water mixtures are shown in Figure 6 and these, together with the slurry temperature/stability relationships mentioned in Section 4.1.1, preclude heating as a method of significant viscosity reduction with coal water mixtures.

Two possibilities were considered for the required viscosity reductions:

1) the addition of viscosity reducing chemicals, and 2) aeration of the coal water slurry. In order to be effective both techniques have to be applied to the fuel as close to the atomiser tip as possible and aeration was chosen as the more practical proposition being more compatible with known twin fluid atomiser design techniques.

Figure 7 shows the theoretical viscosities obtainable by aeration of coal water mixtures, based on calculation techniques used in viscosity blending of oils¹.

4.3 Development of a Coal Water Mixture Burner

Figures 8 and 9 show the general arrangement of the burner used for the small scale development work and a diagrammatic representation of the burner nozzle configuration, incorporating the viscosity reduction by aeration principle.

For the initial exercise on burner nozzle development cold combustion air was used with the gas burner (Figure 8) supplying the initial preheating, ignition and stabilisation of the coal water mixture flame, as required.

The nozzle design incorporates two sets of atomising air holes designated 'shear holes' which give rise to the initial aeration (or viscosity reduction) process and 'swirl holes' which produce a coherent spray from the nozzle tip. Initial qualitative spray trials resulted in three nozzles, designated C, D and E, of varying shear hole/swirl hole diameter ratios, being selected for thermal tests.

Isothermal spray work, using glycerine to represent the viscous coal water mixture, indicated that the nozzles produced good quality atomisation. Figure 10 shows the results of these isothermal tests. Extrapolation of the curves indicates that perhaps nozzle E will produce better atomisation at higher fuel flow rates.

The results of these initial thermal tests together with the variations in nozzle geometry are given in Table 2. In this table the 'apparent viscosities' calculated are based on the assumption that the atomising air supplied to the nozzle divides into shear and swirl air in direct proportion to the shear/swirl hole area ratios.

TABLE 2

Results of Preliminary Small Scale Thermal Tests on

Coal Water Mixture Atomisers

2.1 Nozzle C - Shear Hole/Swirl Hole Area Ratio 0.50

Coal Water Mixture (CWM) feed rate kgs/hr (lbs/hr)	110 (242)	148 (325)	192 (400)
Coal Water Mixture feed pressure bar (psi)	0.6 (8)	0.9 (12.5)	1.2 (16)
Atomising air pressure bar (psi)	4.1 (60)	4.1 (60)	4.1 (60)
Atomising air ratio			
wt air : wt CWM	0.48	0.36	0.29
Heat input to test rig % MCR	58	76	92
Heat input ratio CWM : gas	6.8	9.2	11.3
Excess O ₂ % in flue gas	1.6	1.5	1.4
Flue gas temperature °C	779	805	820
Apparent aerated CWM viscosity cS	300	350	400

2.2 Nozzle D - Shear Hole/Swirl Hole Area Ratio 0.98

Coal Water Mixture (CWM) feed rate kgs/hr (lbs/hr)	110 (242)	148 (325)	182 (400)
CWM feed pressure bar (psi)	0.6 (8)	0.9 (12.5)	1.2 (16)
Atomising air pressure bar (psi)	4.1 (60)	4.1 (60)	4.1 (60)
Atomising air ratio			
wt air : wt CWM	0.48	0.36	0.29
Heat input to rig % MCR	58	76	92
Heat input ratio CWM : gas	6.8	9.2	11.3
Excess O ₂ % in flue gas	1.5/4.4	1.5/4.7	1.5/4.6
Flue gas temperature °C	803/795	806/806	820/817
Apparent viscosity aerated CWM cS	100	150	250

2.3 Nozzle E - Shear Hole/Swirl Hole Area Ratio 2.0

Coal water mixture (CWM) feed rate kgs/hr (lbs/hr)	110 (242)	148 (325)	182 (400)
CWM feed pressure bar (psi)	0.6 (8)	0.9 (12.5)	1.2 (16)
Atomising air pressure bar (psi)	4.1 (60)	4.1 (60)	4.4 (60)
Atomising air ratio			
wt air : wt CWM	0.48	0.36	0.29
Heat input to rig % MCR	58	76	92
Heat input ratio CWM : gas	6.8	9.2	11.3
Excess O ₂ % in flue gas	1.5/4.0	1.5/4.0	1.5/4.0
Flue gas temperature °C	792/820	846/862	925/937
Apparent viscosity aerated CWM cS	60	100	150

The results indicate that at a heat input equivalent to the rated maximum of the small rig (5 million BTU/hr) the ratio of heat input by coal water mixture to that of stabilising gas is 11.29 : 1 when firing with cold combustion air in a relatively cold furnace, which is equivalent to supplying pre-heated combustion air in the temperature range 200 - 315°C (400 - 600°F) depending upon the excess air ratios required for combustion.

Although no heat balances were performed during these first atomiser development tests, the flue gas temperature in Table 2 indicates a tendency for improved burning of the coal water mixtures as the apparent viscosity of the fuel was reduced by aeration. E.g. at the maximum firing rate of 182 kg/hr (400 lbs) of coal water mixture flue gas temperature increased from 820°C - 925°C (1500 - 1700°F) at 1.5% excess oxygen for viscosity changes from 400 - 150 cS.

The thermal work was carried out on the small scale rig with some of the refractory wool lining removed in an attempt to produce conditions similar to those in utility boiler practice with the flame exposed to cool surfaces and adjacent hot flame gases.

A completely refractory brick lined combustion chamber would obviously facilitate combustion stability when firing coal water mixtures, but work is continuing at Derby to study the effect of gas recirculation, the use of pre-heated air and possible a refractory quarl as an aid to combustion stability.

Gas recirculation is controlled by swirler design. The current swirler has a 45° vane angle and overall dimensions giving a swirl number of 1.1. A range of swirlers will be tested to assess the affect of recirculation of hot flame gases on the flame development. Pre-heated combustion air, in the range 100°C - 427°C (200°F - 800°F) will be utilised for this purpose also. It is considered that these two methods of increasing combustion stability are the important factors when considering the application of coal water mixture firing in utility boilers. If further initial heating is considered necessary the use of a refractory quarl to supply radiant heat to the flame root will also be studied.

5. Large Scale Thermal Test Rig Work

The availability of the large rig for coal water mixture work depends on the progress of the conversion programme outlined in Section 2.2. However, it is probable that this will be one of the first exercises carried out on the converted rig, using firing rates in the 2 - 5 tonnes/hr range. The burner design will be based on that used for firing a 40% coal 60% oil mixture on the rig and subsequently on a utility boiler, but incorporating the design features discussed in Section 4.3, in order to produce a coherent coal water mixture spray. The current small scale test work will indicate the level of combustion air preheat and swirl required to achieve stable combustion conditions. With the larger flames it is anticipated that radiation from the main body of the flame, back to the flame root, will obviate the need for incorporation of a refractory quarl.

Reference

1. Technical Data on Fuel - H M Spiers (Editor)
Sixth Edition 1961 (p. 150)

Acknowledgement

The authors would like to thank all their colleagues at NEI International Combustion who have contributed to the preparation of this paper.

