US Army Corps
of Engineers
Construction Engineering
Research Laboratories

USACERL Technical Report FE-93/16
September 1993

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Developing Anthracite Coal Water Slurry Fuel

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The T-Process, a proprietary process developed by Otisca Industries, Ltd., Syracuse, NY, was used to produce anthracite-based coal water slurries for testing and combustion. Although it is feasible to manufacture anthracite water fuel, the slurries used in this research would not burn well without substantial amounts of natural gas cofiring. Stable combustion with reduced support fuel can probably be achieved by chemically or physically modifying the factors that affect combustion.

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29 pp

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
September 1993

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Developing Anthracite Coal Water Slurry Fuel

5. FUNDING NUMBERS
SBIR
4A165502
M860

6. AUTHOR(S)
F.J. Simmon, D.V. Keller, Jr., J. Marino, D.S. Keller, T.E. Ask, J.E. Davidson, and G.W. Schanche

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratories (USACERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR FE-93/16

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Materiel Command
ATTN: AMCRD-SBIR, Rm 8N23
5001 Eisenhower Ave
Alexandria, VA 22333-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS
coal
coal water fuel
anthracite coal
combustion

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
SAR

FOREWORD

This study was conducted for the Department of Defense's Small Business Innovative Research (SBIR) Program, Project Number 4A165502M860.

The work was performed by the Energy and Utility Systems Division (FE), Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL), and by Otisca Industries, Ltd., Syracuse, NY. F.J. Simmon, D.V. Keller, Jr., J. Marino, and D.S., Keller are affiliated with Otisca. Dr. David Joncich is Chief, CECER-FE and Dr. Michael J. O'Connor is Chief, CECER-FL. Gary W. Schanche is Team Leader of the Fuels and Power Systems Team.

LTC David J. Rehbein is Commander of USACERL and Dr. L.R. Shaffer is Director.

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1 INTRODUCTION

Background

The 1986 Defense Appropriations Act (Public Law [PL] 99-190), Section 8110, directed the Department of Defense (DOD) to establish a program to convert steam generating facilities to use coal. A consumption target of 1,600,000 short tons* per year above the 1985 baseline consumption has been set for 1994. The Act further specified a minimum annual purchase level of 302,000 short tons/year of anthracite coal to be included in the target consumption rate. The 1987 Defense Appropriations Act (PL 99-500), Section 9099, directed the DOD to purchase at least 300,000 short tons of anthracite coal in 1987 and to continue the coal conversion program where cost-effective. Currently, most anthracite coal purchased by DOD is shipped overseas for consumption in the U.S. Army and Air Force bases in Europe. However, due to the high transportation costs involved and the international political tensions created by burning U.S. coal (and the sensitive issue of particulate matter and sulfur oxide emissions on the local environment), steps are being taken to dramatically reduce the consumption of U.S. coal in Europe. Because too few continental United States (CONUS) bases are capable of burning enough anthracite coal to reach the targeted anthracite consumption rate of 302,000 short tons/year, the DOD needs to determine the feasibility of alternatives that use anthracite in steam generating facilities in the CONUS.

To meet the requirements set forth by the 1986 Defense Appropriations Act, DOD has identified potential conversions of energy generating facilities from oil or natural gas to coal. However, these conversions will be capable of burning primarily bituminous coal, not anthracite, due to the wide difference in combustion characteristics inherent in the two coal classes.

The U.S. Army Construction Engineering Research Laboratories (USACERL) was asked to provide technical support to both the Army's and DOD's coal conversion and use programs. To develop solutions to the problems associated with burning anthracite, USACERL convened a panel of coal experts from the industry, academia, and USACERL. Alternatives discussed included direct conversion of bituminous facilities to anthracite with significant derating of the boiler, bituminous-anthracite blends, anthracite gasifiers, anthracite coal-oil slurry, retrofit slagging combustors, fluidized bed combustion, erection of new anthracite coal burning facilities, stockpiling, and even buying the coal in the ground to leave as a "strategic" reserve.

The compliance strategy arrived at by the panel was formulated to solve the anthracite coal problem for all of the DOD while supporting the DOD goal of burning more coal in the CONUS. The goals of the strategy are to consume the anthracite coal near the mining region, to require minimal stockpiling, and to not modify facilities so only anthracite coal can be burned for the life of the plant. The strategy consists of three separate phases. The first is to blend anthracite and bituminous coals in existing Army coal-burning facilities. While this phase does not contribute to the total consumption of more coal, it does fulfill the short-term need to consume anthracite. The second phase is to use retrofit technologies such as slagging combustors, coal-oil and coal-water fuel, and gasifiers for existing gas/oil burning plants. The final phase is to construct new facilities using fluidized bed combustion with cogeneration capabilities.

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*A metric conversion table is on page 24.

Objectives

The objectives of this study are to develop and manufacture an anthracite-based coal water fuel and demonstrate the combustion characteristics of the anthracite water fuel in a small boiler.

Approach

Due to the low content of volatiles in anthracite, a small particle size is required to allow the carbonaceous material to oxidized more quickly. Therefore, the T-Process for producing coal water fuel, developed by Otisca Industries, Ltd., Syracuse, NY, was selected because it produces very fine coal particles and therefore had the highest potential for success.

The project was divided into four tasks. The first task was to select the candidate anthracite coal, prepare it using the T-Process, and conduct laboratory tests to determine its agglomeration characteristics as a function of particle size. The second task used these data to select a coarse and a fine particle size distribution for rheological testing that determined the type and concentrations of reagents required for the manufacture of the anthracite water fuel. The third task was to manufacture 600 gallons of anthracite water fuel, 300 gallons each of two different size distributions, at the 2.4-ton-per-day T-Process pilot plant. The fourth task was to conduct combustion evaluation of each of these fuels using the 75-horsepower York-Shipley fire tube boiler in the Otisca combustion laboratory.

Mode of Technology Transfer

It is recommended that the information in this report be transferred as a Public Works Technical Bulletin (PWTB).

2 ANTHRACITE SELECTION AND EVALUATION

Anthracite Selection

The anthracite selection was governed by Otisca's experience and by coal availability. Pea anthracite was obtained from Bethlehem Mines Inc., Greenwood Cleaning Plant, P.O. Box 311, Tamaqua, PA 18252.

The pea anthracite coal was taken directly from the washing plant discharge chute and loaded into polyethylene 55-gal drums for shipment and storage. The raw pea anthracite analysis is as follows.

Ash	7.88 %
Volatile Matter	6.57 %
Fixed Carbon	85.55 %
Total Sulfur	0.58 %
Heat Content	13,587 Btu/lb

T-Process Evaluation

The T-Process is an agglomeration process where a finely milled slurry of water and anthracite, typically 15 μm (micrometer or micron) X 0 at 10 weight percent solids, is subjected to high shear in the presence of an agglomerate, such as pentane. The product anthracite agglomerates and pentane is recovered from the water-mineral matter phase by screening.

