

**FURNACE SORBENT INJECTION: A PILOT-SCALE EVALUATION  
OF ITS EFFECT ON ASH DEPOSITION AND ESP PERFORMANCE**

by

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**ABSTRACT**

Pilot-scale pulverized-coal combustion tests were performed to establish the impact of furnace sorbent injection on combustion system operability. Performance was evaluated on the basis of SO<sub>2</sub> emission control, sorbent utilization, electrostatic precipitator (ESP) efficiency, and fouling potential. Selected coal/sorbent combinations were studied in a 550,000 Btu/hr combustion system. South Hallsville Texas lignite, Sarpy Creek Montana subbituminous, and Illinois #6 bituminous coals were fired using either Linwood or Marblehead high-calcium pressure-hydrated lime (PHL) as sorbents. The pressure hydrates were produced from pulverized commercial lime using a bench-scale hydration unit. Sorbent was pneumatically injected into the furnace to reduce SO<sub>2</sub> emissions by 50% and 90%, representing target control levels for retrofit and new installations, respectively. Ninety percent SO<sub>2</sub> reduction was not always achieved within the limits of the sorbent feed system. On a moisture-free basis, South Hallsville Texas lignite contained about 1.5% sulfur, 15% ash and had a heating value of 10,600 Btu/lb. A reduction of about 50% in sulfur emissions was achieved at a 1.8 Ca/SO<sub>2</sub> mole ratio using Linwood PHL. Sorbent injection did not affect ash deposition, as ash deposits sloughed off probes continuously in all cases. Sarpy Creek Montana subbituminous coal was also used in combination with Linwood PHL for SO<sub>2</sub> control. This coal contained about 0.87% sulfur, 12% ash and had a heating value of 11,400 Btu/lb (moisture-free basis). A Ca/SO<sub>2</sub> mole ratio of 2.1 resulted in about 50% sulfur capture. As with the lignite, this coal was low fouling with or without sorbent injection. Strength tests on the ash deposits showed that the deposits became weaker and more friable with sorbent injection. Illinois #6 bituminous coal was fired with Marblehead PHL injected for SO<sub>2</sub> control. This coal had a heating value of 12,300 Btu/lb, a sulfur content of 3.7%, and an ash content of 12% (moisture-free basis). A Ca/SO<sub>2</sub> mole ratio of 1.1 captured 50% of the sulfur. This coal/sorbent combination was low fouling and produced weak deposits. Sorbent added to reduce sulfur emissions by 50% resulted in a full order of magnitude increase in bulk ash resistivity for the three coal/sorbent combinations. Electrostatic precipitator efficiency data were variable but generally showed poorer performance when SO<sub>2</sub> capture exceeded 50%.

## INTRODUCTION

The objective of the  $\text{SO}_x/\text{NO}_x$  project at the University of North Dakota Energy Research Center (UNDERC)<sup>x</sup> is to control  $\text{SO}_x$  and  $\text{NO}_x$  emissions by developing an economical dry process potentially suitable for new power plants and retrofit applications. A promising process involved the direct furnace injection of a calcium-based sorbent. Initially, limestone was used since it had the lowest cost per unit weight and is widely available. However,  $\text{SO}_2$  reduction and sorbent utilization did not exceed 16% in pilot-scale tests at a  $\text{Ca}/\text{SO}_2$  mole ratio of 1.0. Marked improvement in sorbent utilization was observed in 1982 when tests were conducted using calcitic and dolomitic pressure-hydrated lime (PHL). The sorbent utilization was typically greater than 30% using these materials (1).

Furnace injection of PHL is a simple and effective way to control  $\text{SO}_2$  emissions from utility boilers. The process was demonstrated at Otter Tail Power's Hoot Lake Station on a 50 MW tangentially-fired boiler (2). Seventy percent removal was achieved at a  $\text{Ca}/\text{S}$  mole ratio of 4.0. Compared to earlier results using limestone injection, the mass feed rate of PHL required to reduce the  $\text{SO}_2$  emissions was decreased by a factor of 5. Also, total particulate emissions were controlled at less than 10% opacity using the existing electrostatic precipitator (ESP), and boiler operation was not adversely impacted by sorbent injection. Economic studies of furnace injection of PHL indicate that the process may be more cost-effective than wet or dry scrubbing (3,4).

Recently, a considerable effort has been put forth to improve sorbent utilization by optimizing parameters of physical and chemical processing. These parameters include sorbent injection temperatures and locations, quench rates, calcination temperatures, hydration conditions, flue gas humidification, and additive enhancements. Since sorbent cost substantially impacts process economics, improvements in sorbent utilization continue to be important in overall process development. However, the application of this process as a  $\text{SO}_2$  emission control technique is dependent upon actual performance and operability in full-scale utility boilers.

A data base of pilot-scale investigations is being developed to evaluate performance and operability. High usage coals from various ranks and geographic locations are being evaluated in conjunction with pressure-hydrated calcitic sorbents. Measured parameters include sorbent utilization, deposition rate, deposit strength, particulate loading, and ESP collection efficiency. This paper presents a descriptive analysis of data obtained for three coal/sorbent combinations.

## DESCRIPTION OF FACILITIES AND PROCEDURES

### ASH FOULING COMBUSTION SYSTEM

A schematic diagram of the ash fouling test furnace is shown in Figure 1. The furnace capacity is approximately 75 lb/hr of pulverized lignite (550,000 Btu/hr). The combustion chamber is 30 inches in diameter, 8 feet high, and refractory lined. Particle laden flue gases pass from the furnace

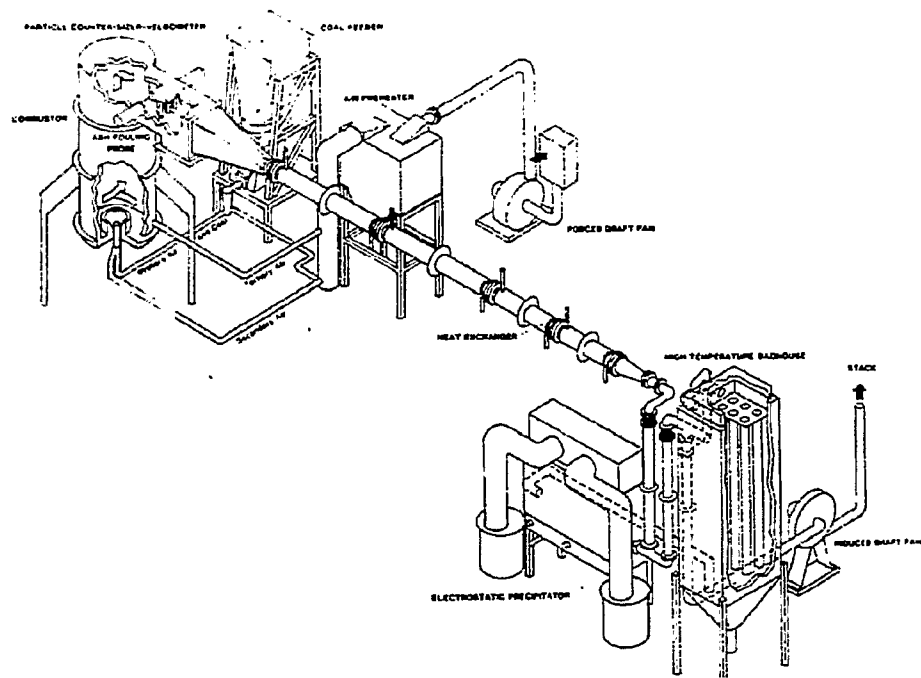


Figure 1. Ash fouling test furnace and auxiliary equipment.

into the 10-inch square refractory-lined duct containing the ash deposition probes. This vertically mounted probe bank was designed to simulate superheater surfaces in the convective pass region of a commercial boiler. The probe bank is located in a hinged door to facilitate inspection and cleaning. Figure 2 details the construction of the probe bank. The bulk flue gas temperature entering the probe bank is maintained at 2000°F, while the surface temperature of the probes is controlled to 1000°F with compressed air. The gas velocity between the tubes is about 25 ft/s.

After leaving the probe duct, the flue gases pass through a series of water-cooled heat exchangers before entering the ESP. The ESP consists of a single-stage rigid-frame electrode design. Two banks of collecting electrode/plate sets are configured in series within the precipitator compartment. The four collecting plates per bank result in a net surface area of 48 ft<sup>2</sup>, and a specific collection area (SCA) of about 150 ft<sup>2</sup>/1000 ACFM. Each bank is energized with an independent transformer/rectifier set capable of maintaining 34 KV under normal operating conditions. Collection efficiencies typically range from 95 to 99 percent, when the ESP is not rapped during the combustion test.

Sorbent is pneumatically injected into the top of the furnace using an air eductor and screw feeder combination. A one-half inch stainless steel tube is inserted (vertically) into the center of the top-face of the furnace to transport the sorbent/air mixture. The pneumatic countercurrent delivery of the sorbent provides good particles dispersion within the furnace.

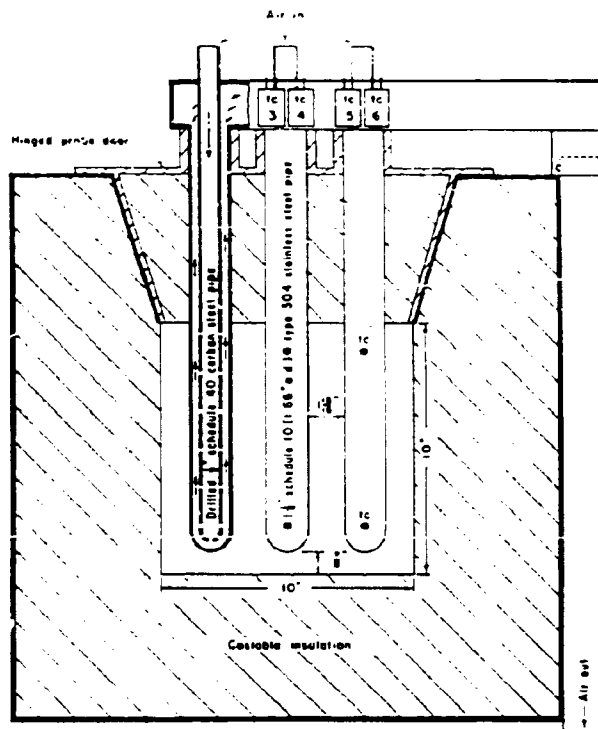


Figure 2. Detailed construction of probe bank.