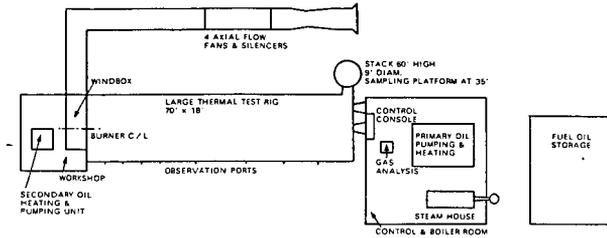


FIGURE 1
GENERAL LAYOUT OF LARGE THERMAL TEST RIG FOR LOW EXCESS AIR OIL BURNER DEVELOPMENT

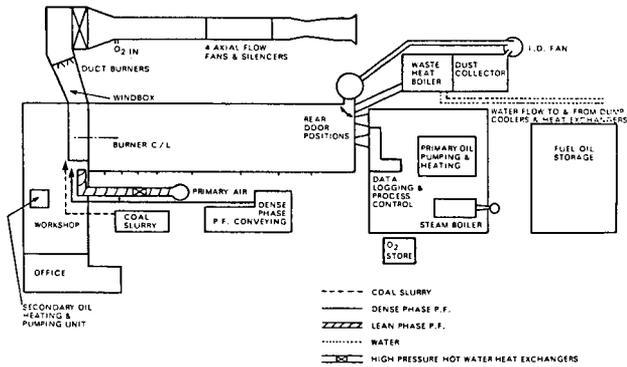
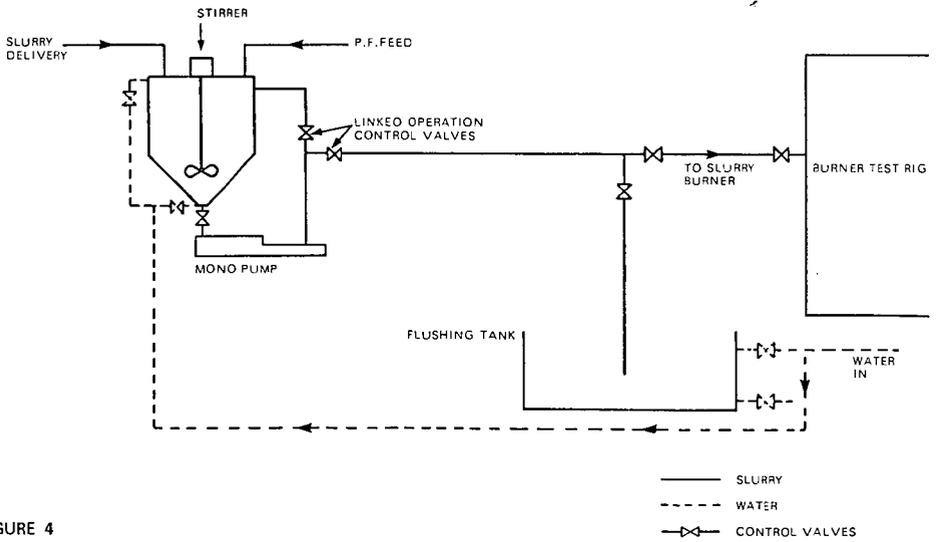
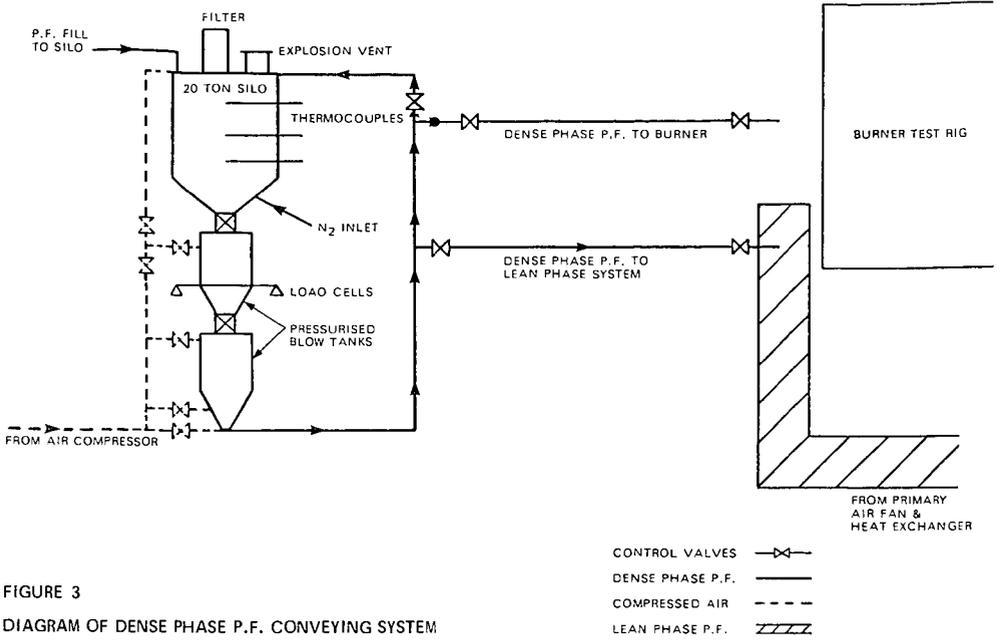