The characteristics of the T-Process are such that more than 97 percent of the carbon is recovered as product coal while virtually 100 percent of the liberated mineral matter and pyritic sulfur are rejected to the refuse. The liberation characteristics of the mineral matter and pyritic sulfur contained within the raw anthracite are affected by milling to different particle sizes. Essentially, the finer the anthracite, the greater the potential for ash and sulfur reduction. For sulfur, however, the true limiting factor in reduction is the percent of the total sulfur present as organic sulfur. The other factor that must be imposed on the particle size selection is the effect of particle size on the rheology (flow properties) of the final anthracite water fuel.

Preliminary laboratory testing consisted of milling the raw pea anthracite to four different particle sizes, and then performing T-Process testing of each size. Milling was accomplished using a standard 3-L laboratory jar mill with 1/4-in. ceramic grinding media. The mill was charged with a 60-mesh X 0 anthracite/water mixture at 30 weight percent solids. The desired particle size was obtained by selecting the total milling time for a given sample based on previous experience. The agglomeration tests were performed using a blender to provide high shear. The typical procedure was to fill the blender with 400 cc of the milled anthracite/water mixture, now at 10 weight percent solids, and mix at high shear while adding the agglomerating liquid, pentane. (The process is proprietary.) Once the agglomerates formed, the blender was stopped and recovery was effected by screening the mixture. The agglomerates remained on the sieve while the excess water and mineral matter passed through. Data obtained from the T-Process testing phase are presented in Table 1.

Anthracite responds similar to bituminous coal in that it exhibits a distinct trend of mineral matter liberation and rejection as a function of the mass mean diameter (D50), when subjected to the T-Process. However, unlike bituminous coals, all of the pyrite rejection (sulfur reduction) occurs after modest milling.

Table 1

T-Process Evaluation of Anthracite

Particle size (Mode, µm)	Ash %	Sulfur %	Volatile %	Btu/lb	Btu Yields %
1.6	0.93	0.48	12.21	14,359	98.1
3.0	1.57	0.48	8.14	14,475	99.5
5.3	2.68	0.48	8.40	14,275	99.3
6.4	4.27	0.49	8.00	13,976	98.9

Rheology Development

The fourth task in this research was to demonstrate the burning characteristics of two sizes of anthracite water fuel, one coarse and one fine, within the nominal operating range of the T-Process. Producing anthracite-based fuel required establishing the rheological characteristics relative to the base of experience with bituminous coal fuels. After ash liberation studies, a 3-µm mode and a 7-µm mode product size were selected for the rheology testing. Sufficient feedstock material of each size was prepared using the procedures outlined in the previous section. Analysis of these feedstocks are presented in Table 2.

Slurries were prepared by blending an appropriate amount of anthracite feedstock with a solution of dispersant additive dissolved in water. The slurries were mixed sufficiently to ensure homogeneity and equilibrated for one day. Mild remixing was conducted before viscosity testing. The slurry viscosities were determined using a Haake model RV-3 rotoviscometer equipped with an MK-500 measuring head and an MV-IIP concentric-cylinder sensing system. Sample temperature was maintained at 24 °C, +/- 1 °C. Concurrently, the solid content of each slurry was determined using a microwave moisture analyzer.

Two separate paths of investigation were followed for both the coarse (7-µm) and fine (3-µm) anthracite slurries. The first test series determined the type and minimum amount of dispersant required to provide satisfactory anthracite slurry viscosity levels. In the second test series, the dispersant type and concentration were fixed and the viscosity was recorded as a function of solids content as the slurries were diluted.

Five slurries were prepared using different concentrations of dispersant solution blended with 125 grams of the 3-µm anthracite product coal at about 60 weight percent solids. The dispersant, an ammonium lignosulfonate, Lignosol TSD from Reed Lignin Inc., was added at concentrations of 0.5, 1.0, 2.0, and 3.0 weight percent relative to anthracite on a dry basis. Figure 1 shows the rheograms for 2.0 and 3.0 weight percent Lignosol TSD.

Four slurries were prepared using different concentrations of dispersant solution blended with 125 grams of the 7-µm anthracite product coal at about 61.5 weight percent solids. An ammonium lignosulfonate, ORZAN AL-50, from ITT Rayonier, was added at concentrations of, 0.5, 1.0, 2.0, and 3.0 weight percent relative to anthracite on a dry basis. Figure 2 shows the rheograms for these concentrations.

Combining the results of these tests, it was determined that an ammonimum lignosulfonate concentration of 2 weight percent produced acceptable rheologies for both the 3-µm and 7-µm anthracite slurries.

Table 2

Rheology Testing Feedstock Analyses

Particle size (Mode, µm)	Ash %	Sulfur %	Volatile %	Density (g/cc)*
3	1.97	0.49	5.87	1.66
7	3.31	0.52	5.21	1.68

* - dry coal basis, measured using a Helium pycnometer.