The relative fouling tendencies of the test coals are determined by burning the samples under standard conditions. When starting with a natural gas furnace, the combustor is preheated for 8 hours with natural gas followed by a 5 1/4-hour test burn on coal. The coal feed rate is adjusted to keep the flue gas temperature entering the upper duct to the probe bank at 2000°F with 25% excess air. Coal samples are taken periodically to form a composite sample. Flue gas oxygen, carbon dioxide, nitrogen oxides, carbon monoxide, and sulfur dioxide are continuously monitored by recording analyzers.

At the completion of the test period, the probe door is opened and photographs are taken of the deposit. The deposit is then removed from the probes in two fractions, an inner and an outer layer, and each is weighed and analyzed separately. Normally the inner white layer is less than 10 grams as compared with 100 to 500 grams for the outer sintered deposit.

The weight of ash deposited on the probe bank during a standard test is used to rank the coal by its relative fouling potential. Based upon comparisons between results obtained in the ash fouling combustor and actual operating experience in full-scale utility boilers, the typical relationship between deposit weight and the fouling potential of the fuel is indicated below:

<u>Deposit Weight, grams</u>	<u>Relative Fouling Potential</u>
0-150	Low
150-300	Medium
Above 300	High

Following each test run, proximate, ultimate, and heating value analyses are determined for the composite coal sample obtained during the run. Elemental ash analysis is also performed for the composite coal sample, for ash samples from the probe inner and outer layers, and for fly ash collected in the ESP.

Strength of the ash deposits is measured using drop impaction tests. In addition, during removal the hardness and breakability of deposits is rated by the system operating personnel on a scale from 1 to 10 with "1" representing a soft, crumbly, unconsolidated deposit, and "10" a hard and unfragmented deposit. Based on previous studies, friability as measured by the drop impactor test and operator observations have generally provided the best estimate of deposit strength.

The impact test involves dropping a 3.8-oz. weight from a height of 24 inches onto a 1-inch cross-section deposit sample. The fragmented sample is then sieved (using 5.66, 3.66, 0.84, 0.42, and 0.21 mm screens) to obtain friability measurements (similar to the ASTM Tumbler Test, ASTM-441-45). In addition to friability, strength indicators obtained from this test include impulse, impact, crush factor, dust index, and mass mean diameter. The dust index is indicative of the tendency of the deposit to form dust on impaction, with values ranging from about 10% for hard deposits to 25% for soft deposits. The mass mean diameter is the average size of the fragmented particle, and usually varies from about 5 mm for hard deposits to 1.3 mm for a very soft deposit.

To assure that the test results from the ash fouling furnace are meaningful for evaluation of ash fouling potential in full-scale utility boilers, calibration tests have been conducted with low-rank coals which are known to produce low and high fouling conditions when used in utility boilers. Comparisons of pilot-scale ash fouling data have been made with information from a number of power stations throughout the western U.S.: Monticello (Texas Utilities), Big Brown (Texas Utilities), Four Corners (Arizona Public Service Company), St. Clair (Detroit Edison Company), Jim Bridger (Pacific Power and Light), Big Stone (Otter Tail Power Company), Leland Olds (Basin Electric Power Cooperative), and San Miguel (San Miguel Electric Cooperative). Based on the results of these comparisons, the ash deposit buildup rate on the probe bank was found to be a good indicator of the fouling potential (4).

#### BATCH PRESSURE-HYDRATOR

A batch pressure-hydrator was designed and fabricated at UNDERC to produce up to 8 lbs of hydrate per run. A schematic of the unit is presented in Figure 3. The reaction vessel consists of an 8-inch diameter schedule 80 carbon steel pipe 12 inches in length, with carbon steel flanges capping both ends. A paddle-wheel stirrer is used to mix the lime and water thoroughly in

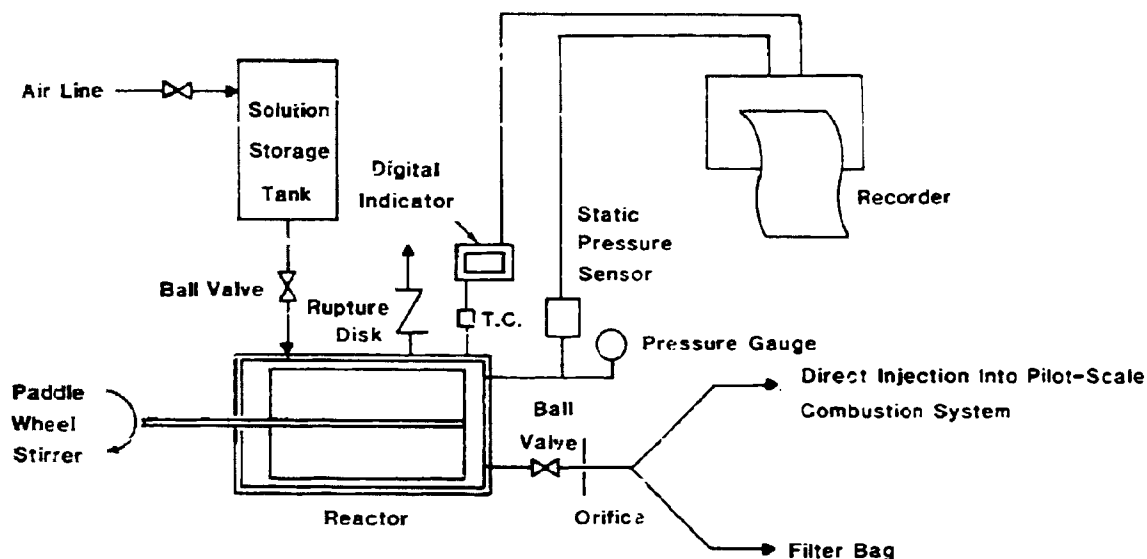


Figure 3. Bench-scale pressure hydrator.

the vessel, turning at a rate of 2 revolutions per minute. Pressurized water enters the hydrator through 1/8 inch nozzles affixed to the hollow stirrer shaft.

Approximately 6 lbs of quicklime (minus 140 mesh) are placed in the hydrator at the beginning of a run. The solution storage tank is charged with 2.7 lbs. of deionized water when high-calcium pressure hydrated lime is prepared. High-pressure air is used to pressurize the solution tank to 100 psig. When the inside skin temperature of the reactor reaches approximately 350°F, the hydration solution is carefully added under pressure. Excess water is used to ensure complete hydration of the lime and saturate the reactor with steam. Due to the exothermic reaction of hydration, the reactor temperature rises to about 370°F, and pressure is held constant at about 150 psig. As the hydration reaction proceeds, hydrator pressure is maintained by adding the hydration solution at a controlled rate. After completion of the reaction and during hydrate expulsion, reactor pressure is maintained using a regulated source of nitrogen or compressed air. About 20 minutes after addition of solution to the vessel, the internal temperature begins to decrease, indicating that the reaction is virtually complete. Hydrated lime is then flashed to ambient pressure through a ball valve. Upon expulsion of the hydrate/saturated steam mixture from the hydrator, water trapped inside the pore network of the hydrate particles is released explosively, yielding flash dried, submicron particles with high external surface area. The particles are collected in a nylon fabric filter bag, and stored for subsequent furnace injection tests.

## LABORATORY RESISTIVITY UNIT

Electrical resistivity measurements of bulk ash were made with the apparatus shown in Figure 4. The resistivity measurement unit was designed and built according to the American Society of Mechanical Engineers Power Test Code 28. Temperature is maintained by an oven consisting of two concentric cylinders separated by three inches of ceramic fiber insulation. The oven can be maintained at any temperature between room temperature and 800°F. Steady state oven temperature is maintained by an automatic controller, while precise sample (ash) temperature is measured by a second thermocouple mounted near the ash layer. The inside atmosphere of the oven is continuously flushed with simulated flue gas at a rate of 13 scfh. Compressed gas cylinders containing pure O<sub>2</sub>, CO<sub>2</sub>, SO<sub>2</sub>, and N<sub>2</sub> are used to synthesize the flue gas through careful mixing of the constituents. Moisture is provided by bubbling the non-reactive gases through a humidity bath controlled to the appropriate temperature. The reactive/non-reactive gas streams are joined just prior to entering the oven.

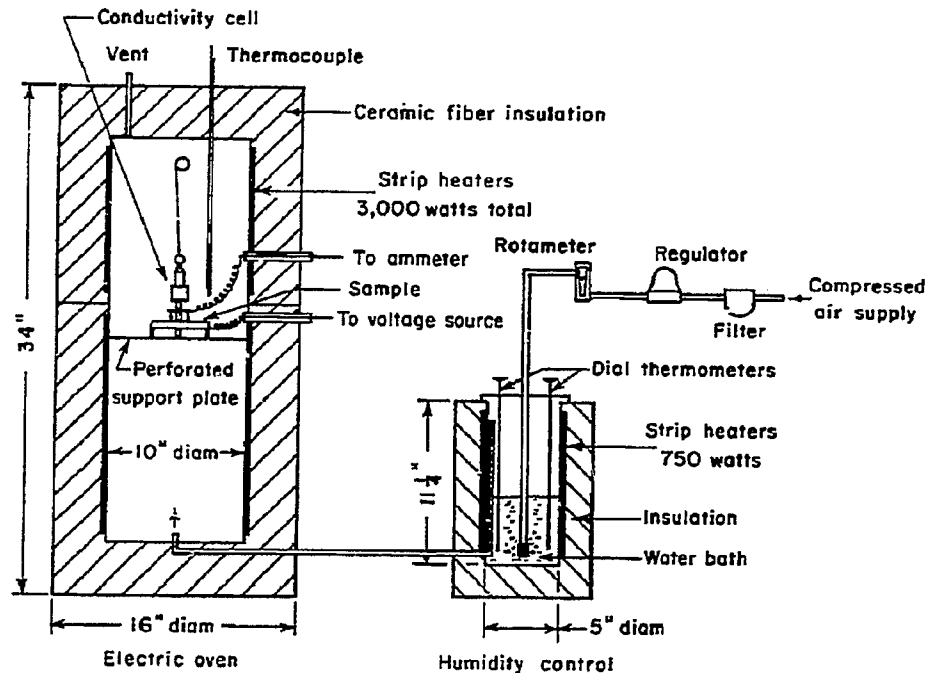


Figure 4. Schematic of ASME laboratory resistivity apparatus.

A uniform ash layer 5 mm thick is introduced to the conductivity cell. The electrode, designed to place 10 grams per square centimeter pressure on the ash, is placed on the surface of the ash layer. The electrode is energized to 750 volts, producing a constant field strength of 1.5 kV/cm. The oven is heated to a designated temperature and allowed to stabilize for 40 minutes before measuring current through the ash. Using this procedure, a resistivity versus temperature (200° to 750°F) curve is completed in 8 to 10 hours.