FIGURE 2
GENERAL LAYOUT OF LARGE THERMAL TEST RIG FOR MULTI-FUEL BURNER DEVELOPMENT



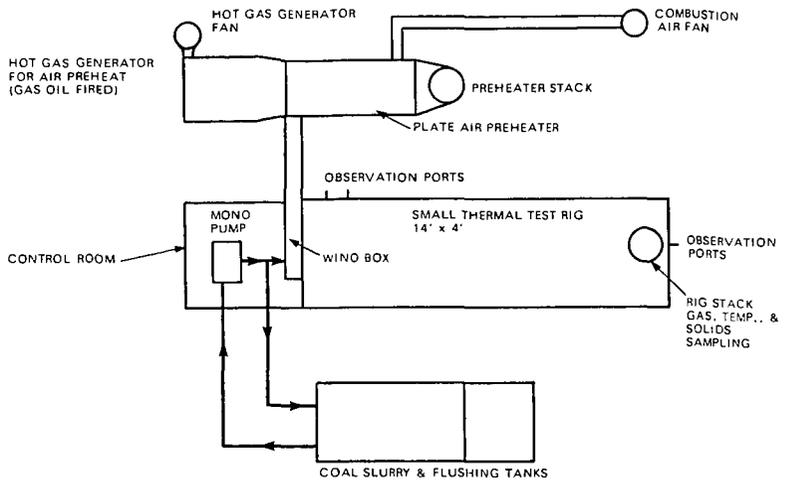


FIGURE 5
GENERAL LAYOUT OF SMALL SCALE THERMAL TEST RIG

FIGURE 6
COMPARISON OF COAL WATER MIXTURE & HEAVY FUEL OIL VISCOSITIES

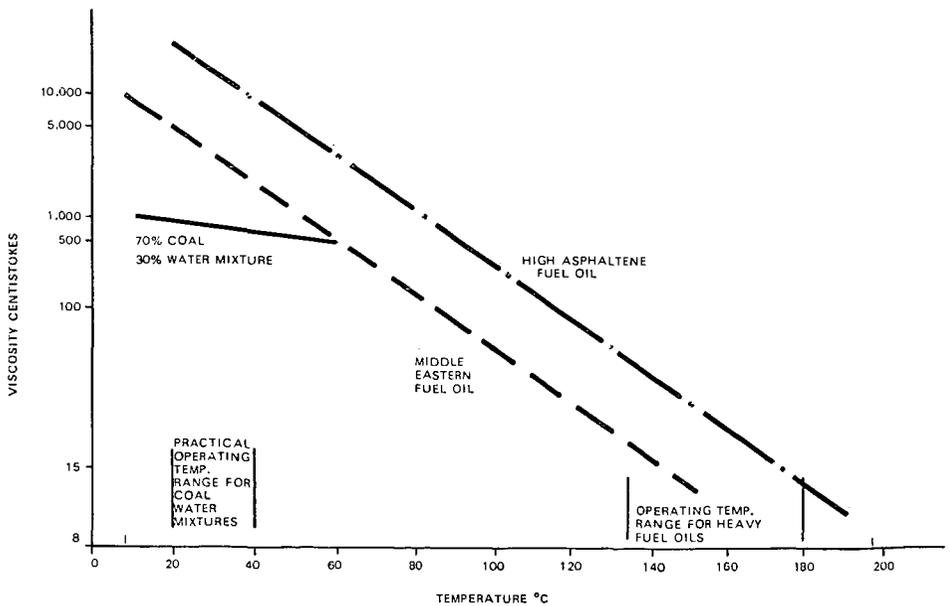


FIGURE 7

VISCOSITY VARIATION, BY AERATION, OF COAL WATER MIXTURES AT 20°C

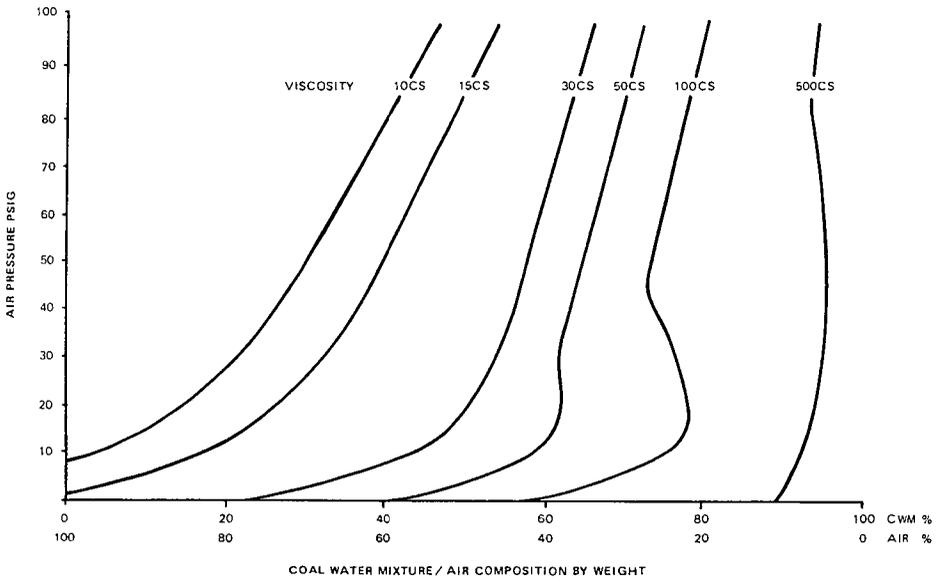
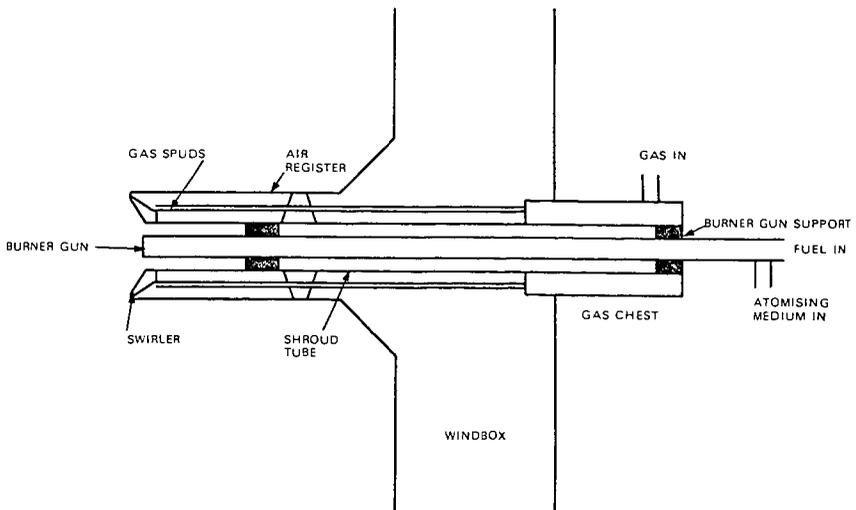


FIGURE 8

GENERAL ARRANGEMENT OF SMALL SCALE RIG BURNER



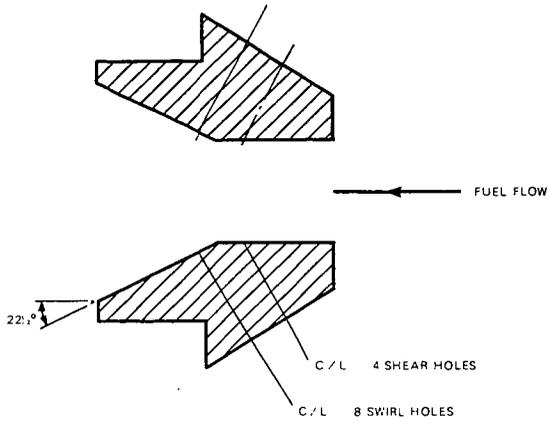
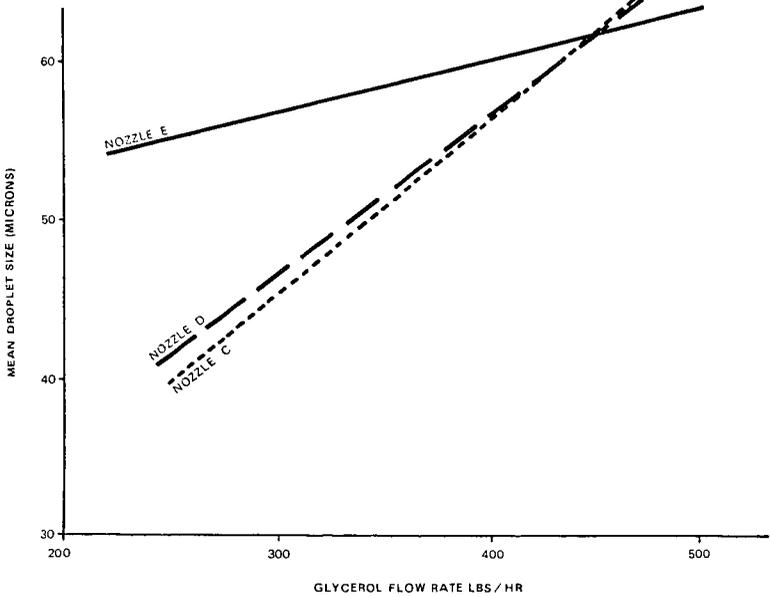


FIGURE 9
 DIAGRAM OF COAL WATER MIXTURE BURNER NOZZLE

FIGURE 10
 ISOTHERMAL BURNER NOZZLE COMPARISON



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 Mynno 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 known 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 additives 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 hysteresis, 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

<u>FUEL ANALYSIS PROCEDURE</u>	<u>PARENT COAL</u>	<u>CWF</u>	<u>METHOD</u>
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 Sintering 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

	V E N D O R									
	A		B		C M F		D		E	
	Coal	C M F	Coal	C M F	Coal	C M F	Coal	C M F	Coal	C M F
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				
θ @ 1700°F (Classification)	(Med)	(Severe)	(Low)	(Med)	(Low)	(Severe)				
Other Indicators										
Na as Na ₂ O (g)	0.85	2.56	0.39	0.61	0.92	3.02	0.40	0.92		
Fe as Fe ₂ O ₃ (%)	9.02	9.37	5.43	5.93	7.51	9.20	8.20	40.26		
Softening Temp. (°F)	2630	2400	2750+	2750+	2750+	2400	2750+	2140		
										(reducing atmosphere)

Babcock & Wilcox LAB ASHING FACILITY

- 1 ELECTRIC FURNACE
- 2 ELECTRIC FURNACE CONTROL CABINET
- 3 STEAM DRUM
- 4 PULVERIZED FUEL TWIN-SCREW FEEDER
- 5 NATURAL GAS
- 6 COAL TRANSPORT LINE
- 7 EXHAUST FAN
- 8 SECONDARY AIR HEATER
- 9 FLY ASH BAG
- 10 SLAG COLLECTOR
- 11 CYCLONE ASH COLLECTOR
- 12 MAIN CONTROL PANEL
- 13 COMBUSTION PRODUCTS
- 14 HEAT EXCHANGER
- 15 SECONDARY AIR
- 16 HIGH PRESSURE TREATED WATER PUMP
- 17 BLOW DOWN DRAIN
- 18 PLANT STEAM
- 19 FEED RATE MONITOR
- 20 RELIEF VALVE (250 PSIG)
- 21 MANUAL STEAM VENT
- 22 EXHAUST TO ATMOSPHERE (FLUE GASES)
- 23 HEATED SECONDARY AIR
- 24 SLAGGING, FOULING, AND SOOTBLOWING TEST SECTION