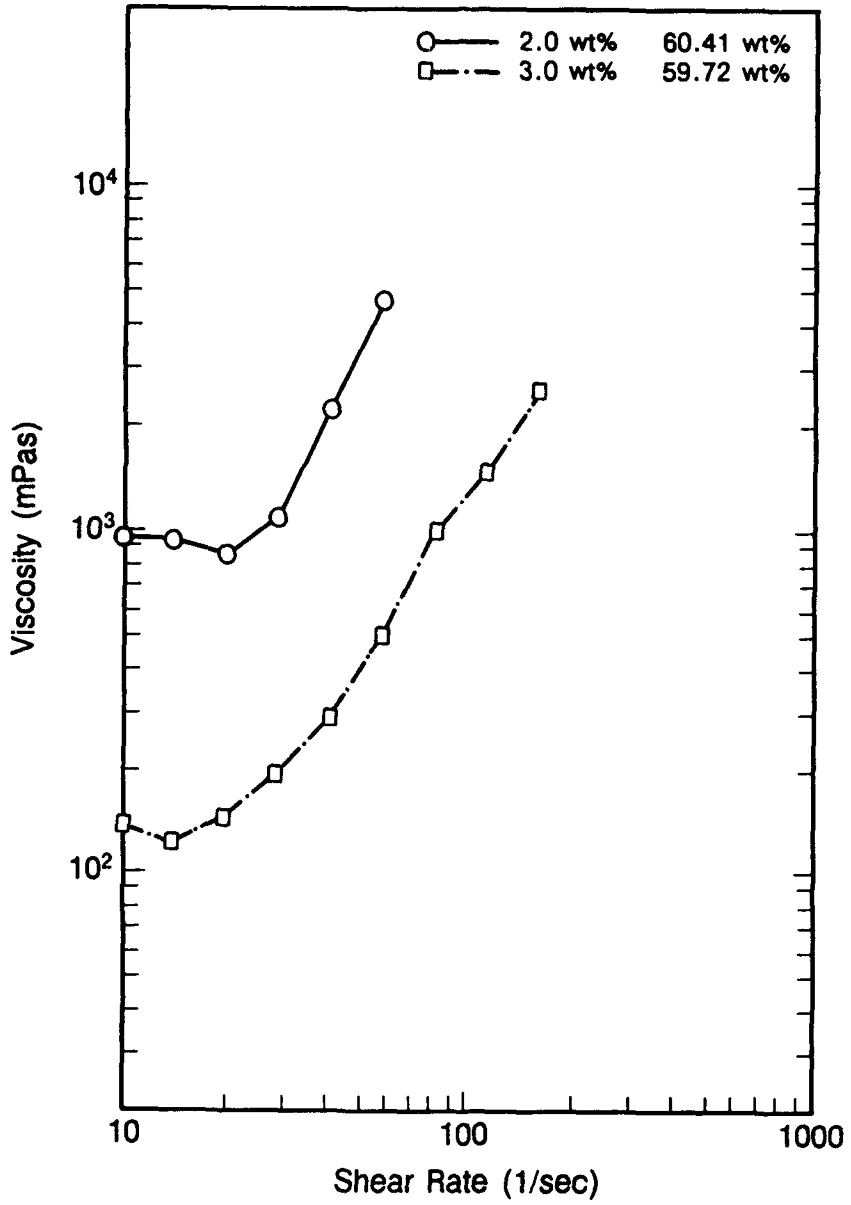

Figure 1. Rheology of 3-µm Anthracite Fuel With Different Concentrations of Lignosol TSD.

In the second test series, three anthracite slurries were prepared using the 3-μm product coal, each with a different dispersant. One slurry was prepared with 2 weight percent (dry coal basis) of ORZAN AL-50. The second slurry contained 2 weight percent (dry coal basis) of Lignosol TSD. The third slurry contained 1 weight percent (dry coal basis) of an ammonium condensed naphthalene sulfonate (CNS), MCG 32A-LS from Morristown Chemical Group. One slurry was prepared using the 7-μm product coal and 2 weight percent (dry coal basis) of the ORZAN AL-50. Each of the slurries were treated in the following manner; the solid content was measured and the shear stress versus shear rate curve was determined from 0 to 1000 sec^{-1}. Immediately thereafter, that slurry was diluted by 1 percent water, mildly remixed, the weight percent solids measured and a second shear stress versus shear rate curve produced. The procedure was repeated until further dilution resulted in minimal changes in rheology. Each slurry was tested at 8 to 12 solid contents. The results obtained from testing the three 3-μm slurries of ORZAN AL-50, Lignosol TSD, and MCG 32A-LS, are illustrated in Figures 3, 4, and 5, respectively. Figure 6 illustrates the results obtained from testing the 7-μm slurry prepared with ORZAN AL-50.

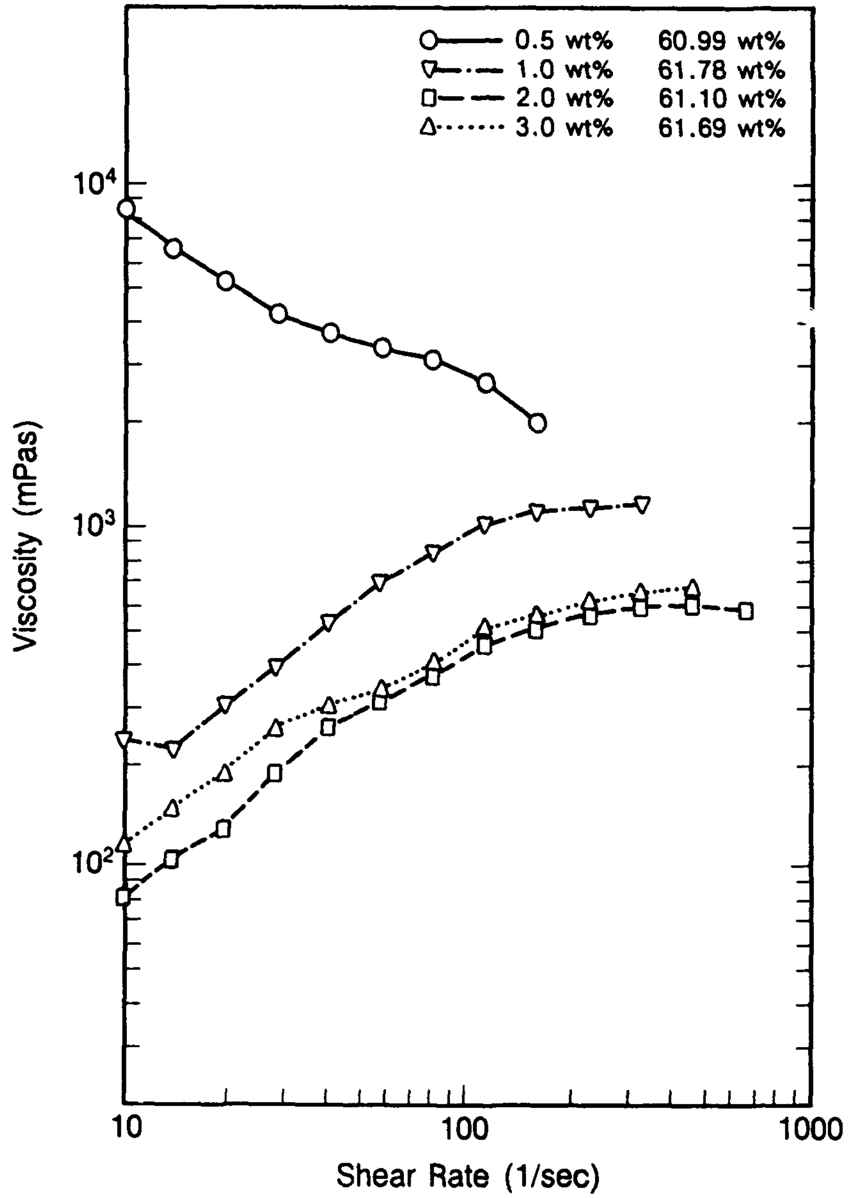

Figure 2. Rheology of 7-μm Anthracite Fuel With Different Concentrations of ORZAN.

On the basis of both T-Process and rheology data, it was concluded that the behavior of this sample of anthracite is consistent with the behavior exhibited by a typical eastern bituminous coal. These data were used to establish the operational control settings for the T-Process pilot plant and combustion laboratory.