## RESULTS AND DISCUSSION

South Hallsville Texas lignite, Sarpy Creek Montana subbituminous, and Illinois #6 bituminous coals were selected for evaluation on the bases of marketability, geographic location, and rank. The proximate and ultimate analyses, and the calorific values are shown in Table 1. Data presented in Table 1 are average values for three composite coal samples for each fuel. Fuel variability was minimal with the exception of sulfur content in the South Hallsville lignite which ranged from 1.3% to 1.7%. The fuel rank designations are clearly indicated for moisture, volatile matter, fixed carbon, oxygen, and higher heating value. Also shown in Table 1 is the mass median diameter of the pulverized coals as determined by sieve analysis. Table 2 presents the

**TABLE 1**  
PROXIMATE, ULTIMATE, CALORIFIC, AND  
SIEVE ANALYSES OF SELECTED COALS<sup>a</sup>

	<u>South Hallsville Lignite</u>	<u>Sarpy Creek Subbituminous</u>	<u>Illinois #6 Bituminous</u>
<u>Proximate (As Rec'd):</u>			
Moisture	29.1	18.2	7.3
Ash	10.5	9.6	11.3
Volatile Matter	30.3	31.8	34.9
Fixed Carbon	30.1	40.4	46.5
<u>Ultimate (Dry):</u>			
Carbon	61.31	66.21	68.01
Hydrogen	4.61	4.52	4.77
Nitrogen	1.10	0.83	1.16
Sulfur	1.47	0.86	3.66
Oxygen	16.74	15.84	10.21
Ash	14.81	11.74	12.19
<u>Higher Heating Value:</u>			
Btu/lb (Dry)	10,610	11,417	12,263
<u>Pulverized-Coal MMD<sup>b</sup>:</u>			
μm (As-Fired)	52	64	64

<sup>a</sup>Data presented in the table are average values for three composite samples analyzed for each fuel.

<sup>b</sup>Mass median diameter.



TABLE 2  
ASTM COAL ASH AND ASH FUSION ANALYSES FOR SELECTED COALS

Element	Oxide	Normalized Wt. % as Oxides		
		South Hallsville Lignite	Sarpy Creek Subbituminous	Illinois #6 Bituminous
Silicon	SiO <sub>2</sub>	38.3	32.1	45.3
Aluminum	Al <sub>2</sub> O <sub>3</sub>	15.0	18.3	20.0
Iron	Fe <sub>2</sub> O <sub>3</sub>	13.2	5.4	16.5
Titanium	TiO <sub>2</sub>	1.1	1.1	1.1
Phosphorus	P <sub>2</sub> O <sub>5</sub>	0.5	0.9	0.2
Calcium	CaO	11.7	20.5	6.6
Magnesium	MgO	3.4	3.4	1.4
Sodium	Na <sub>2</sub> O	0.2	1.5	0.5
Potassium	K <sub>2</sub> O	1.0	0.5	2.0
Sulfur	SO <sub>3</sub>	15.6	16.3	6.4
Total		100.0	100.0	100.0
Ash Fusion Temperature, °F				
Deformation		2194	2091	2145
Softening		2233	2123	2188
Fluid		2317	2225	2280

ASTM coal ash and ash fusion analyses for each coal. All coal ashes showed low alkalinity and low to moderate iron concentrations. Ash alkalinity is usually associated with ash fouling in western coals, and iron with fouling and slagging phenomena in eastern coals. The ash fusion temperatures were determined under reducing conditions and showed similar trends in the deformation/fluid differential temperature.

The calcitic pressure-hydrated lime (PHL) sorbents were prepared in the batch hydration unit just prior to use. Linwood lime was used extensively at UNDERC for SO<sub>2</sub> control experiments, and was selected for use with South Hallsville and Sarpy Creek coals for reference. Marblehead lime is readily available near the mine from which the Illinois #6 coal was obtained, and was selected for the geographic location and convenience. The physical properties and composition of the pressure hydrated sorbents are shown in Table 3. Within the error of the respective analyses, there are no significant differences between the sorbents.

**TABLE 3**  
SORBENT PHYSICAL PROPERTIES AND COMPOSITION

	<u>Linwood PHL<sup>a</sup></u>	<u>Marblehead PHL<sup>b</sup></u>
Residual Moisture, Wt. %	0.0	0.0
Ignition Loss, Wt. %	22.9	22.7
Elemental Oxides, Wt. %		
SiO <sub>2</sub>	0.6	1.2
Al <sub>2</sub> O <sub>3</sub>	0.1	0.4
Fe <sub>2</sub> O <sub>3</sub>	0.1	0.4
TiO <sub>2</sub>	0.0	0.0
P <sub>2</sub> O <sub>5</sub>	0.0	0.0
CaO	75.7	74.6
MgO	0.4	0.6
Na <sub>2</sub> O	0.0	0.0
K <sub>2</sub> O	0.0	0.0
SO <sub>3</sub>	0.2	0.1
Total %	100.0	100.0
Surface Area <sup>c</sup> , m <sup>2</sup> /g	7.6	6.5
Mass Median Diameter <sup>d</sup> , μm	5.0	5.3

<sup>a</sup>Used with South Hallsville and Sarpy Creek coals

<sup>b</sup>Used with Illinois #6 coal

<sup>c</sup>Measured with Quantachrome BET analyzer

<sup>d</sup>Measured with Coulter Counter particle sizer

#### SORBENT UTILIZATION

Pilot-scale pulverized-coal combustion tests were performed to establish the impact of furnace sorbent injection on system operability. For each coal selected, one test was run without sorbent injection to establish baseline characteristics. Two additional tests were performed with sorbent addition, where sulfur emissions were to be reduced by 50% and 90%, representing the target SO<sub>2</sub> control levels for retrofit and new installations, respectively. These control levels were chosen to project possible requirements if acid rain legislation is promulgated. Due to sorbent feeder limitations, 90% SO<sub>2</sub> control was not achieved with any coal/sorbent combination.

Table 4 presents SO<sub>2</sub> emissions, stoichiometric ratios of calcium-to-sulfur dioxide, SO<sub>2</sub> reduction, and sorbent utilization for nine combustion tests. All SO<sub>2</sub> values were corrected to a dry, 3% excess oxygen basis. The sorbents were injected at a stoichiometric ratio based upon the actual SO<sub>2</sub> concentration in the flue gas stream. This, in effect, maintains the sorbent independent of inherent sulfur capture. As seen in this table, Ca/SO<sub>2</sub> mole ratios of 2 were required to reduce flue gas SO<sub>2</sub> levels by 50% when firing either South Hallsville or Sarpy Creek coals, and using Linwood PHL. When firing Illinois #6 coal and using Marblehead PHL, a Ca/SO<sub>2</sub> mole ratio of 1.0 was required. Better utilization of the Marblehead PHL may have resulted from sorbent characteristics, fly ash interaction, or initial SO<sub>2</sub> concentration. Evaluation of available data presents no clear indication of the specific reason for the reduced utilization observed for the Linwood PHL. Previous tests with similar coals had typically resulted in 35% to 40% utilization at a Ca/SO<sub>2</sub> mole ratio of ~2.0 (2).

TABLE 4

SULFUR DIOXIDE EMISSIONS, STOICHIOMETRIC RATIO,  
SULFUR REDUCTION, AND SORBENT UTILIZATION DATA

Coal/ Sorbent	SO <sub>2</sub> Emissions (ppm) <sup>a</sup>		Ca/SO <sub>2</sub> Mole Ratio <sup>b</sup>	SO <sub>2</sub> Reduction (%)	Sorbent Utilization (%)
	Baseline	Test			
<u>South Hallsville</u>					
---	1473	--	--	--	--
Linwood PHL	1153	558	1.75	51.6	29.5
Linwood PHL	1022	334	3.26	67.3	20.6
<u>Sarpy Creek</u>					
---	615	--	--	--	--
Linwood PHL	568	293	2.10	48.4	23.0
Linwood PHL	587	125	4.14	78.7	19.0
<u>Illinois #6</u>					
---	2591	--	--	--	--
Marblehead PHL	2633	1321	1.06	49.8	47.0
Marblehead PHL	2676	570	1.99	78.7	39.5

<sup>a</sup>All values presented on a 3% O<sub>2</sub> basis.

<sup>b</sup>Ratio based upon available SO<sub>2</sub> in flue gas.

## ESP PERFORMANCE

The interaction of fly ash/sorbent mixtures with respect to ESP performance was also examined. A summary of the ESP operating conditions and performance data are shown in Table 5. Under the conditions of the combustion tests, the ESP temperatures were variable and ranged from 497°F to 668°F, increasing with increasing ash loading. These temperatures would most closely represent "hot-side" ESP application where higher temperatures are used to exploit lower ash resistivity. The specific collection area ranged from 132-180 square feet/1000 cubic feet of flue gas, with treatment times varying from 2.9 to 3.9 seconds.

The effects of the sorbent contribution can be seen in Table 5 for the ESP dust loadings, the efficiency, and the bulk ash resistivity. For South Hallsville and Illinois #6 coals, the sorbent addition decreased ESP efficiency, and increased resistivity. When firing Sarpy Creek coal, sorbent addition increased ash resistivity, but only slightly decreased ESP efficiency. This observation was attributed to the lower initial fly ash resistivity, and also to the absolute dust loading. Since Sarpy Creek coal contained a lower level of sulfur, it also contained a lower sorbent concentration in the ash. From an operational standpoint, the Illinois #6 coal/sorbent ash produced the most ESP sparking and required the lowest operational potentials (25 KV).

Resistivity is one of the most important parameters for predicting ESP performance. It is well known that resistivity is directly proportional to the ash concentrations of calcium, magnesium, aluminum, and silicon and inversely proportional to moisture, sodium, potassium, carbon, and sulfur trioxide contents. In addition, temperature affects resistivity dramatically. Maximum ash resistivity usually occurs between 250°F and 450°F. Above the peak temperature, resistivity decreases with increasing temperature, while below the peak temperature resistivity increases with increasing temperature (6).

Figures 5, 6, and 7 present the plots of bulk ash resistivity as a function of temperature for each of the coal/sorbent combinations. Resistivities determined by the laboratory resistivity unit are not quantitative, but are good qualitatively for relative comparisons between samples analyzed on the same unit. The effect of increasing the calcium content of the ash on resistivity is evident from these graphs. It is interesting to note that not only does sorbent injection raise the resistivity curve, but also shifts the peak resistivity to a higher temperature, which could be of consequence for retrofit furnace injection applications.