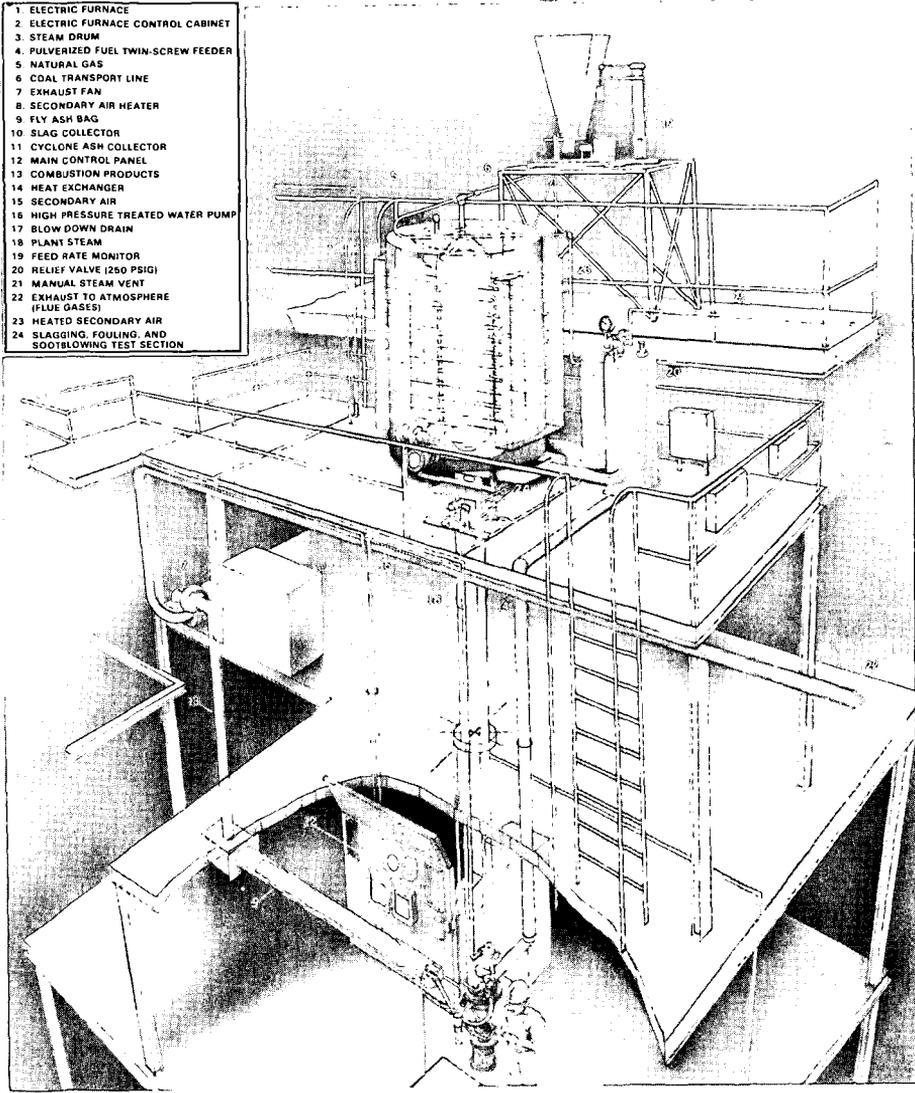


Figure 1. Laboratory Ashing Furnace.

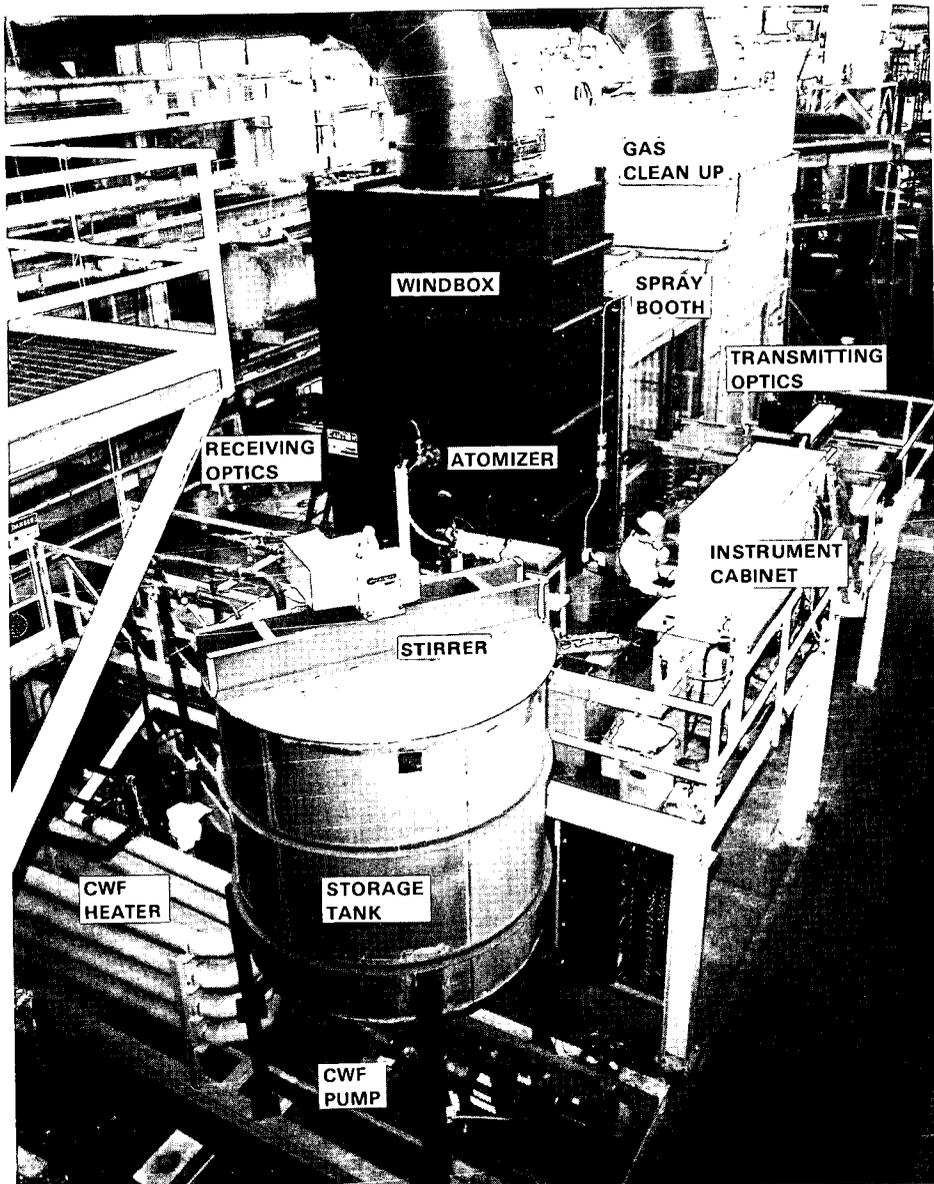


Figure 2. Atomization Facility.