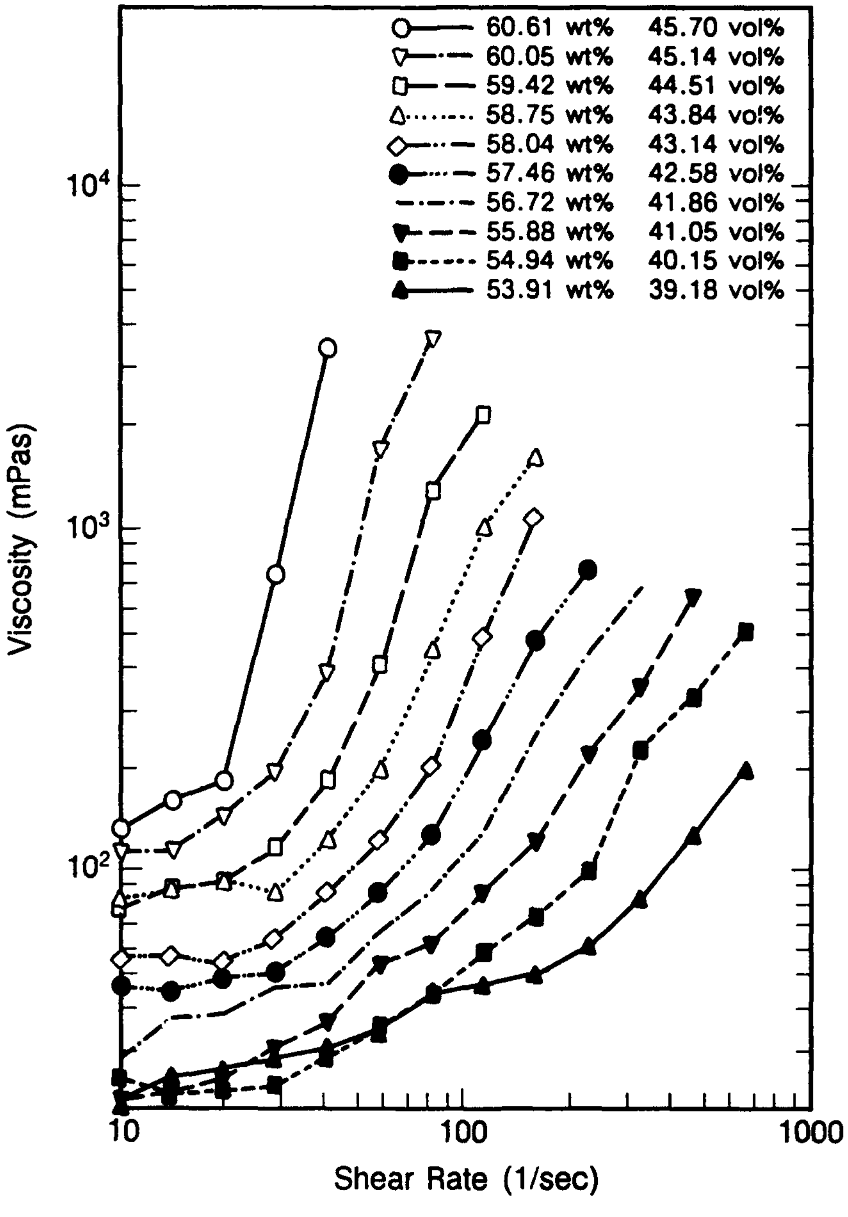

Figure 3. Rheology of 3-μm Anthracite Fuel With 2 Percent ORZAN AL-50 at Various Solid Contents.

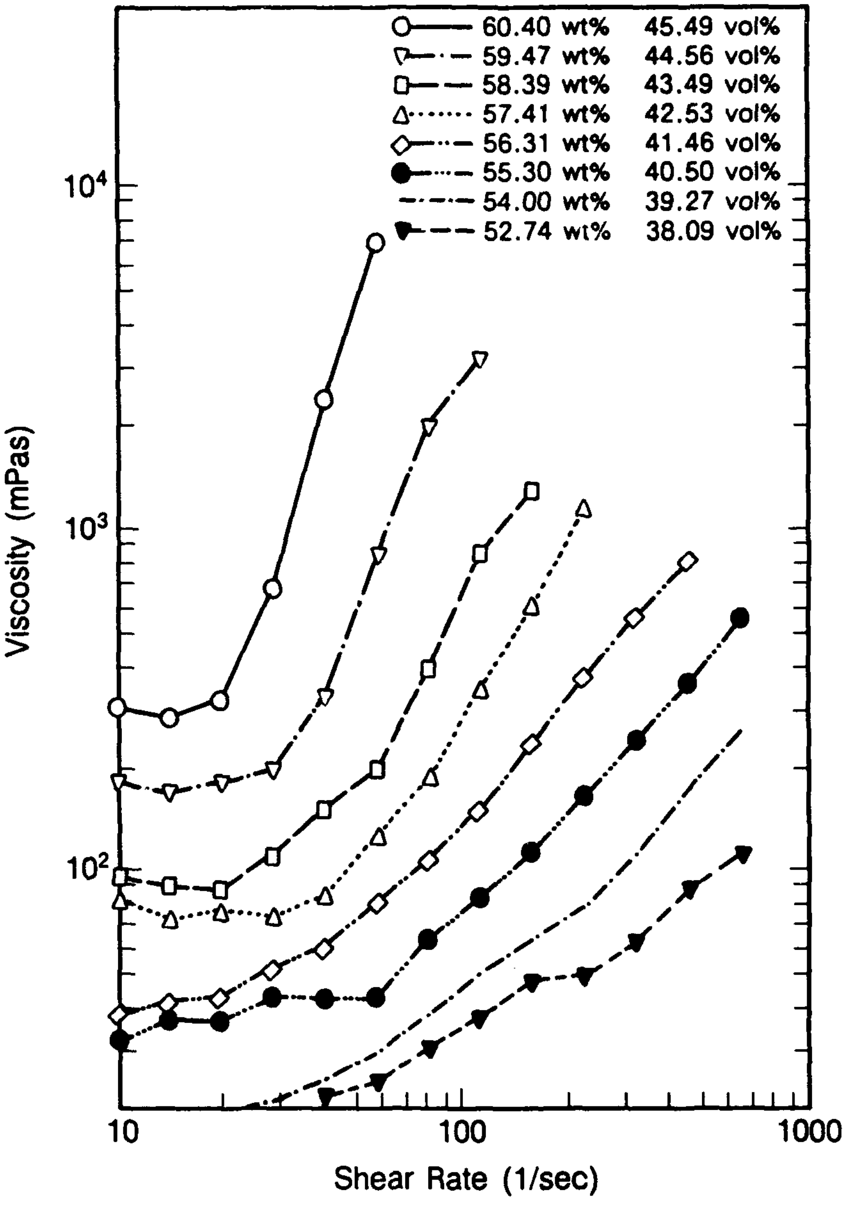

Figure 4. Rheology of 3-μm Anthracite Fuel With 2 Percent Lignosol TSD at Various Solid Contents.