## ASH DEPOSITION

The impact of furnace sorbent injection on ash deposition and deposit strength was also investigated. Table 6 shows the accumulated deposit weight, the deposition rate, and the relative fouling potential of coal ash and coal ash/sorbent mixtures. Also included for reference are the sorbent and coal feed rates, and the percent ash and sodium in the coal. The deposit weight

TABLE 5

## ESP OPERATING CONDITIONS AND PERFORMANCE DATA

	Sorbent Addition (lb/hr)	Theoretical Ash <sup>a</sup> (gr/SCF)	ESP Dust Loading		ESP		Ash Resistivity <sup>b</sup> (ohm-cm)	Flue Gas Moisture (%)
			Inlet (gr/SCF)	Outlet (gr/SCF)	Efficiency (%)	Temp. (°F)		
<u>South Hallsville:</u>								
1	0	7.86	2.6088	0.05854	97.8	497	$1.5 \times 10^{11}$	13.2
2	3.26	7.94	3.6664	0.4733	87.1	595	$5.5 \times 10^{12}$	15.4
3	5.41	8.96	3.8814	1.2701	67.3	610	$6.0 \times 10^{12}$	13.0
<u>Sarpy Creek:</u>								
1	0	5.70	2.6199	0.07671	97.1	532	$6.0 \times 10^9$	9.19
2	1.68	5.86	2.6882	0.1208	95.5	584	$6.0 \times 10^{11}$	8.66
3	3.67	6.89	3.3732	0.1690	95.0	553	$1.7 \times 10^{12}$	9.24
<u>Illinois #6:</u>								
1	0	4.30	1.6606	0.0677	95.9	571	$1.0 \times 10^{10}$	7.86
2	4.45	7.48	4.9553	0.7750	34.4	622	$1.0 \times 10^{13}$	7.48
3	8.60	9.26	6.5525	2.1512	67.2	668	$1.0 \times 10^{13}$	7.73

<sup>a</sup>Theoretical ash was calculated as 100% of the coal ash plus 100% of the injected sorbent. Injected sorbent was assumed to be CaO in the calculation.

<sup>b</sup>Ash resistivity at ESP operating temperature

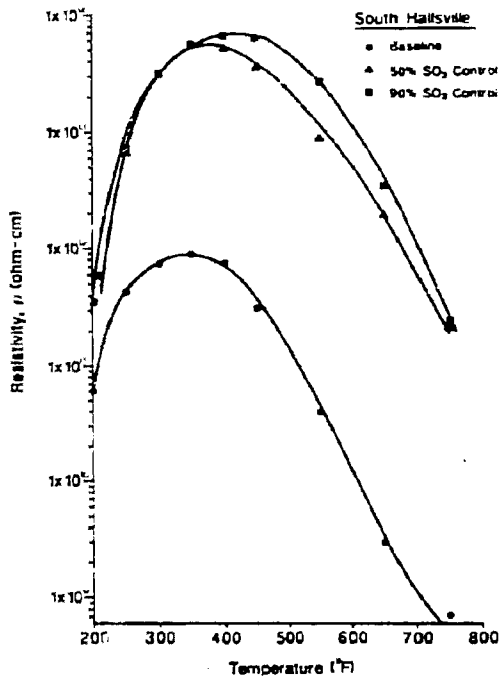


Figure 5. Resistivity as a function of temperature for South Hallsville ash with and without Linwood PHL injection.

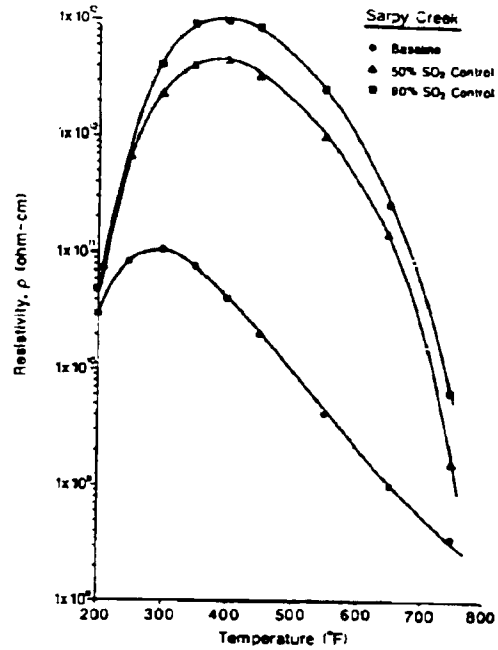


Figure 6. Resistivity as a function of temperature for Sarpy Creek ash with and without Linwood PHL injection.

Figure 7. Resistivity as a function of temperature for Illinois #6 ash with and without Marblehead PHL injection.

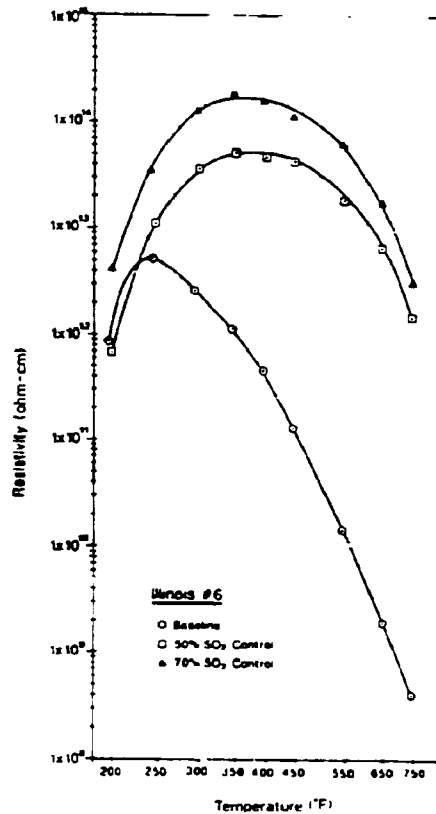


TABLE 6

DEPOSIT WEIGHT, DEPOSITION RATE, AND RELATIVE FOULING POTENTIAL  
OF COAL ASHES AND COAL ASH/SORBENT MIXTURES

<u>Coal/Sorbent</u>	<u>Sorbent Feed Rate (lb/hr)</u>	<u>Coal Feed Rate (lb/hr)</u>	<u>Ash in Coal (wt%)</u>	<u>Coal Ash Na<sub>2</sub>O (wt%)</u>	<u>Deposit Weight (g)</u>	<u>Deposition Rate<sup>b</sup> (g Ash/lb Theoretical Ash)</u>	<u>Relative Fouling Potential</u>
<u>South Hallsville:</u>							
---	0	86.82	12.0	0.0	12.0	0.22	Low
Linwood PHL	3.26	86.46	9.9	0.4	10.8 <sup>a</sup>	0.17	Low
Linwood PHL	5.41	86.34	9.5	0.5	200.0 <sup>a</sup>	3.17	Medium
<u>Sarpy Creek:</u>							
---	0	64.53	10.6	1.7	91.3	2.52	Low
Linwood PHL	1.68	60.18	10.0	1.1	114.3 <sup>a</sup>	2.83	Low
Linwood PHL	3.67	71.40	9.0	1.4	132.5 <sup>a</sup>	2.50	Low
<u>Illinois #6:</u>							
---	0	56.00	10.4	0.8	55.0 <sup>a</sup>	1.80	Low
Marblehead PHL	4.45	56.76	11.7	0.6	165.0 <sup>a</sup>	2.83	Medium
Marblehead PHL	8.60	57.14	11.8	0.0	163.2 <sup>a</sup>	2.03	Medium

<sup>a</sup>Deposits known to have sloughed and redeposited during test

<sup>b</sup>Includes sorbent

increased with sorbent addition to some extent, while the rate of deposition was variable. As noted in the table, the deposits sloughed off the probes at least once per test when sorbents were injected. These deposits were removed from the duct and weighed collectively as the best approximation. As stated previously, relative fouling potential was determined from coal ash deposit weights. Low to moderate fouling was indicated for all coal/sorbent combustion tests, when the weights of the sloughed deposits were included in the total. Whether adding sloughed deposits to the total deposit weight was appropriate could be argued, but in any event, it presents a worst case-scenario for evaluation.

The strength of deposits was determined using the drop impaction test. Table 7 summarizes the results of these tests as well as the subjective strength rating factor. Overall, the strengths of the deposits were weak with or without sorbent injection. The dust index and friability tended to increase with sorbent injection, while the mass median diameter decreased. These trends indicate a weakening of the deposit due to sorbent injection. The reversal of this trend shown with the tests performed on Illinois #6 deposits is difficult to interpret. One possible explanation is that when the deposits were sloughed into the duct, increased sintering may have occurred. A deposit sloughed early in the combustion test could show a higher degree of strength, because of the time dependency of sintering.

The simplest model for explaining the weakening of the deposits is related to the differences in particle history between the fly ash and the sorbent. The fly ash particles experience chemical reactions and blending before approaching the probes. The sorbent, being essentially pure CaO, is injected well above the flame as discrete particles. The sorbent particles, therefore, retain their high melting point when attaching to a developing deposit. The melting points for CaO and CaSO<sub>4</sub> are about 4570°F and 2640°F, respectively. These particles then bridge between fly ash particles of lower melting points, reducing the number of contact points for the fusion of additional fly ash particles. The distribution of sorbent in the fly ash would in effect appear to reduce the ability to solidify the deposit by mass fusion. Chemical reactions resulting in the scavenging of fluxing materials by the sorbents may also explain the weakening of deposits, although a combination of effects is most probable.

The strength rating factor is a subjective test performed by the operations personnel. This is their estimate of breakability and difficulty in removing the deposits from the probe bank. The majority of their observations supported a weak and/or easily removed deposit. Since the deposits are weak and not very tenacious, conventional soot blowing equipment should remove any deposits formed.