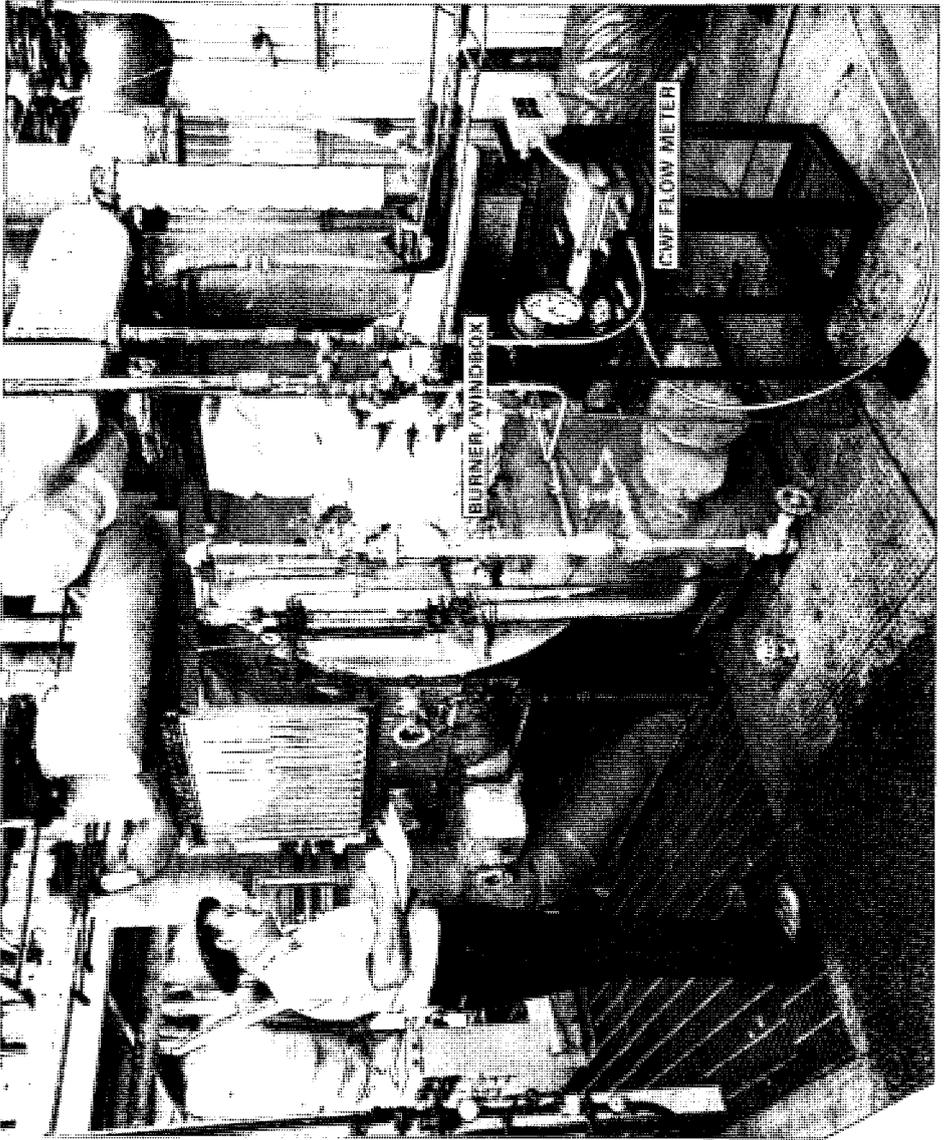


Figure 4. Basic Combustion Test Unit.

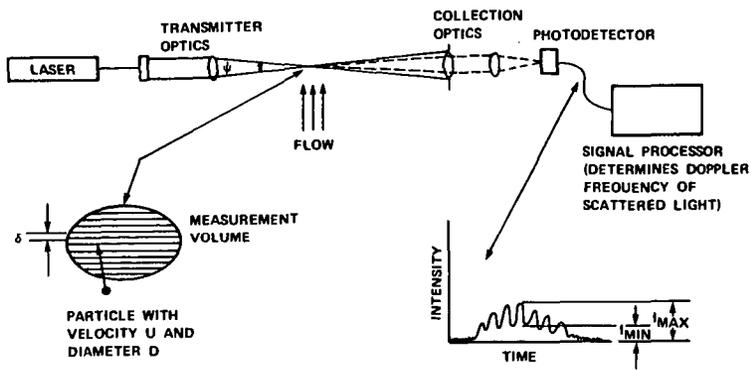


Figure 3. Laser Doppler Velocimeter (LVD) System Used to Size Particles by the Visibility Technique.

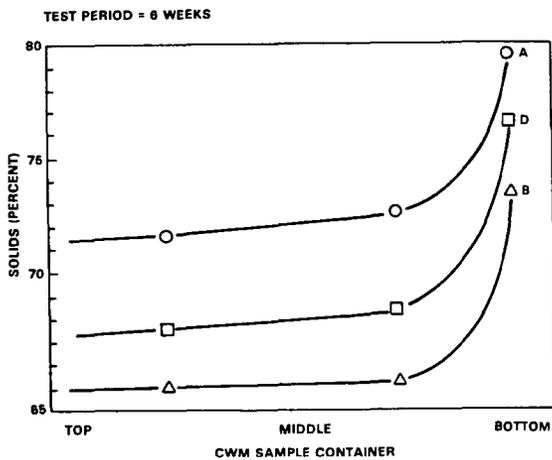


Figure 5. Static Stability Test Results.

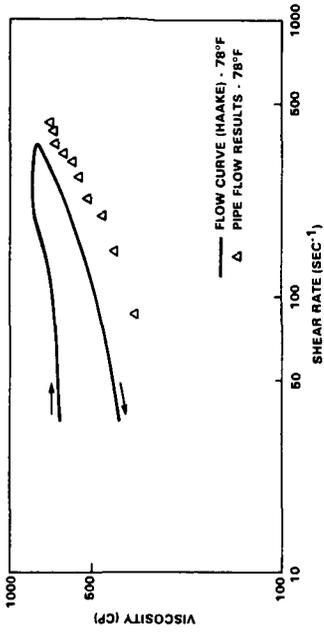


Figure 7. Rheology Test Results - CWF - D.

TRANSPORTATION MODE - TRUCK
 TEST CONDITIONS: 100 - 200 HZ.
 0.6 B
 3 DAYS

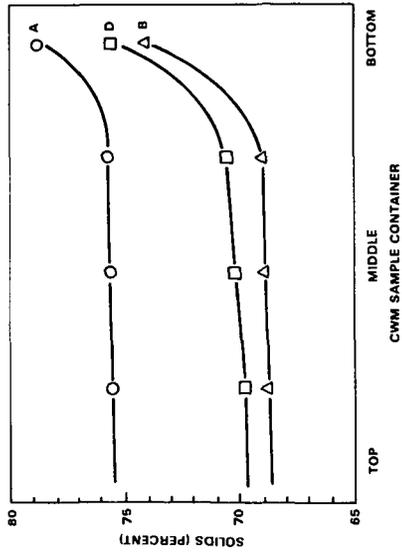


Figure 6. Dynamic Stability Test Results.

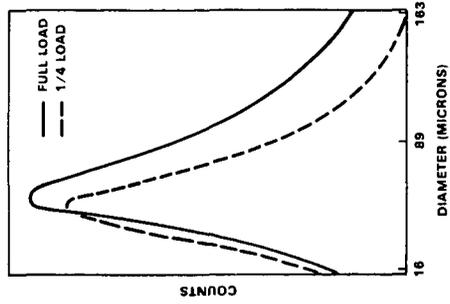


Figure 8. Droplet Size Distributions for CWF Sprays.

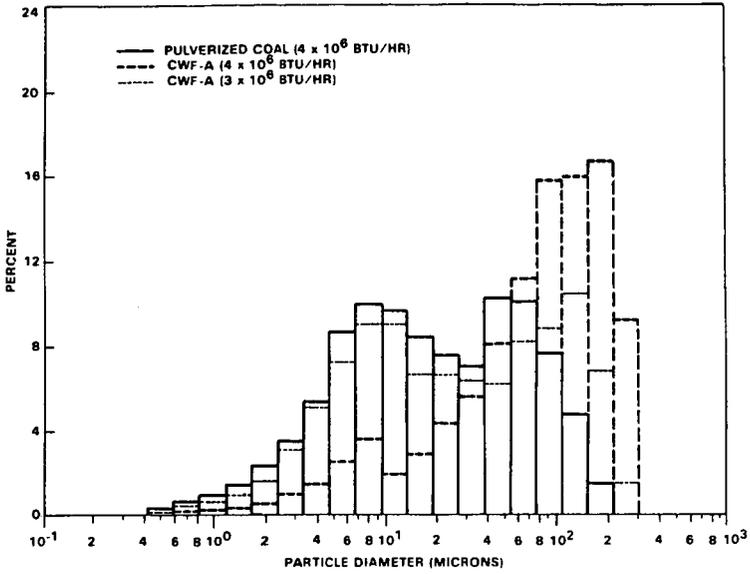


Figure 9. Fly Ash Particle Size Distributions.