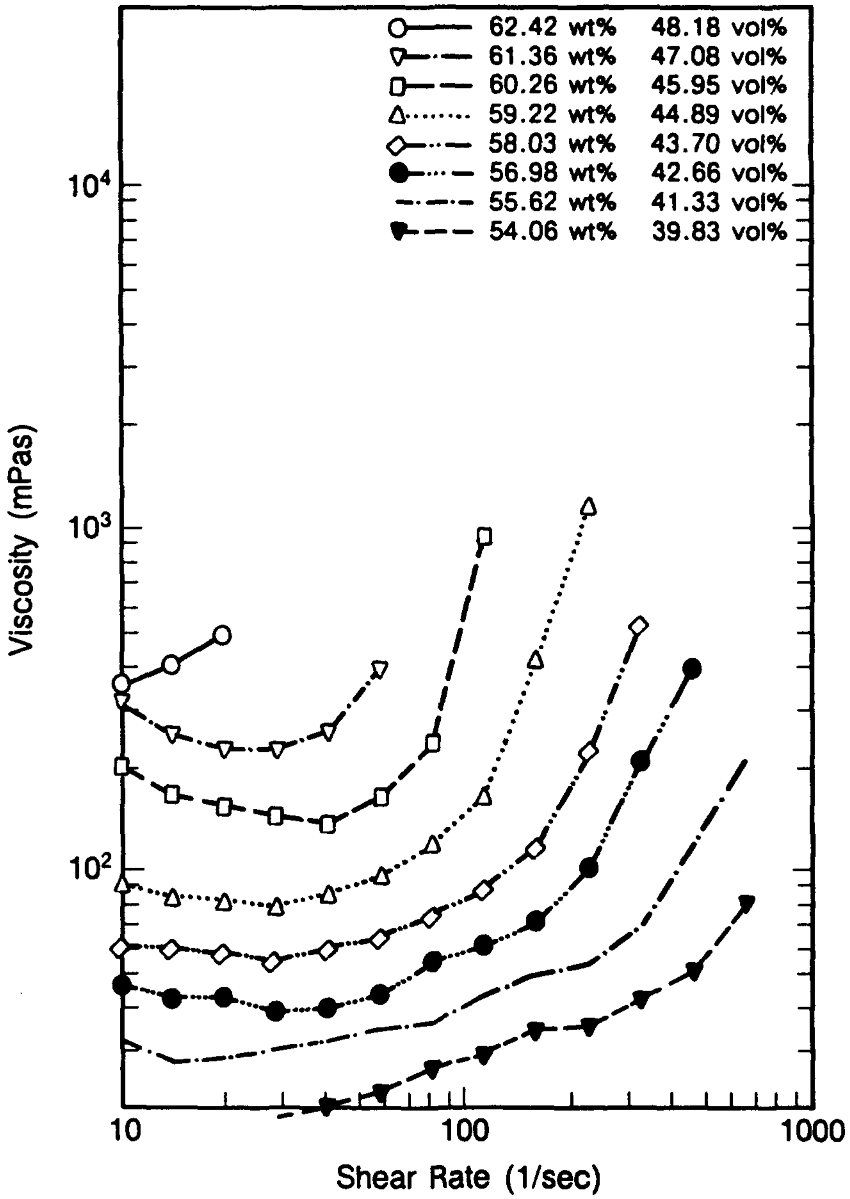

Figure 5. Rheology of 3-µm Anthracite Fuel With 1 Percent MCG-32A at Various Solid Contents.

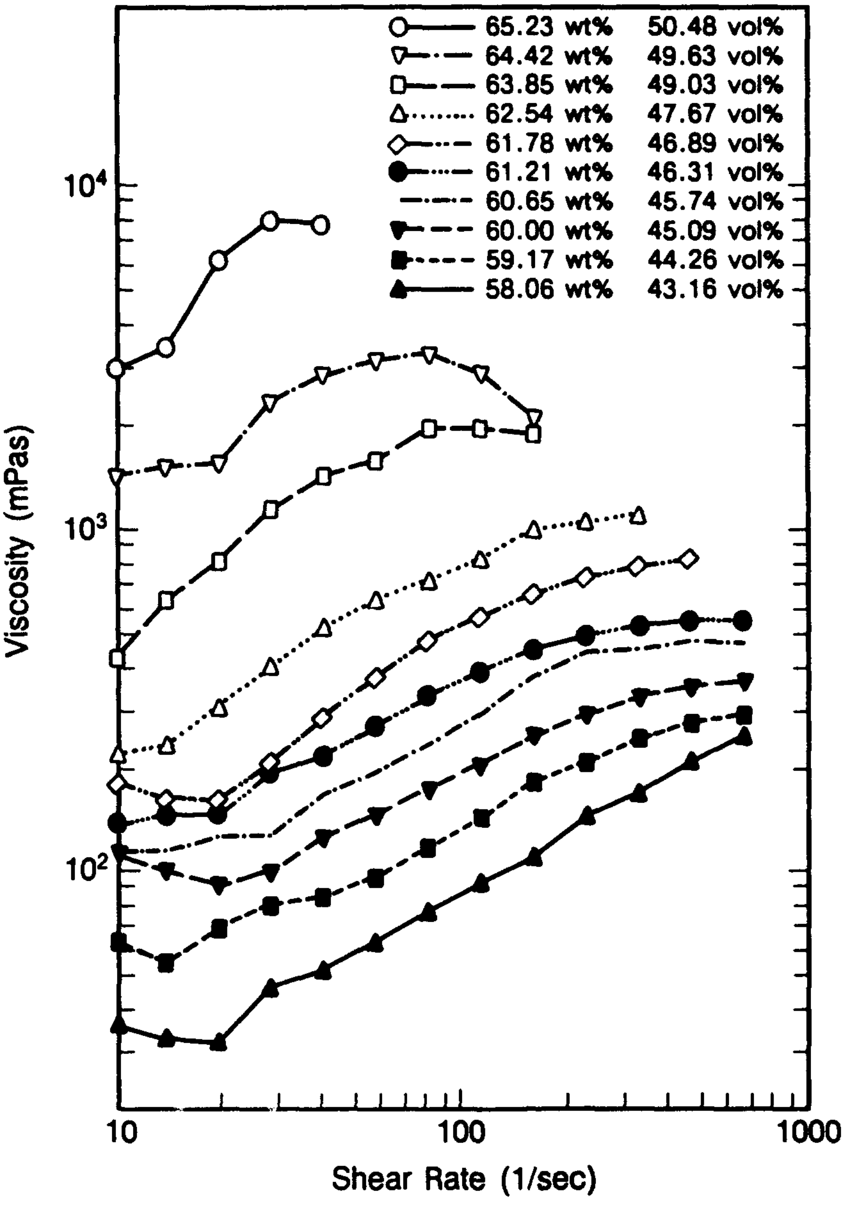

Figure 6. **Rheology of 7-μm Anthracite Fuel With 2 Percent Lignosulfonate at Various Solid Contents.**

3 ANTHRACITE WATER FUEL PRODUCTION

T-Process Pilot Plant

During 1983, Otisca constructed and began operating a 2.4-ton-per-day pilot plant to prepare product coal by the T-Process. Raw coal up to 10 cm X 0 is delivered to a series of standard hammer mills that reduce the raw coal size to 60 mesh (250 µm) X 0. The raw coal is then slurried with recycled water to establish a solids content in the range of 50 weight percent that acts as a feed to a stirred ball mill. Although a number of commercially available stirred ball mills might have been satisfactory, the mill in the plant was designed by Otisca to produce a 15-µm x 0 product at 200 lb/hr consuming about 30 kWh/ton. The ultrafine product from that mill is further diluted with recycled water in preparation for mineral separation.