Table 6: Additional Species Concentrations (mg/kg) and pH Range  
in Extracts Obtained With Different Methods

--Continued--

Chemical "Species"	Texas Lignite				North Dakota Lignite			
	Flue Ash		Bottom Ash		Flue Ash		Bottom Ash	
	Hot H <sub>2</sub> O Extract	HNO <sub>3</sub> Extract	Hot H <sub>2</sub> O Extract	HNO <sub>3</sub> Extract	Hot H <sub>2</sub> O Extract	HNO <sub>3</sub> Extract	Hot H <sub>2</sub> O Extract	HNO <sub>3</sub> Extract
Molybdenum	3.68-5.12	11-19	<.2-1.0	<2-11	6.7-15.3	16-23	<.2-3.7	14-34
Nickel	<.2	18-79	<.2-1.9	5-61	<.2	30-39	<.2	37-490
Strontium	28.8-174.8	920-2380	3.9-53.2	360-1598	262.4-432	4120-5460	13.9-146	4000-4660
Zinc	<.2	7-85	<.2-.7	7-41	<.2	24-37	<.2	23-24
pH	10.8-11.6	N/A	4.33-10.5	N/A	11.8-12.1	N/A	10.7-11.7	N/A

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## CONCLUSIONS

Based upon the results of this preliminary investigation, the following conclusions and observations can be drawn:

1. Firing South Hallsville and Sarpy Creek coals required sorbent injection at a Ca/SO<sub>2</sub> mole ratio of approximately 2.0 to achieve 50% SO<sub>2</sub> control. Illinois #6 required a Ca/SO<sub>2</sub> mole ratio of 1.0 for the same level of control.
2. ESP efficiency decreased with sorbent injection due to increased dust loading and ash resistivity. Efficiency was least affected when firing Sarpy Creek coal due to lower ash resistivity and dust loadings.
3. Sorbent injection increased ash resistivity and shifted the peak resistivity temperature upward by ~100°F, from about 300°F to 400°F.
4. Sorbent injection increased probe ash deposition, but remained at a low to moderate level of fouling. Deposits were not very tenacious and sloughed continuously during sorbent injection.
5. The overall deposit strength tended to decrease with increasing levels of sorbent injection.

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## PERFORMANCE CHARACTERISTICS OF TEXAS LIGNITES IN AFBC

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### ABSTRACT

Tests were performed on UNDERC's 2.25 ft<sup>2</sup> AFBC assessing the operability and environmental performance for the AFBC of South Hallsville (Wilcox Group) and Gibbons Creek (Jackson Group) Texas lignites. Performance was characterized over a range of conditions--bed temperature (1450°, 1550°, and 1650°F), superficial gas velocity (3, 5, and 7 ft/sec), and expanded bed height (3 and 4 ft). Both silica sand and Paris, Texas limestone were used as bed materials. In addition, a 1000-hour test was completed on UNDERC's 0.44 ft<sup>2</sup> AFBC to assess corrosion/erosion potential of typical materials of construction for an AFBC boiler with the South Hallsville lignite.

The highest sulfur capture was obtained at 1450° for South Hallsville and for Gibbons Creek lignites. Sorbent addition at an alkali-to-sulfur ratio of 3.5 to 4.0 was required to meet 1979 NSPS. NO<sub>x</sub> emissions were below 1979 NSPS at all conditions tested. Combustion efficiency was as high as 99.8% for optimum test conditions. Baghouse collection efficiencies and particulate size distributions and resistivities were determined at various conditions. EP leachate testing on solid wastes resulted in all RCRA elements below established federal limits. Based on the results of the 1000-hour corrosion/erosion test; it is projected that metal loss rates for the stainless steels tested would be acceptable if the metal surface temperature is maintained below 1300°F; and less deposition, pitting, and sulfide attack would occur to tubes in the convective sections of the boiler compared to the tubes located in the bed and splash zone.

### INTRODUCTION

A large market potential for fluidized bed combustion (FBC) technology exists in Texas because of high industrial growth. Coal in the Gulf Coast Region is used extensively by utilities for producing electricity and by smaller industrial and commercial users for both steam and electricity. Although current combustion technology allows for utilization of this coal, several problems such as boiler tube fouling and slagging are inherent with the conventional technologies due to the high moisture and ash content of this coal. Fluidized bed combustion offers potential advantages such as reduced fouling, higher heat transfer rates, and lower emissions of gaseous pollutants (SO<sub>2</sub> and NO<sub>x</sub>) over other combustion technologies. However, the availability of operating experience and data on the performance of these coals in an AFBC is limited.

The objective of the Department of Energy funded research presented here is to broaden the current governmental and industrial data bases by performing tests on coals where data is lacking using FBC technology. In this paper, results will be presented from AFBC testing performed on two Texas lignites; from the Wilcox formation, South Hallsville mine and the Jackson seam, Gibbons Creek formation.

## **TECHNICAL APPROACH**

### **Test Matrix**

To fully characterize Texas lignites in AFBC, testing was performed over a full range of operating conditions that are expected when using the characteristic methods of turndown. Tests were performed at bed temperatures ranging from 1450 to 1650 F, velocities from 3 to 7 ft/sec, and fluidized bed depths from 2 to 4 ft. To characterize the effect of the inherent coal properties and of the limestone on combustor performance, tests were performed using a silica sand bed, a silica sand bed with ash recycle, a limestone bed, and a limestone bed with ash recycle. Parameters were varied in accordance with the test matrix presented in Table 1. Data was analyzed to determine the effects of these variables on sulfur dioxide, nitrogen oxides, and particulate emissions, combustion efficiencies, and solid waste characteristics. Limestone from Paris, Texas was used as sorbent. The typical range of properties for the coal and limestone used during the testing are presented in Table 2.

In addition to the parametric testing, a test 1000 hours in duration was performed using the South Hallsville lignite to determine the corrosive and/or erosive potential of this coal. This test was performed at a bed temperature of 1550°F, velocity of 8 ft/sec, excess air level of 30%, and Paris limestone addition at a rate to control SO<sub>2</sub> emissions within NSPS.

### **Facilities Description**

Parametric testing for emissions and operability characterization was performed using UNDERC's 2.25 ft<sup>2</sup> AFBC system shown schematically in Figure 1. The AFBC facility consists of a refractory lined steel shell combustor, 18" x 18" inside dimensions; a forced draft fan, a flue gas heat exchanger, and a natural gas-fired preheater which provides combustion air and fluidizes the bed; a screw feed system for injecting coal and sorbent and, a pneumatic ash injection system; a flue gas system consisting of two cyclones, two heat exchanger, and a baghouse; and a sampling system capable of measuring and recording flue gas O<sub>2</sub>, CO<sub>2</sub>, CO, NO<sub>x</sub>, SO<sub>2</sub>, and concentrations. A more detailed description of the test system has been presented previously (1).

The 1000-hour corrosion/erosion test was performed on UNDERC's 8" x 8" AFBC test facility. This system is similar in design to the larger unit. Differences include an electrical preheater rather than natural gas-fired, only one cyclone in the flue gas system, and reduced flue gas sampling capabilities consisting of O<sub>2</sub>, CO, and CO<sub>2</sub>. To facilitate corrosion/erosion measurements, this unit is equipped with 29 horizontally oriented tubes distributed throughout the bed, splash zone, and convective pass and coupon samples located in the bed and splash zone to simulate water walls. These

TABLE 1

## TEST MATRIX FOR CHARACTERIZATION TESTS

Coal Size	-1/4"		
Coal Feeding Method	Underbed Screw Feed		
Bed Material Type and Size	No. 10 Silica Sand		
Excess Air Level	20 5%		
Sorbent Size	-8 x +20 mesh		
Sorbent Feed Rate	Variable to meet 1979 NSPS		
Ash Reinjection	50% of coal feed rate		
Static Bed Height	2.9 ft tests A-1, 2.1 ft tests J-R		
<u>Run No.</u>	<u>Coal</u>	<u>Limestone</u>	<u>Ash Reinjection</u>
GC1	Gibbons Creek	None	No
GC2	Gibbons Creek	None	Yes
GC3	Gibbons Creek	Paris	No
GC4	Gibbons Creek	Paris	Yes
SH1	South Hallsville	None	No
SH2	South Hallsville	None	Yes
<u>Period</u>	<u>Temperature (°F)</u>	<u>Velocity (ft/s)</u>	
A/J	1450±5	3.0±0.2	
B/K	1450±5	5.0±0.2	
C/L	1450±5	7.0±0.2	
D/M	1550±5	3.0±0.2	
E/N	1550±5	5.0±0.2	
F/O	1550±5	7.0±0.2	
G/P	1650±5	3.0±0.2	
H/Q	1650±5	5.0±0.2	
I/R	1650±5	7.0±0.2	

tubes and coupons are either air-, water-, or non-cooled to provide a variety of surface temperatures ranging from 250 to 1550°F. Metallurgies used include type 304, 310, 316, and 347 austenitic stainless steels, type AS192 carbon steel, and Incoloy alloy 800. Figures 2 and 3 present a schematic of the AFBC. Details on the system and the operating procedures are presented elsewhere (2).

TABLE 2  
COAL, ASH AND LIMESTONE ANALYSIS

	Gibbons Creek		South Halleville 1		South Halleville 2 <sup>b</sup>		Paris, Texas
	<u>Average</u>	<u>Range</u>	<u>Average</u>	<u>Range</u>	<u>Average</u>	<u>Range</u>	<u>Limestone<sup>c</sup></u> <u>Average</u>
<u>Proximate Analysis, dry, %:</u>							
Moisture, <sup>a</sup>	32.9	30.70-34.20	26.1	23.1-28.8	32.4	28.4-34.0	--
Volatile Matter	37.0	36.75-37.32	41.3	40.0-44.3	43.2	41.2-45.0	--
Fixed Carbon	25.1	24.13-25.90	45.3	44.4-46.9	42.2	38.8-44.9	--
Ash	36.9	36.78-39.13	13.4	11.2-15.6	14.6	10.6-19.0	--
Heating Value, Btu	7491	7317-7646	10355	9996-10558	10643	9957-11273	--
<u>Ultimate Analysis, %:</u>							
Hydrogen	3.83	3.57-3.98	2.29	2.02-2.53	4.68	4.33-4.97	--
Carbon	41.89	40.95-42.79	66.72	62.41-70/75	61.16	57.64-63.96	--
Nitrogen	0.64	0.60-0.65	1.33	1.19-1.47	1.05	0.48-1.21	--
Sulfur	2.17	2.01-2.49	1.42	1.27-1.56	1.44	1.22-1.75	--
Oxygen	13.56	13.35-13.88	14.83	11.84-18.39	17.04	15.49-18.13	--
Ash	37.91	36.78-39.13	13.40	11.2-15.6	14.63	10.6-19.0	--
<u>Coal Ash, %:</u>							
SiO <sub>2</sub>	62.0	61.4-63.0	33.0	28.8-36.6	38.0	29.5-45-3	2.7
Al <sub>2</sub> O <sub>3</sub>	18.5	17.9-18.9	12.3	11.1-12.8	16.0	14.4-17.2	0.4
Fe <sub>2</sub> O <sub>3</sub>	3.6	3.3-3.9	33.8	21.6-25.4	12.0	9.7-15.1	0.5
TiO <sub>2</sub>	1.0	1.0-1.4	1.4	1.3-1.4	1.2	1.1-1.3	--
P <sub>2</sub> O <sub>5</sub>	0.2	0.2-0.3	0.4	0.3-0.6	0.5	0.3-0.7	--
CaO	6.2	5.9-6.5	11.2	9.0-14.0	13.0	9.1-18.0	55.1
MgO	1.4	1.4-1.4	3.3	2.8-3.9	3.4	2.6-4.3	0.3
Na <sub>2</sub> O	0.5	0.2-0.7	0.1	0.0-0.7	0.2	0.0-0.5	0.0
K <sub>2</sub> O	0.8	0.8-0.8	0.4	0.3-0.5	0.9	0.5-1.1	--
SO <sub>3</sub>	5.9	4.6-6.5	14.3	11.3-17.8	14.8	11.0-19.5	0.1
Ca/S (Molar Ratio)	0.618	0.546-0.655	0.602	0.535-0.645	0.753	0.569-0.894	--
Na/S (Molar Ratio)	0.045	0.014-0.063	0.006	0.000-0.029	0.010	0.000-0.025	--

<sup>a</sup>Values taken from as-fired samples. As-mined moisture levels can be significantly higher.