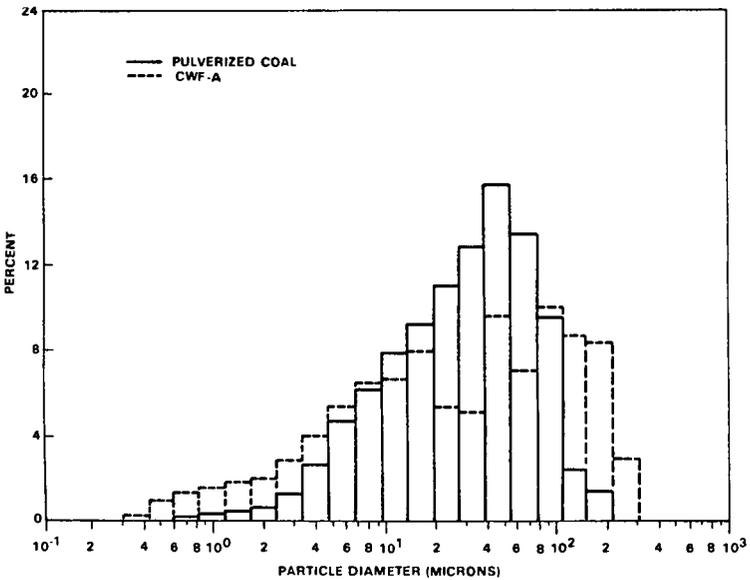


Figure 10. Particle Size Distributions - Pulverized Coal and CWF - A.

PROGRESS IN THE DEVELOPMENT OF A COAL/WATER MIXTURE
AS A FUEL OIL SUBSTITUTE

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INTRODUCTION

Coal/water mixtures (CWM) provide boiler and furnace operators with the opportunity to replace natural gas or oil with coal. CWM can be pumped, stored, and atomized like a liquid fuel; thus it has advantages over pulverized coal. However, unlike natural gas or oil, coal contains significant quantities of inorganic material (ash) which can adversely influence boiler performance and fuel-handling equipment. Burners can be modified to provide satisfactory ignition and flame stability characteristics with CWM and problems associated with nozzle lifetime can be solved. However, to solve problems associated with ash, we will probably have to resort to coal beneficiation, derating, or both. Based on available data, the optimum level of coal beneficiation cannot be defined. It will be determined from trade-offs among beneficiation, burner, and boiler/furnace-related costs.

CWM is clearly outside the range of fuel parameters used to design most oil and gas-fired units. Not only are the physical properties of the fuel different, but the ash and sulfur content of CWM is at least several orders of magnitude higher than it is in most oil and gas fuels. The differences in fuel properties can cause problems in virtually every portion of the firing system/furnace. Figure 1 illustrates some of these problems, which must be addressed and solved if CWM is to be used successfully.

EFFECTS OF FUEL PROPERTIES

Fuel properties and the extent of coal cleaning will affect the potential cost of firing CWM in boilers. Fuel properties will affect:

- Ignition and stability of CWM flame
- Emission of pollutants
- Availability.

Ignition and Flame Stability

Satisfactory ignition and flame stability with adequate turndown ratio are essential to the successful use of CWM. Ignition and flame stability are related and are controlled by the aerodynamics of the flame, heat transfer in and out of the ignition zone, and fuel properties. The most important fuel property is volatility. To achieve adequate ignition and flame stability, the coal must be heated to the point where the fuel devolatilizes and ignites. Although water in

CWM makes it more difficult to ignite than coals with less moisture, naturally occurring coals and wood bark with up to 60-percent moisture have been successfully burned commercially.

Emissions

Many oil- and gas-fired boilers are located in areas that already have significant emissions problems. Hence steps must be taken to control particulate emissions from CWM firing which, although greater than from gas or oil, can be adequately controlled by electrostatic precipitators or bag filters.

Temperatures in CWM-fired boilers may be somewhat lower than in oil- or gas-fired boilers, tending to suppress the formation of thermal NO_x . However, fuel NO_x is temperature insensitive, and CWM will have a higher fuel nitrogen content than oil or gas. Thus NO_x emissions are expected to be higher. NO_x can be controlled by a range of techniques. Burner and combustion modifications have been successfully applied to reduce NO_x emissions when combusting coal to levels comparable to those with oil firing.

The potential for sulfur oxide (SO_x) emissions can be higher when firing CWM than for oil or gas firing. Even though most of the coals considered for CWM will be cleaned to some extent, they will be higher in sulfur than most oils. Although SO_x can be controlled by flue gas desulfurization (FGD), this technique is expensive and troublesome and is rarely used on oil-fired units. The anticipated low flame temperatures in the boiler and intimate mixing of water in CWM firing offer potential for removing sulfur compounds in the furnace by injection of calcium compounds. Furnace injection of the sorbent is much less expensive than FGD. There is an additional advantage to this approach for use with beneficiated CWM. For new, large units, Federal regulations require a 90-percent reduction of SO_x when firing high-sulfur coals. This level of removal cannot be achieved solely by sorbent injection in a boiler. However, sulfur removed during beneficiation of the coals is credited toward total sulfur removal. Therefore, if capture in the boiler can remove a significant fraction of the sulfur, the required SO_x reduction can be achieved.

Availability

Fuel properties definitely affect boiler availability. The potential problems from firing CWM in boilers designed to fire oil or gas are worse than they will be when firing it in boilers designed for coal. The cost of an inoperative 500-MWe boiler exceeds \$100,000/day. The down time of an average coal-fired boiler in the United States is almost 30 days a year--at a cost of \$3 million. About 60 percent of the down time is caused by boiler problems; ash characteristics--both quantity and quality of constituents--account for a significant portion of this time.

Table 1 compares parameters for gas-, oil-, and coal-fired boilers. Heat-release rates and tube-bank velocities are smaller and tube spacings in the superheater are greater in a coal-fired boiler. CWM introduces more ash, which can promote fouling, slagging, and erosion and it may contain corrosion-promoting materials.

Figure 1 shows potential problem areas where slagging and fouling can occur when firing coal in a utility-size boiler.

Table 1 Characteristics of Gas-, Oil-, and Coal-Fired Boilers

Description	Gas	Oil	Coal
Furnace Volume, Relative	1	1.3	1.9
Furnace Surface Area, Relative	1	1.3	1.7
Heat Release/Volume (10^6 Btu/h·ft ²)	25-50	25-50	10-22
Heat Release/Cooled Surface (10^6 Btu/h·ft ²)	200	200	70-120
Tube Bank Velocities (ft/s)	120	90	40-70
Superheater Spacing (in.)	2	4-6	8-16+

Difficult-to-remove slag deposits reduce heat flux through the wall, increasing furnace temperature. This deposit/temperature cycle can result in load reduction or shutdown.

As coal firing rates are increased to provide heat-release rates equivalent to those required in an oil-fired boiler, slagging may result. The higher heat-release and heat-transfer rates promote melting of particles flung to the wall above the burners. This action reduces the furnace heat extraction rate, allows higher temperatures to exist in the upper furnace, and increases the prospects of fouling the superheater. Consequently, slagging could inhibit the use of CWM in boilers designed to fire oil or gas.

TESTING

Hydraulic and burner testing have been performed at Forney Engineering Company in Addison, Texas. A test program initiated in 1981 in collaboration with a major United States CWM vendor included requirements to store, pump, transport, and burn CWM. The hydraulic test loop had typical connectors and piping, including two 10-ft sections of 1- and 2-in. Schedule 40 pipe. The test furnace is an 8-ft-dia cylindrical furnace with a water jacket. It is capable of 70×10^6 Btu/h for short durations and up to 40×10^6 Btu/h continuously. The furnace system includes a forced-draft fan with an in-line combustion air heater (gas fired), a steam generator for atomizing steam, an air compressor for atomizing air, and an ignitor system that uses No. 2 oil or natural gas. The windbox can be easily disconnected from the furnace and air duct to facilitate changing configurations.

Several pumps were tested. Diaphragm and vane types were troublesome, with discharge pulsations and accumulations in the liquid end. The progressive cavity pump was the most successful but required special care during extended periods of shutdown.