The raw coal slurry is mixed with pentane as an agglomerant and the agglomeration is completed in a high shear mixer. The coal-pentane agglomerates appear as "black cottage cheese" that is readily separated from the water-mineral matter dispersion. Once separated, the product coal mixture is fed to an indirect-fired, conductive evaporator that causes the agglomerant, pentane, to evaporate leaving a coal product for coal/water slurry preparation. The pentane vapors are condensed into the liquid state for reuse in the system. The mineral matter/water slurry is placed in a thickener that permits recovery of the water for recycling and the clay for disposal. The majority of the product coal shipped from the 200 lb/hr pilot plant is as a coal/water slurry. It is shipped to customers engaged in coal-fueled turbine and engine development. Over 80 tons has been produced to date with an average analysis of 0.7 weight percent ash and 0.7 weight percent sulfur.

The refuse, which is 100 percent common mineral matter consisting of nominally 60 to 70 percent clay, 20 to 30 percent sand, and 5 to 10 percent other minerals, might be used as liners for landfills or as a feedstock for ceramic production.

Fuel Production

Anthracite water fuel was produced using the T-Process pilot plant without modification. The first step in production was to mill the raw anthracite. This was accomplished using an average feed slurry of 30 weight percent solids. As a practical matter, since two different particle sizes were being used for fuel production, all of the raw anthracite was subjected to coarse milling and the resultant raw anthracite slurry was divided into two lots. This ensured a constant feed coal chemistry for both lots of product slurry. Upon analysis of the first milling step, it was discovered that the anthracite responded by producing a finer average diameter (4.0-µm) than the 7-µm expected. The entire lot of 4.0-µm raw anthracite slurry was mixed by recirculating through pumps and then divided into two equal lots by pumping the mixed slurry through a mechanical splitter. However, the increase in specific gravity of the anthracite (1.67 g/cc) over the plant design point for bituminous coal (1.30 g/cc) presented some problems in maintaining a uniformly mixed slurry. The problem was overcome by temporarily increasing the mixing and circulating system capacity. Analyses of the 4.0-µm raw anthracite slurries are presented in Table 3. As indicated by the percent ash solids data, the split was successful.

After the split, one lot (designated as lot A), was reserved for continued milling while the lot designated as B was processed into anthracite water fuel. Lot A was milled under the same conditions as before. The resultant raw anthracite slurry had an average particle diameter of 1.9 µm.

Table 3

Analyses of Intermediate Milled Raw Anthracite

Sample (Mode, µm)	Particle size	Ash %	Volatile %	Moisture %
Full Lot	4.0	7.72	11.14	29.31
Split 1	4.0	7.75	10.09	27.87
Split 2	4.0	7.70	9.92	27.88

Each lot of raw milled anthracite was processed into a slurry fuel using the agglomeration circuit of the T-Process pilot plant. The pilot plant was operated using the same control settings as experience with bituminous coal dictated. The only change in the pilot plant normal operating window was additional mixing in the raw coal process feed tank. Incremental samples of the product slurry and the refuse material, which covered the full production run, were taken during processing. Data from the production run samples from the 1.9-µm product are presented in Table 4, and data from the 4.0-µm product are presented in Table 5. A total of twelve 55-gal drums of anthracite water fuel were produced, six each of the two raw coal sizes. Analyses of the individual drums of fuel are presented in Table 6.

Data Analysis

The two main areas of concern are the milling characteristics and agglomerating kinetics of the raw coal. The laboratory testing of the raw anthracite coal produced data equivalent to data from a typical eastern bituminous coal with respect to milling conditions, agglomeration kinetics using pentane, and recovered agglomerate (product) water content. On this basis, however, the results from the pilot plant were not consistent with past experience.

For the equivalent milling conditions (pulp solids content, energy input), the anthracite milled to a finer size than experienced using bituminous coal. This is counter to the laboratory tests where the milling characteristics were virtually identical for anthracite and bituminous coal. Apparently the mechanism change from a roller ball mill to a stirred ball mill highlighted a difference in the coals.

The agglomeration kinetics of the raw anthracite were evaluated with respect to agglomeration time, agglomerate (pentane) requirement, and product agglomerate water content. The agglomeration time was less than 30 seconds under all test conditions, which is nominal for a fresh, unoxidized raw coal. The agglomerate (pentane) requirements were a 1:1 ratio on a volume basis, coal-to-agglomerate, which again is nominal for a fresh, unoxidized raw coal. The water content of the agglomerates was also in the nominal range at a 1:1.3 volume ratio of coal-to-water. These data are typical for most raw, unoxidized coals. The T-Process pilot plant performed well within the above criteria, except for the higher moisture and ash content of the product slurry fuel. The 1.9-µm product slurry had a coal-to-water volume ratio of 1:1.8; the 4.0-µm product slurry had a coal-to-water ratio of 1:1.6.

The differences in ash content and moisture level were not detected by standard laboratory raw coal evaluation procedures, and should be considered for further investigation. The milling differences do not present a specific problem; however, researchers were forced to use a finer product coal size than originally planned for this project. The higher than expected water and ash content of the slurry fuel was unexpected, and will require some investigation before more fuel is produced.

Table 4

1.9-µm Product Slurry

Sample	Ash Product	Volatile	Solids Refuse	Ash	Product Yield
Product #1	2.33	8.81	47.74	-	91.06
Refuse #1	-	37.85	0.13	64.43	-
Product#2	2.10	9.01	47.17	-	93.10
Refuse #2	-	13.08	0.58	85.87	-
Product#3	2.27	8.99	45.42	-	93.33
Refuse #3	-	10.88	0.84	86.42	-
Product#4	2.41	9.10	44.52	-	93.52
Refuse #4	-	14.19	0.81	86.76	-
Product#5	2.42	9.27	46.00	-	93.74
Refuse #5	-	11.93	0.79	89.62	-
Product#6	2.58	9.47	46.58	-	93.84
Refuse #6	-	12.36	2.02	88.61	-
Product#7	2.50	9.17	49.13	-	93.60
Refuse #7	-	13.54	0.99	86.53	-
Product#8	2.75	9.88	44.87	-	93.68
Refuse #8	-	16.42	1.01	83.88	-
Product Average	2.42	9.21	46.43	-	93.23
Refuse Average	-	16.28	0.90	84.01	-