<sup>b</sup>Two different samples from the South Halleville mine were tested.

<sup>c</sup>Moisture and loss-on-ignition for Paris limestone was 40.0%.

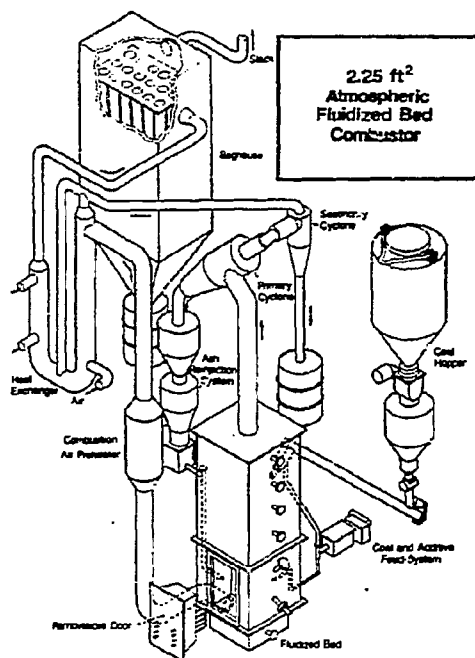


Figure 1. Isometric View of UNDERC's 2.25 ft<sup>2</sup> Pilot-Scale AFBC.

## RESULTS

Summaries of selected data points from parametric testing of the Texas lignites are presented as Tables 3 and 4. The data has been analyzed using regression analysis to determine the effects of the main parameters and the performance characteristics of the AFBC. The regression equations and plots of the data follow for the main variables studied.

### Sulfur Emissions

Tests were performed with two different samples of South Hallsville coal. Both sets of tests were performed with an inert bed material without ash recycle or sorbent addition. Sulfur retention appeared to be extremely variable during both sets of tests. Retentions determined ranged from 39% to less than 0%, with sulfur retentions varying inversely with temperature. The large variability in the calculated retentions and the negative values are probably due to the high variability within the coal samples. Large differences were seen in the sulfur, calcium, and ash content of the South Hallsville coal.

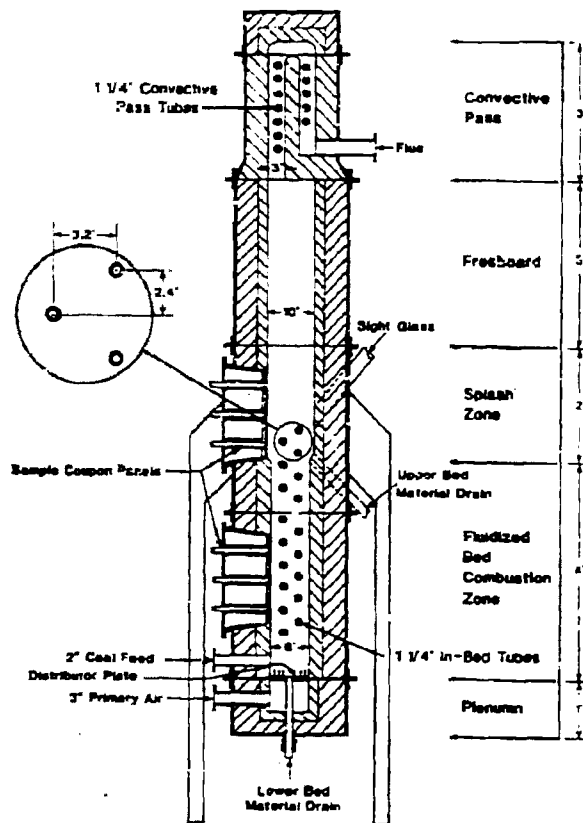


Figure 2. Cross Sectional View of 0.44 ft<sup>2</sup> AFBC

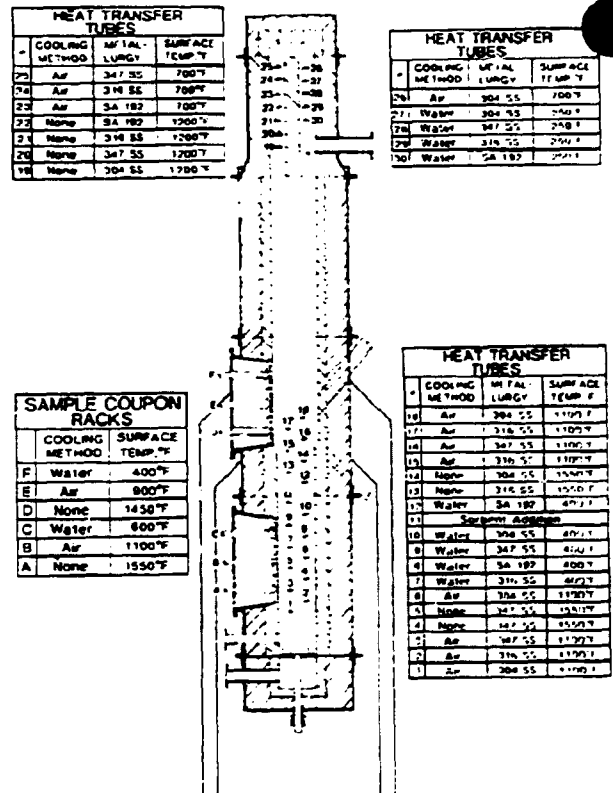


Figure 3. Metallurgies and Approximate Operational Metal Surface Temperatures of Heat Transfer Tubes and Sample Coupons.

Using Gibbons Creek lignite, sulfur retentions ranged from 5 to 15% with an inert bed. The lowest retentions occurred at the highest bed temperature, 1650°F. The NSPS require approximately 90% sulfur retention when burning Gibbons Creek lignite. Testing with sorbent addition indicated that substantial amounts of limestone (added alkali-to-sulfur of at least 3.7) are necessary to obtain 90% retention. No significant change in sorbent utilization or sulfur capture was noted when primary cyclone ash was recycled in addition to adding sorbent.

The most important operational parameters on sulfur retention are bed temperature and alkali-to-sulfur ratio. Sulfur retention as predicted by equation 3 is plotted as a function of bed temperature in Figure 4. The plotted data show no optimum (peak) temperature for sulfur capture. This indicates that the optimum temperature for sulfur capture for the Texas lignites tested is less than 1450°F.



TABLE 3

## SUMMARY OF TEST CONDITIONS AND RESULTS FROM FCC TESTING OF GIBBONS CREEK, TEXAS LIGNITE

Bed Temp °F	Freeboard Temp °F	Gas Velocity fps	Excess Air %	Bed Depth ft	Coal Feed pph	Coal Feed 3tu/hr	Alkali-to-Sulfur Ratio	Sulfur Retention %	Comb Sulfur Emission Lb/MMBtu	NO <sub>x</sub> Emissions Lb/MMBtu	Overall Heat Transfer Coef BTU/Hr-Ft <sup>2</sup>	Carbon Monoxide Conc %
<u>3-GC1-0785</u>												
1449	1534	2.9	19.1	2.1	110.4	807797	0.68	12.2	5.05	0.16	45.2	0.010
1451	1541	4.9	20.4	2.1	183.6	1343401	0.68	14.8	4.91	0.18	44.4	0.020
1451	1540	6.7	19.0	2.1	237.7	1739251	0.68	15.2	4.88	0.21	43.3	0.020
1550	1605	2.9	18.8	2.1	100.9	738285	0.68	10.2	5.17	0.22	45.7	0.010
1551	1620	4.9	17.9	2.1	169.1	1237305	0.68	13.1	5.00	0.23	45.0	0.010
1548	1620	6.7	20.1	2.1	253.5	1855079	0.68	13.6	5.13	0.27	46.3	0.010
1651	1698	3.0	18.9	2.1	109.9	804138	0.68	5.1	5.46	0.25	48.9	0.010
1650	1702	5.1	19.7	2.1	168.9	1235696	0.68	8.3	5.28	0.29	49.6	0.000
1650	1713	6.7	19.6	2.1	228.6	1672666	0.68	8.6	5.26	0.31	48.9	0.010
<u>3-GC2-0886</u>												
1451	1551	3.1	20.1	2.1	131.2	973898	0.72	14.4	4.84	0.16	44.3	0.010
1453	1548	5.1	19.4	2.1	191.7	1422889	0.72	20.1	4.51	0.16	42.9	0.021
1450	1531	6.9	18.6	2.1	245.7	1823831	0.72	17.4	4.62	0.19	45.3	0.030
1552	1597	2.9	19.8	2.1	123.6	917483	0.72	10.1	5.07	0.20	51.9	0.010
1552	1611	4.9	22.2	2.1	172.3	1278983	0.72	18.8	4.54	0.25	48.5	0.010
1549	1611	6.7	21.0	2.1	216.0	1603368	0.72	11.4	4.95	0.23	47.1	0.010
1651	1695	2.9	18.6	2.1	117.4	871460	0.72	13.5	4.84	0.24	54.1	0.010
1650	1691	4.9	20.6	2.1	143.3	1063716	0.72	-6.3	5.95	10.30	50.8	0.000
1652	1696	6.9	18.4	2.1	218.4	1621183	0.72	2.9	5.75	0.29	50.8	0.010
<u>3-GC3-0986</u>												
1451	1531	3.0	18.6	2.1	108.7	831120	5.44	90.2	0.64	0.12	51.0	0.020
1450	1523	4.9	18.7	2.1	183.0	1399218	5.87	91.0	0.58	0.21	43.9	0.020
1449	1527	6.8	20.4	2.1	258.6	1977256	5.64	90.6	0.61	0.27	41.6	0.020
1552	1581	3.0	21.0	2.1	107.2	819651	4.38	91.9	0.53	0.27	48.5	0.010
1547	1596	5.0	19.4	2.1	180.9	1383161	5.43	91.4	0.56	0.28	44.8	0.010
1549	1603	7.0	20.6	2.1	237.7	1817454	5.06	90.2	0.64	0.32	45.1	5.222
1651	1657	3.1	20.2	2.1	101.8	778363	9.58	91.0	0.68	0.35	48.0	0.010
1647	1678	4.8	17.4	2.1	164.2	1255473	9.10	92.1	0.51	0.36	47.0	0.010
1651	1690	6.9	21.0	2.1	229.5	1754757	9.57	91.9	0.53	0.37	44.5	0.010
<u>3-GC4-1086</u>												
1448	1509	3.0	20.4	2.1	121.0	917059	4.81	88.0	0.64	0.13	49.9	0.020
1449	1506	5.1	19.7	2.1	196.4	1488516	4.40	88.6	0.60	0.21	43.9	0.020
1450	1513	6.9	19.9	2.1	268.2	2032688	4.57	88.5	0.61	0.21	43.0	0.030
1552	1565	3.1	18.5	2.1	112.9	855669	6.16	90.0	0.53	0.26	48.2	0.010
1551	1588	5.0	19.6	2.1	173.8	1317230	5.69	90.1	0.52	0.26	46.8	0.020
1550	1595	7.1	20.4	2.1	273.9	2075888	4.28	89.8	0.54	0.28	44.3	0.010
1652	1664	3.0	18.7	2.1	114.1	864764	8.94	89.9	0.53	0.27	50.1	0.010
1649	1676	5.0	19.5	2.1	169.5	1284641	7.81	89.2	0.57	0.28	47.5	0.010
1652	1679	7.1	21.1	2.1	231.2	1752255	6.92	89.7	0.55	0.40	44.6	0.010