Based on CWM properties, the following needs were identified for burner tip design:

- Rapid mixing of the air and fuel to dry and ignite the coal in the primary recirculation zone.
- A strong recirculation zone maintained to create a highly radiant burning zone in the burner throat to dry the coal.
- No flame contact on any burner part because of anticipated slagging problems.
- Conventional burner parts for ease in retrofit applications.

Forney has several commercial burner designs for various applications:

- Parallel Air Flow (PAF)
 - Fast mixing
 - Low excess air applications
- Rotating Air Register (RAR):
Highly turbulent
- Variable Flame Pattern (VFP): Variation of PAF with flame-shaping ability with rotational secondary air register.

Historically, Y-jet (YJ) and internal mix (IM) atomizers had been successfully used with high-gravity fuels. We attempted to adopt the basic features of each in two different atomizer designs--both incorporating a conical plug rather than individual orifices. Concepts for both atomizer tips, shown in Figure 2, have been patented.

After a matrix of tests including YJ and IM atomizers in RAR and VFP air registers, the following requirements were noted:

- Burner with two airflow paths with the primary path having a rotational, low flow
- Secondary airflow with high swirl to provide the recirculation zone
- Means of providing a highly radiant zone at burner exit.

These considerations were included in the design shown in Figure 3. This patented design provides dual velocities and two-throat configuration to maintain a radiant zone at the burner exit. A series of tests were successfully conducted under the usual burner performance parameters.

BOILER DESIGN VS. CONVERSION POTENTIAL

Designs of existing utility steam generators vary substantially depending upon the original design fuel. Generally, the pressure-part arrangement of a boiler can be classified as one of the following types:

- Category A Unit--Two pass (Coal/Oil-Gas)
- Category B Unit--Two pass (Oil/Gas)
- Category C Unit-- Box type (Oil/Gas or Gas only).

The design configuration of each type of unit greatly affects its conversion potential in terms of both capital expenditure and derating requirements. Figure 4 shows a comparison of unit configurations that will be discussed.

Category A Unit-- Two Pass (Coal/Oil-Gas)

Design Features. This type unit is characterized by a generously sized furnace (i.e., large plan area and a substantial distance from the burner zone to the first vertical radiant surface at the furnace exit). These features result in a sufficient radiant absorption in the furnace area, which lowers the furnace exit gas temperature entering the vertical convection sections, thus limiting slag formation. Also typical of this type of unit is a lower furnace hopper slope of at least 45 to 50 deg and a hopper throat opening of approximately 3 to 4 ft, both of which facilitate bottom ash collection and removal. The horizontal convection passes of a Category A steam generator are designed with adequate tube-to-tube clear spacing to prohibit fouling and possible plugging and to alleviate excessive flue gas velocities and associated tube erosion possibilities.

Conversion Potential. This type of unit was originally intended for burning coal as its primary fuel. Therefore, it should achieve full load output if reconverted to a similar type of coal or a CWM. The capital expense of the boiler portion of the conversion would be limited to refurbishment of original equipment, normal maintenance, and pollution control upgrading, if required.

Category B Unit-- Two Pass (Oil/Gas)

Design Features. The Category B classification includes those steam generators with a furnace configuration similar to that of a Category A unit but with a less conservative convection pass arrangement. This type of unit was originally designed for oil or gas firing. The similarities in furnace arrangement when compared with the unit previously discussed are readily apparent. Generally, the furnace of a Category B steam generator is smaller than that of a Category A steam generator. Specifically, the former has a lower furnace hopper slope and opening and the furnace plan area is not as conservative. However, the overall furnace design for this type of unit is conducive to the firing of an ash-laden fuel. For this reason, based solely on furnace design criteria, a Category B unit is a viable candidate for conversion to pulverized-coal or CWM firing with minimal or no unit derating.

However, the convection pass arrangement in this unit can present several major obstacles when converting to coal or a coal-derived fuel. The clear spacings between tube sections of a Category B unit are less than those of a Category A unit. If such a unit were to fire coal or a coal-derived fuel, excessive fouling or erosion of the tubes could result, since the flue gas temperature and velocity of the unit would exceed the acceptable values for oil firing. To decrease flue gas temperatures and velocities so that the potential for fouling or erosion of existing convection pass tube banks can be reduced, the maximum unit load must be restricted. These design constraints are directly related to the fuel being considered, particularly the quantity and quality of its ash. Therefore, as might be expected, the derating requirements for coal and CWM vary.

Conversion Potential--Coal. Coal inherently has the highest ash content of the fuels being considered and will also exhibit the highest furnace exit gas temperature for any particular boiler load and furnace size. Consequently, the potential for convection pass fouling and tube erosion can restrict the maximum allowable output to approximately 70 percent of the design rating of a Category B Unit. This derating requirement can often be minimized or eliminated through substantial pressure-part modification. As indicated previously, the furnace of such a unit is normally capable of supporting full output while firing coal, and thus modifications to the furnace (which would be prohibitively expensive) would generally not be required.

Conversion Potential--CWM. Because of the ash and sulfur reductions that occur during the fuel preparation process, a Category B unit can be converted to CWM firing with less derating than would be required with coal. Reductions in ash (approximately 70 to 90 percent) and sulfur (50 to 70 percent) are possible during CWM beneficiation. Furthermore, the ash fusion temperatures of a beneficiated CWM are 100 to 200°F higher than those of the parent coal.

Consequently, higher furnace exit gas temperatures are allowable when firing CWM as opposed to coal. In a Category B boiler, higher temperatures translate to an allowable load of approximately 80 to 90 percent of full unit output. Again, convection pass pressure-part modifications could possibly restore such a unit to full load capability while firing a CWM.

Category C Unit--Box Type (Oil/Gas or Gas Only)

A Category C unit could be subject to a considerable derating if converted to coal or CWM. The horizontal convection passes of such a unit have closer tube-to-tubeside spacings than those of either Categories A or B boilers. The most critical disparity lies in the furnace design. A Category C unit has little or no provision for ash collection or removal, and the furnace is inadequately sized to reduce the potential for slagging associated with coal firing. The hopper slope is very shallow (or nonexistent), and the lower furnace throat opening (if any) is minimal. Burner spacings are generally close, and the distance from the lowest burner level to the hopper knuckle (or to the furnace floor) is generally inadequate. Both of these features result in a high furnace slagging potential. However, the most critical design limitation in evaluating the conversion of a Category C unit to firing coal or a coal-derived fuel is the inadequate furnace plan area. Modifications to the furnace hopper and burner pattern in many cases prove feasible and can minimize derating. This is also often the case with respacing of the convection passes, as was indicated in the previous discussion concerning a Category B unit.

However, furnace plan area enlargement is not feasible either physically or economically. Thus the derating for a Category C unit is more severe than that associated with the previously discussed boiler designs. Moreover, pressure-part modifications, within the realm of technical and economic feasibility, cannot alleviate these load restrictions.

Conversion Potential. Typically, conversion of a Category C unit to firing pulverized coal would involve a derating to 50 to 60 percent of design output because of furnace and convection pass design limitations previously identified. CWM presents the better conversion alternative for a Category C unit. Because of the ash and sulfur reduction that occurs during the fuel preparation process, slagging and fouling potential is considerably reduced. Even so, unit output may be restricted to approximately 70 to 80 percent of design rating.

Table 2 presents a summary of the typical feasible unit deratings for coal and CWM and for each type boiler.

Table 2 Maximum Allowable Load, %

<u>Fuel</u>	<u>Category</u>		
	<u>A</u>	<u>B</u>	<u>C</u>
Coal	100	70	50 - 60
CWM	100	80 - 90	70 - 80

Balance-of-Plant Considerations

The utilization of either coal or CWM in a boiler fuel conversion project significantly affects the required balance-of-plant equipment, impacting both the capital cost of the conversion and the site requirements. Each of the fuels studied has been examined in terms of the balance-of-plant considerations arising from a potential conversion project. The scope and costs of such equipment vary, depending on the original design fuel for each specific unit.

Balance-of-plant considerations must, at the very least, include:

- Refurbishment of coal-handling equipment (if it exists)
- Fuel handling
- Land requirements (coal yard and ash disposal)
- Fan systems

- Ash collection, storage, and removal systems
- Fly ash collection
- FGD system.