Table 5

4.0-μm Product Slurry

Sample	Ash % Product	Volatile %	Solids %	Ash % Refuse	Product Yield %
Product#1	2.76	8.37	54.50	-	93.74
Refuse #1	-	15.07	0.56	84.50	-
Product#2	2.89	7.78	51.62	-	93.94
Refuse #2	-	15.49	0.81	85.26	-
Product#3	3.03	7.94	50.08	-	94.13
Refuse #3	-	17.05	0.75	85.72	-
Product#4	3.15	8.19	48.48	-	94.41
Refuse #4	-	13.02	1.14	87.77	-
Product#5	3.13	8.00	49.14	-	94.40
Refuse #5	-	13.35	1.20	87.94	-
Product#6	3.08	8.60	48.30	-	94.34
Refuse #6	-	14.17	1.07	87.83	-
Product Average	3.01	8.15	50.35	-	94.16
Refuse Average	-	14.69	0.92	86.50	-

Table 6

Analyses of the Final Anthracite Water Fuel

Sample		Ash%	Volatile%	Solids%	Total Sulfur%	Btu/lb
1.9 µm						
Drum	-A1	2.27	9.00	47.55	0.52	13,942
	-A2	2.37	9.71	46.97	0.49	-
	-A3	2.44	8.97	46.50	0.50	-
	-A4	2.41	9.28	46.50	0.48	14,224
	-A5	2.38	9.18	46.90	0.51	14,209
	-A6	2.41	9.36	47.30	0.50	13,737
Lot	A	2.38	9.25	46.87	0.50	14,028
4.0 µm						
Drum	-B1	2.95	8.17	51.06	0.52	14,177
	-B2	3.05	7.77	50.76	0.52	13,887
	-B3	2.99	8.16	50.89	0.52	14,111
	-B4	3.01	8.08	50.65	0.51	13,703
	-B5	2.99	7.87	50.93	0.53	-
	-B6	3.01	8.02	50.59	0.52	13,754
Lot	B	3.00	8.01	50.81	0.52	13,926

4 ANTHRACITE WATER FUEL COMBUSTION

Combustion Laboratory

The anthracite slurry combustion trials were conducted in the Otisca combustion laboratory using the modified 70-horsepower York-Shipley 3 pass fire tube boiler. The principal modification to the boiler is the addition of a 26-in. long cylindrical refractory tube including a 30 degree quarl between the burner exit and the boiler firing tube.

The burner was a designed swirl burner where the main combustion air enters through radial swirl vanes with an axial discharge concentric with both the main gas injector and the coal/water fuel (CWF) atomizer. A portion of the combustion air is also introduced through a second location 16 in. downstream from the fuel injector at the end of the refractory cylinder. The air entering through the main burner is further divided into the previously described swirl air, which represents 80 percent of the burner flow, and a nonswirl component (20 percent) that enters the combustion zone through a diffuser surrounding the CWF nozzle. The gas is injected radially into the swirling burner air stream through 8 holes at the entrance to the quarl.

The CWF is atomized using a standard Parker-Hannifin external mix air atomizing slurry nozzle. Atomizing air enters through the same nozzle at selected air pressures up to 120 pounds per square inch gauge (psig). Atomizing airflow was not measured during these trials, but was calculated from a previous calibration run.

Combustion airflow is measured using pitot tubes located in the air lines to both the main burner and the chamber and connected to inclined manometers. The flow is controlled by motor driven dampers in each of the two ducts.

Gas input is measured using a concentric orifice in the gas line connected to an inclined manometer, and is controlled by a motor driven valve.

CWF is measured using a positive displacement meter with a direct electronic readout, and is controlled by a variable speed positive displacement rotary lobe pump. Speed is controlled using a variable frequency alternating current drive.

The boiler control is equipped with an electronic fuel/air ratio controller that automatically adjusts output signals to both the air motor and the fuel pump converter drive to maintain a preselected ratio. For the purposes of these preliminary trials, the automatic control was disabled and outputs to the air and fuel motors were separately controlled manually.

Stack monitoring consists of instrumentation that measures stack temperature and the percent of dry volume of carbon monoxide, combustibles, and oxygen.

It should be noted that the combustion test laboratory was designed to operate with a bituminous coal-based medium to high volatile matter (> 30 percent) CWF and that no equipment changes were made to refine the system operation for the anthracite-based CWF.

Test Procedure

Before introducing CWF into the boiler, the combustion chamber refractory was preheated for approximately 1 hour using natural gas. At the conclusion of this preheat, the gas input was held at a preselected level and the combustion air was preset to an anticipated firing rate. The fuel nozzle was then purged with water for approximately 1 minute. CWF was introduced at the conclusion of the purge at a calculated rate to match the airflow.

Input rates were adjusted for both the fuel and air and the atomizing pressure to obtain fuel ignition, and were further adjusted to visually obtain a stable flame at the minimum attainable oxygen level. When this condition was achieved, data was recorded. In some cases, several different firing rates were attempted to determine an acceptable input capacity. The data taken was later analyzed to determine the combustion level actually achieved.

Data Summary

A total of 17 tests were conducted during these trials. Six of these tests were conducted using the 1.9-µm (A) slurry and 11 using the 4.0-µm (B) slurry. Test results are shown in Table 7. The initial tests were conducted on 4.0-µm slurry at the pilot plant production solids concentration of 51.0 weight percent. The solids level was raised to 52.7 weight percent for the second series with the 4.0-µm slurry. The 1.9-µm slurry was tested next after adjusting the solids concentration to 53 weight percent. Finally, the 4.0-µm formulation was retested at 57.9 percent solids.

All tests were cofired with natural gas at a constant firing rate. For test B-17, the natural gas support flame was varied to determine what minimum support level was required.

In most of the early tests, the fuel input was increased based on visual observation to obtain a minimally acceptable stable flame. However, later calculation showed that in most cases the fuel input had exceeded the theoretical stoichiometry even though the stack was still recording excess oxygen. Table 7 records the quantity of fuel consumed during the test as the Calculated CWF input.

Early tests indicated that flame quality improved with a reduction in the chamber airflow, so all tests after B-5 were run without any chamber air. For tests B-3 and following, the atomizing air pressure was adjusted at each stable point to optimize flame appearance. From B-12 on, atomizing pressure was adjusted for both visual impact and minimum carbon monoxide and oxygen concentrations.

Data Analysis

The most significant conclusion from tests B-1 to A-11 is that the solids concentrations were too low for proper flame propagation. In tests B-1 and B-2, ignition was nearly impossible because of the low solids.

The minimum gas support appears to be around 43 percent of the total heat input. Full load fuel input for this boiler requires a combustion intensity of approximately 150,000 Btu/hr/cu ft. The maximum combustion intensity achieved with satisfactory results was 90,000 Btu/hr/cu ft, but the available gas support also appears to limit the maximum heat input to 1800 x 103 Btu/hr, which is also roughly the same intensity. These trials were not definitive enough to determine which factor (gas support or intensity) is rate controlling.