## Nomenclature for Regression Equations:

T = (bed temperature (°F) - 1550)/100

V = (Velocity (fps) - 5)/2

D = (static bed depth (ft) - 2.5) / 0.4

A = (alkali/sulfur - 3.5) / 3

R = -1 for no ash recycles, +1 for 50% ash reinjection

SR = sulfur retention, pct sulfur in feed coal retained in the bed

NO<sub>x</sub> = NO<sub>x</sub> emissions, lb/MMBtu

CEEF = combustion efficiency, pct

TABLE 4

## SUMMARY OF TEST CONDITIONS AND RESULTS FROM FCC TESTING OF SOUTH HALLSVILLE, TEXAS LIGNITE

Test No.	Bed Temp., °F	Free board Temp., °F	Gas Velocity, fps	Excess Air, %	Bed Depth, ft	Coal Feed, tph	Coal Feed, Btu/hr	Alkali-To-Sulfur Molar Ratio	Sulfur Retention, %	Comb Sulfur Emission, Lb/Mbtu	No Emissions, Lb/Mbtu	Overall Heat Transfer Coef., Btu/Hr-Ft <sup>2</sup> -°F	Carbon Monoxide Conc., %
Run FB2-SH1-0685													
A	1649	1648	4.0	23.5	2.9	--	--	0.61	21.8	2.14	0.37	54.9	0.021
B	1651	1705	6.1	19.7	2.9	--	--	0.61	21.8	2.14	0.35	51.8	0.071
C	1651	1686	6.6	22.2	2.9	--	--	0.61	9.0	2.49	0.31	53.8	0.061
D	1554	1635	3.2	18.6	2.9	--	--	0.61	19.2	2.21	0.28	56.0	0.021
E	1554	1574	5.0	20.6	2.9	--	--	0.61	17.7	2.25	0.33	53.1	0.031
F	1553	1613	7.0	18.7	2.9	--	--	0.61	24.5	2.07	0.33	51.1	0.410
G	1452	1550	3.2	18.1	2.9	--	--	0.61	23.1	2.10	0.30	53.2	0.021
H	1451	1528	5.1	19.6	2.9	--	--	0.61	14.4	2.34	0.30	41.1	0.011
I	1447	1538	7.0	16.8	2.9	--	--	0.61	25.6	2.04	0.27	48.3	0.061
J	1655	1740	3.1	20.2	2.1	--	--	0.61	14.5	2.34	0.32	54.5	0.000
K	1652	1717	4.9	20.5	2.1	--	--	0.61	19.2	2.21	0.35	53.3	0.000
L	1653	1711	6.8	19.8	2.1	--	--	0.61	14.6	2.34	0.36	52.1	0.021
M	1556	1691	5.1	20.8	2.1	--	--	0.61	20.8	2.17	0.30	55.6	0.000
N	1549	1667	5.0	19.4	2.1	--	--	0.61	23.0	2.11	0.32	52.3	0.002
O	1554	1622	7.0	18.9	2.1	--	--	0.61	16.3	2.29	0.31	50.7	0.011
P	1451	1577	3.1	18.9	2.1	--	--	0.61	21.5	2.15	0.28	50.6	0.000
Q	1450	1549	5.0	19.6	2.1	--	--	0.61	15.0	2.33	0.29	49.4	0.011
R	1450	1545	6.9	20.2	2.1	--	--	0.61	23.1	2.11	0.25	48.2	0.021
Run FB2-SH2-0186													
A	1653	1675	2.8	17.1	2.8	86.9	925302	0.76	-1.4	2.74	0.32	44.2	0.010
B	1658	1696	5.0	22.2	2.8	122.4	1302277	0.76	-4.3	2.82	0.37	47.3	0.010
C	1653	1700	6.8	18.7	2.8	176.7	1880618	0.76	-5.2	2.84	0.36	51.7	0.010
D	1550	1625	3.2	20.8	2.9	93.2	992034	0.76	2.9	2.62	0.34	48.8	0.010
E	1550	1614	5.2	20.0	2.7	127.0	1351980	0.76	30.4	1.88	0.29	48.7	0.010
F	1553	1616	6.9	19.7	2.8	162.7	1731510	0.76	0.6	2.68	0.35	50.5	0.010
G	1454	1544	3.1	18.0	2.8	98.7	1050890	0.76	38.6	1.66	0.32	45.0	0.010
H	1451	1542	4.8	19.6	2.9	128.1	1363368	0.76	37.2	1.70	0.28	47.4	0.020
I	1445	1532	6.9	17.5	2.7	182.2	1939580	0.76	10.4	2.42	0.30	56.9	0.020
J	1653	1761	3.1	20.8	2.1	96.2	1023431	0.76	-15.1	3.11	0.31	44.1	0.010
K	1645	1767	5.0	16.9	2.1	135.0	1437124	0.76	-10.2	2.98	0.28	52.3	0.010
L	1649	1716	6.8	20.7	2.1	169.5	1804201	0.76	1.4	2.66	0.35	48.0	0.010
M	1553	1705	3.2	19.7	2.2	95.9	1020132	0.76	2.8	2.62	0.29	48.2	0.010
N	1551	1685	5.0	20.4	2.3	149.3	1589319	0.76	-9.2	2.95	0.33	47.8	0.010
O	1551	1645	6.9	20.0	2.1	172.6	1836982	0.76	15.5	2.28	0.32	47.6	0.010
P	1450	1666	3.1	18.9	2.1	109.5	116551	0.76	-1.2	2.73	0.23	44.4	0.010
Q	1449	1588	5.3	19.7	2.3	146.7	1560796	0.76	19.8	2.17	0.31	46.8	0.010
R	1450	1592	6.7	20.8	2.2	173.2	1843261	0.76	6.9	2.52	0.30	45.9	0.010

Test data was analyzed using multiple regression analysis to determine the effects of the main operating parameters on the retention of sulfur. The following equations were found to best fit the data at a 90% confidence level:

$$SR (SH1) = 19.2 - 1.8 T \quad (1)$$

$$SR (SH2) = 6.78 - 11.7 T + 5.7 D - 7.1 VD \quad (2)$$

$$SR (GC) = 61.5 - 3.3T + 45.2A - 2.8T2 - 18.3A2 - 2.7TR \quad (3)$$

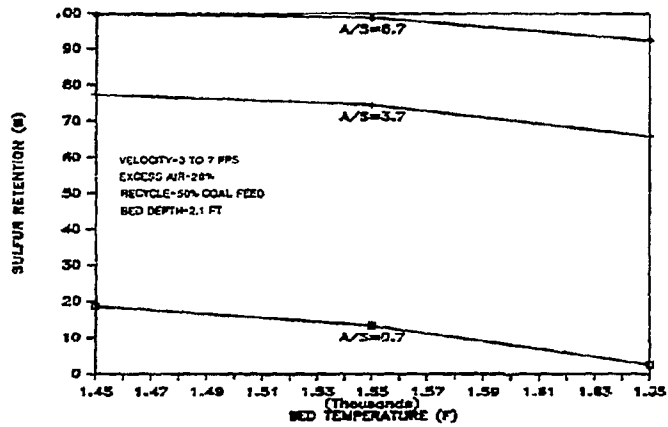


Figure 4. Sulfur Retention as a Function of Temperature at Various A/S Ratios When Burning Gibbons Creek Lignite.

Figures 4 and 5 show the effect of the added sorbent on sulfur capture. As can be seen from these figures, the effect of the alkali-to-sulfur ratio is the dominate factor determining sulfur capture. With the lignites tested, alkali must be added to achieve NSPS of 90% sulfur retention. For example, at optimal conditions for sulfur capture using the Gibbons Creek lignite, sorbent must be added at a rate of approximately 17% of the coal feed rate. This equates to an added alkali-to-sulfur ratio of 3.7. The sorbent add rates needed to meet NSPS will increase with temperature.

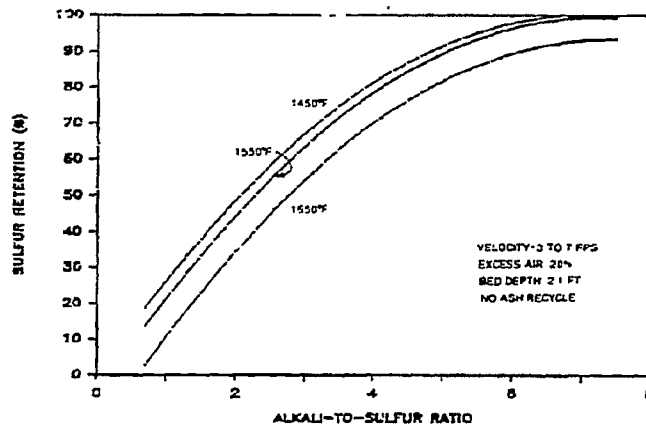


Figure 5. Sulfur Retention as a Function of A/S Ratio at Various Bed Temperatures When Burning Gibbons Creek Lignite.