Compared with total plant conversion costs, boiler/island-related work is approximately 10 to 20 percent of the total project cost. However, the steam generator remains the primary consideration for potential derating.

ECONOMICS OF CONVERSION

An evaluation of the capital expenses vs. the fuel savings of a potential conversion project is unique to the steam generator under consideration. Some general observations regarding the effect of basic unit design criteria and site considerations have been discussed. Such generalities are not possible regarding the specific economics of a conversion. To provide an indication of these economics, a specific unit has been selected as a test case for comparison of conversion to coal or CWM. The analysis is specific to that unit but the methods will be common to any conversion project.

The selected Category B steam generator is a natural-circulation, balanced-draft, reheat unit utilizing a parallel pass gas flow arrangement. The unit, originally designed to fire oil as the primary fuel, could be converted to coal firing in the future, because of the relatively large furnace plan area, the lack of lower furnace radiant superheater surface, and the presence of a lower furnace hopper with an adequate angle of slope.

As discussed earlier a unit of this type--even with these design features--requires some pressure-part modification to achieve full load output if converted to coal or CWM firing. In this instance, these modifications consist of:

- Some horizontal convection surface respacing
- An upper furnace radiant superheater installation (to reduce furnace exit gas temperature)
- Burner respacing.

The cost of these items, although high, is not substantial when compared with total project costs or with the cost of replacement power purchased in the event of a derating.

Table 3 summarizes an economic evaluation of the conversion alternatives being considered. Several conclusions are evident from a detailed review of the table:

- As indicated previously, the cost of the boiler modifications necessary to avoid derating of a unit of this type is approximately 10 percent of total conversion costs and is thus, in this case, economically justifiable.

- Both fuels present viable conversion options, even if only 50 percent of the accrued fuel savings are recoverable toward payback of capital investment.
- The total capital cost of a conversion to pulverized coal is significantly higher than conversion to CWM, primarily because of the expense of a coal yard.
- Based on the comparison of benefit-to-cost ratios of the conversion fuels considered, CWM is the more economically justifiable conversion option.

Foster Wheeler and its family of companies is dedicated to the commercialization of CWM as a boiler fuel, as evidenced by our participation in:

- Boiler conversion design studies
- Burner development
- Coal cleaning and slurry preparation
- Fuel-production plant design
- Small utility conversion demonstration.

Foster Wheeler views CWM as one of the most promising alternatives to foreign oil dependence while using one of the most abundant resources available in the Western Hemisphere.

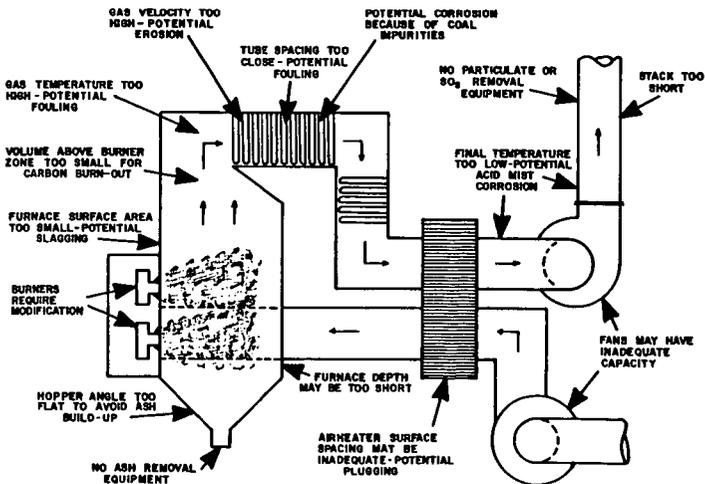
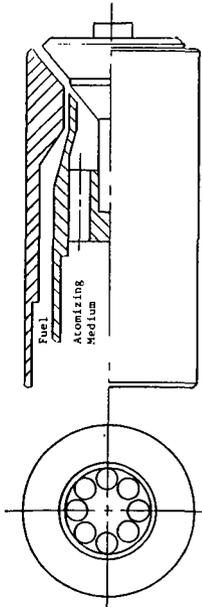


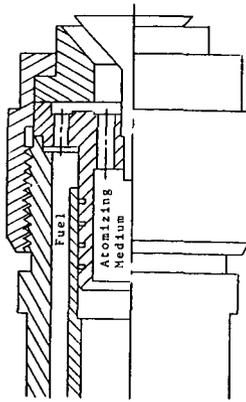
Figure 1 Potential Problem Areas in Retrofitting an Oil-Fired Furnace to CWF Firing

Table 3 Conversion Economics Evaluation

Fuel	\$ Million	
	Coal	CWM
Annual Fuel Costs	39.1	70.1
Annual Fuel Savings (vs. Oil)	67.4	36.4
Recoverable Portion of Savings	33.7	18.2
Levelized Annual Present Worth of Recoverable Savings	51.9	28.1
Capital Equivalent of Recoverable Savings	259.5	140.5
Conversion Costs		
Fuel System	96.4	9.3
Boiler Modification	4.7	2.3
Ash Systems	18.4	16.2
FGD System	41.7	41.7
Total	161.2	69.5
(w/o FGD)	(119.5)	(27.8)
<hr/>		
Capital Payback Period, years	3.1	2.5
(w/o FGD)	(2.3)	(1.0)
Benefit-to-Cost Ratio	1.6:1	2:1
(w/o FGD)	(2.2:1)	(5.1:1)



Conical Y-Jet Atomizer



Conical Internal-Mix Atomizer

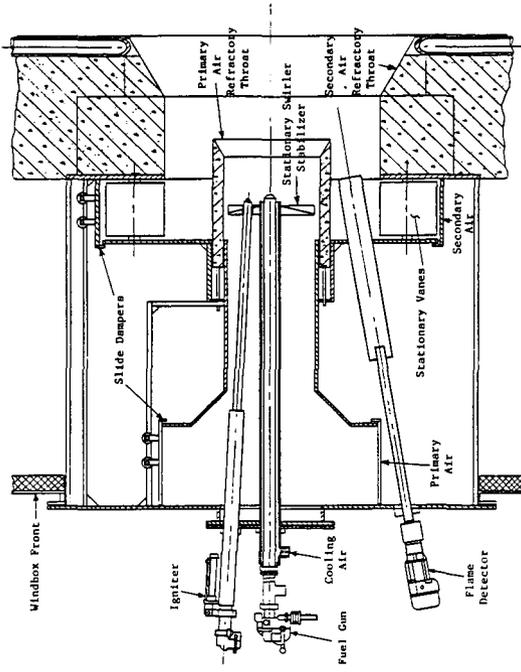
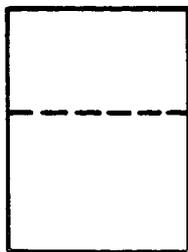


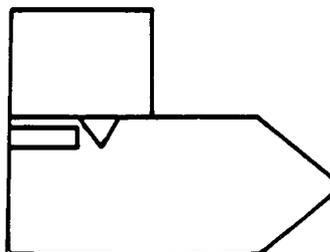
FIGURE 3 FORNEY CWF BURNER

FIGURE 2 SPECIAL CONICAL ATOMIZERS

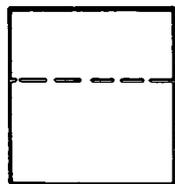
CATEGORY-A



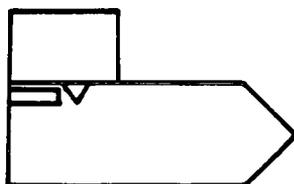
**COAL/OIL-GAS
COAL TYPE**



CATEGORY-B



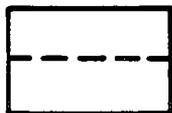
**OIL/GAS
COAL TYPE**



CATEGORY-C



**GAS(OIL/)
BOX TYPE**



**OIL/GAS
BOX TYPE**



Figure 4 Comparison Boiler-Fuel Configurations

Symposium on Shape Selective Catalysis and Synthesis Gas Chemistry.

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