Table 7

Anthracite CWF Combustion Data

Fuel-Test #	Solids %	Btu/Gal	CALC CWF, gph	MSD CWF, gph	Atom Air psig	CWF Btu/h $X10^3$	NG Btu/h $X10^3$	Total Btu/h $X10^3$	Total Air Stoich	Main Air Stoich	Cham Air Stoich	O2 %	CO ppm	Comb %
B-1	51.00	74,518	17.30	36.80	75	1,289.16	880.00	2,169.16	1.25	0.97	0.28	4.00	586	0.01
B-2	51.00	74,518	14.00	27.40	75	1,043.25	877.00	1,920.25	1.52	1.06	0.46	7.30	1360	0.01
B-3	52.70	77,629	12.50	22.30	48	970.36	877.00	1,847.36	1.20	1.00	0.20	3.40	512	0.01
B-4	52.70	77,629	13.10	27.20	47	1,016.94	877.00	1,893.94	1.32	1.09	0.23	5.00	772	0.02
B-5	52.70	77,629	12.50	24.50	47	970.36	877.00	1,847.36	1.23	1.06	0.17	3.50	678	0.02
A-6	53.00	78,184	10.30	28.00	55	805.30	731.00	1,536.30	1.33	1.33	0.00	5.20	1900	0.02
A-7	53.00	78,184	7.90	29.00	47	616.65	708.00	1,325.65	1.31	1.31	0.00	5.10	>2000	0.04
A-8	53.00	78,184	9.20	20.10	48	719.29	708.00	1,427.29	1.31	1.31	0.00	4.90	1623	0.04
A-9	53.00	78,184	8.30	20.30	50	648.93	776.00	1,424.93	1.39	1.39	0.00	5.90	1738	0.06
A-10	53.00	78,184	14.30	27.00	75	1,118.03	731.00	1,849.03	1.36	1.36	0.00	5.60	>2000	0.09
A-11	53.00	78,184	16.30	27.80	100	1,274.40	776.00	2,050.40	1.22	1.22	0.00	3.80	1392	0.08
B-12	57.90	87,470	8.40	17.30	48	734.75	708.00	1,442.75	1.26	1.26	0.00	4.50	971	0.02
B-13	57.90	87,470	8.40	18.90	49	734.75	708.00	1,442.75	1.23	1.23	0.00	3.80	1025	0.03
B-14	57.90	87,470	8.70	18.70	49	760.99	684.00	1,444.99	1.20	1.20	0.00	3.50	921	0.03
B-15	57.90	87,470	8.50	8.50	70	743.50	700.00	1,443.50	1.26	1.26	0.00	4.40	392	0.01
B-16	57.90	87,470	10.60	13.60	77	927.18	730.00	1,657.18	1.25	1.25	0.00	4.10	678	0.03
B-17	57.90	87,470	9.10	9.10	79	795.98	578.00	1,373.98	1.35	1.35	0.00	5.60	695	0.04

Column Heading	Definitions
Fuel Test	run number A = 1.9-µm fuel, B = 4.0-µm fuel, Tests are in chronological sequence.
Solids Wt %	weight percent anthracite in slurry fuel.
Btu/gal	the calculated Btu/gal based on laboratory measurement of water in the slurry multiplied by the specific gravity of the slurry.
Calc CWF (gph)	the theoretical amount of slurry (gallons per hour) that would be burned based on the measured amount of air, subtracting that required for the gas support fuel, and the measured 0_2 in the stack.
Msd CWF (gph)	gallons per hour flow meter readings.
Atomizing Air (psig)	atomizing air psig.
CWF (Btu/h $X10^3$)	fuel combustion rate in thousands of Btu per hour.
NG (Btu/h $X10^3$)	natural gas input rate in thousands of Btu per hour.
Total Air Stoichiometry	total excess air above stoichiometry.
Main Air Stoichiometry	fraction of total air entering main burner area.
Chamber Air Stoichiometry	fraction of total air entering as secondary air.
Oxygen, %	percent oxygen in the stack gases.
Carbon Monoxide, ppm	number of parts per million of carbon monoxide in stack gases.
Combustible Vapor, %	percent combustible vapors in stack gases.

Unlike the bituminous based CWF, this fuel appears to require a minimum excess air level of 25 percent (about 4 percent oxygen in the stack). Increasing the fuel input at a given airflow to reduce this excess air level results in higher carbon monoxide and unburned fuel in the combustion chamber.

The atomizer used in these trials has an included spray angle of about 25 to 300 to prevent fuel impingement on the walls of the boiler firing tube. Atomizing air pressure (actually the jet momentum of the atomizer stream of fuel and compressed air) has a significant effect on flame stability. As the fuel solids increased, it was possible to increase the air pressure from 50 psig to 75 psig without blowing the flame off the burner. Higher air pressure presumably results in better atomization. However, trials B-3 to B-5 operated better at 50 psig at 52.7 percent solids, and higher pressures actually caused the flame to deteriorate. Tests B-15 to B-17 at 57.9 percent solids had better atomization up to nearly 80 psig, after which deterioration was noted.

5 CONCLUSIONS AND RECOMMENDATIONS

Otisca's proprietary T-Process for producing coal water fuel was used to develop coarse (7-μm) and fine (3-μm) anthracite slurries with an ammonium lognosulfonate concentration of 2 weight percent. Based on the test results of the fuels produced, two characteristics do not carry through from the slurries made in the laboratory to the slurries made at the pilot plant. First, anthracite appears to mill to finer sizes than bituminous coals for the same operating conditions when using a stirred ball mill. While this is not a major problem and is easily controlled by adjusting the flow rate through the mill, the laboratory milling tests did not highlight this difference. The second problem encountered is the increased ratio of water to coal observed in the product slurry fuel. A change in pilot plant operating procedures will compensate for this characteristic. However, the fact that this possibility was not evident in the laboratory testing will require investigation.

Although it is feasible to manufacture anthracite water fuel, the slurries used in this research did not burn well despite the small particle size. Combustion of the anthracite water fuel required substantial firing of support fuel but was accomplished despite the fact that the boiler system was designed for a higher volatile content fuel. Stable combustion with reduced support fuel can probably be achieved by determining the effect of factors such as fuel chemistry, nozzle type and geometry, refractory zone, and flame intensity on the overall combustion process, and then modifying those variables to afford stable combustion.

To obtain further insights into anthracite slurry production, it is recommended that a program be implemented to determine what properties control the differences observed in the milling characteristics and product slurry water content of anthracite water fuels compared to bituminous slurry fuels.

Those technologies that provide a long residence time for anthracite slurry combustion will probably prove to be more successful than anthracite water fuel in an oil-designed boiler. Furthermore, since water is not a fuel burning carrier, perhaps future studies on anthracite coal oil fuel, rather than anthracite coal water slurry fuel, may yield better results. Other anthracite retrofit technologies should be considered to increase the use of anthracite coal.

METRIC CONVERSION TABLE

1 in. = 2.54 cm
1 lb = 0.453 kg
1 cu in. = 0.06102 cc
1 μm = 1x10^{-6}m
1 gal = 3.78 L
1 short ton = 907.18 kg
°F = (°C + 17.78) x 1.8
1 Btu = 1055.06 J

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