Other factors that were found to impact the sulfur retention included bed depth, ash recycle, and velocity. Sulfur retention was found to vary directly with bed depth and inversely with velocity. Velocity had less of an effect at the higher bed depth. Ash recycle also improved the sulfur capture, with the largest effect noticed at the lower bed temperatures. The effect of each of these variables was minimal when compared to alkali-to-sulfur and temperature.

### Nitrous Oxides Emissions

Under the conditions tested,  $\text{NO}_x$  emissions ranged from 0.12 to 0.40 lb/MMBtu, well below the 1979 NSPS of 0.6 lb/MMBtu in spite of the small combustor size which favors higher  $\text{NO}_x$  emissions. The  $\text{NO}_x$  emission level for the two lignites tested is best represented by the following equations:

$$\text{NO}_x (\text{SH1}) = 0.325 + 0.029T - 0.023V^2 \quad (4)$$

$$\text{NO}_x (\text{SH2}) = 0.314 + 0.022T + 0.016V + 0.016D - 0.011VD \quad (5)$$

$$\text{NO}_x (\text{GC}) = 0.261 + 0.033V + 0.020A - 0.010R - 0.014T^2 - 0.055TD \quad (6)$$

The two main effects apparent from the data are the temperature and velocity effects. Figure 6 plots  $\text{NO}_x$  emissions as a function of bed temperature at three different velocities for the data generated from the the Gibbons Creek lignite.  $\text{NO}_x$  emissions are plotted as a function of velocity at three different bed temperatures for the second South Hallsville lignite sample in Figure 7. In all cases, the trends observed were basically the same with  $\text{NO}_x$  emissions increased with increasing temperatures.

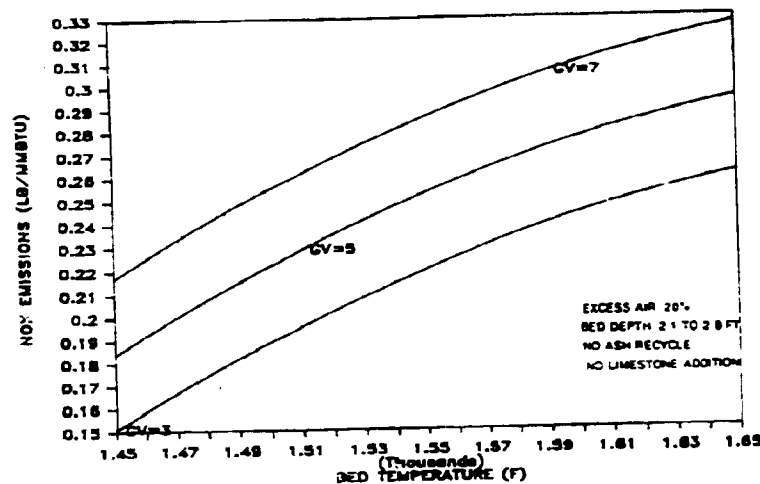


Figure 6.  $\text{NO}_x$  Emissions as a Function of Bed Temperature at Various Gas Velocities When Burning Gibbons Creek Lignite.

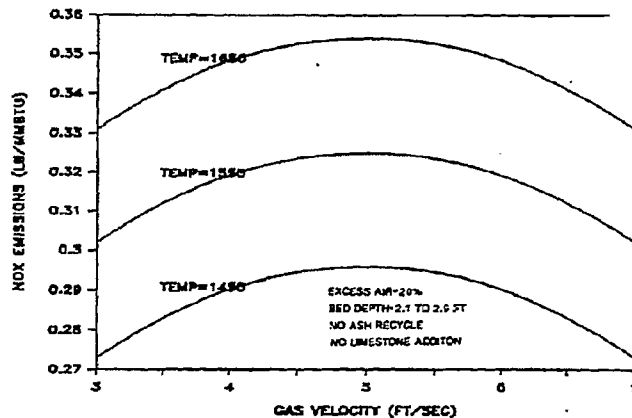


Figure 7. NO<sub>x</sub> Emissions as a Function of Gas Velocity at Various Bed Temperatures When Burning South Hallsville Lignite.

Emissions increased with increasing velocity for the tests with the Gibbons Creek lignite. With the South Hallsville lignite, the rate of NO<sub>x</sub> emissions first increased with velocity, and then decreased. The change in NO<sub>x</sub> emission level with velocity is related to the change in gas residence time. Correlations between gas in-bed residence times and NO<sub>x</sub> emissions have been reported by other investigators (3). The reduction in NO<sub>x</sub> emissions with longer residence times (lower velocities) is attributed to the increasing reaction of NO<sub>x</sub> and char or carbon monoxide. Other investigators have observed that NO<sub>x</sub> emissions will first increase and then decrease with an increase in gas velocity at constant bed depth, indicating that NO formation-decomposition mechanisms and/or rate-determining steps change with temperature (4). This relationship is evident with the current data.

The inorganic nitrogen contained in the bed material and sorbent additives is low and should contribute only minimally to the NO<sub>x</sub> emissions. However, the extent to which bed material and additives are important is not fully understood at the present time. Current data indicate that the presence of limestone sorbent may have a small effect on the emissions of NO<sub>x</sub>. The potential cause for this change is not known. The data also indicate the use of ash recycle will reduce NO<sub>x</sub> emissions. This may be due to the presence of more char for NO<sub>x</sub> reduction reactions in the case of ash recycle as compared to without recycle.

It should be noted that the quantity of NO<sub>x</sub> detected emitting from combustion systems is also dependent on the individual systems. Small units have larger surface-to-volume ratios than larger units which results in a larger percentage of the heat content of the gases being transferred from the system through the walls. The higher heat loss in smaller units lowers the temperature of the system more rapidly, causing the system to freeze NO<sub>x</sub> emissions at a greater level than generally found in larger units. Also, differences in fluid dynamics, local stoichiometry, and mass transfer effects in various size units may account for higher NO<sub>x</sub> emissions in smaller units (5). This must be taken into account when interpreting the current data.

## CO Emissions and Combustion Efficiency

The concentration of CO in the flue gas was continuously monitored using an infrared absorption analyzer. The emissions of CO for the Texas lignites tested are given in Tables 3 and 4, and are less than 300 ppm for all conditions tested.

Combustion efficiencies were determined for coal by the input-output method (1). This method of calculation determines the difference between the ratio of incompletely-combusted carbon in the product and that of the carbon content of the feedstream and assumes that gaseous products contribute little to any inefficiency. Using this method, the overall efficiency for the South Hallsville lignite was determined to be 99.2%. This very high efficiency is characteristic of most low-rank coals and was obtained without ash recycle. Combustion efficiencies were not determined as a function of operational parameters during the South Hallsville testing.

Combustion efficiency data was collected for individual test periods with the Gibbons Creek lignite. Efficiencies ranges from 91.0% to 99.8%, and is best represented by the following equation:

$$CEEF (GC) = 97.64 - 0.68V - 1.56A + 0.45R + 0.55TV + 0.60TA - 0.48VA \quad (7)$$

Examination of Equation 7 shows combustion efficiency to generally decrease with decreasing bed temperature, increasing gas velocity, and increasing alkali-to-sulfur ratio. The effects of bed temperature and velocity are graphically displayed in Figure 8. The effect of velocity decreased as the temperature approached 1650°F. The effect of ash recycle on efficiency was significant.

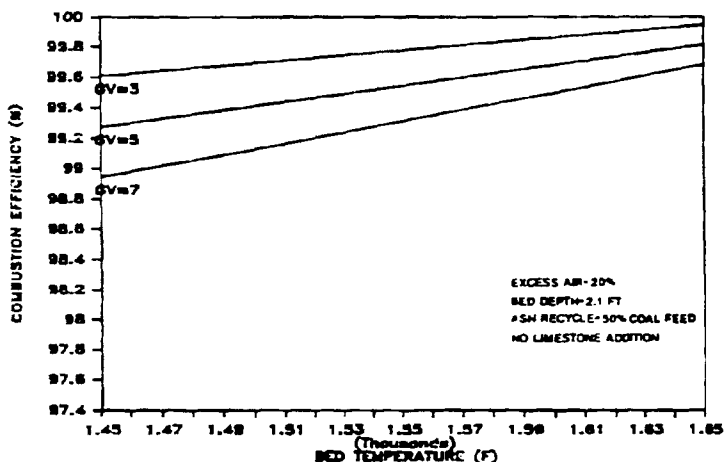


Figure 8. Combustion Efficiency as a Function of Temperature at Various Gas Velocities When Burning Gibbons Creek Lignite.

As indicated by the regression Equation 7, alkali-to-sulfur (A) is significant for the range of data presented. The significance of the alkali-to-sulfur ratio is thought to be a result of the method of determining combustion efficiency. Apparently uncalcined limestone ( $\text{CaCO}_3$ ) is being elutriated into the primary cyclone during limestone addition tests. The presence of  $\text{CaCO}_3$  in this ash "artificially" decreases the calculated combustion efficiency. The decrease in combustion efficiency is especially apparent at high velocities and high alkali-to-sulfur ratios.

#### Particulate Characterization

There is little practical experience on the performance of particulate control devices when collecting particulates generated by an AFBC system. As a part of the testing reported here, the AFBC fly ashes were characterized in order to determine their collectability by either fabric bag filter or electrostatic precipitator (ESP).

Particulate collection is accomplished by first removing entrained overbed material and other large-sized particles using a two cyclones in series. Finer particles are removed by a pulse jet baghouse that uses eighteen 6-inch diameter bags which are 108 inches in length. Under normal operating conditions the air-to-cloth ratio is between 1.5 and 2.0. The baghouse is designed to provide high efficiencies over a wide range of conditions.

EPA Method 5 was used to determine the inlet dust loadings prior to the cyclones and the dust loading at the outlet of the baghouse. A flow sensor multicyclone was used to provide particle size distribution and particulate loading data at the inlet to the baghouse after the cyclone. A laser aerodynamic particle sizer (APS) was also used at the inlet and outlet of the baghouse to provide particle size distribution data and fractional collection efficiencies. The APS is a real-time particle sizer that measures particle sizes in the range of 0.5 to 15 microns. Results of these measurements from the test using Gibbons Creek lignite are presented in Table 5.

TABLE 5  
RESULTS FROM PARTICULATE CHARACTERIZATION

Test	Loadings in gr/scf				
	Cyclone Inlet	Baghouse Inlet	Baghouse Outlet	Cyclone Efficiency	Baghouse Efficiency
Baseline (Silica Sand Bed)	28.7435	2.4436	0.1760	91.5%	92.8%
Ash Recycle	50.0437	2.3985	0.1702	95.2%	92.9%
Limestone Addition	47.5618	0.4558	0.0136	99.0%	97.0%
Limestone Addition & Ash Recycle	95.3513	1.1293	0.0672	98.8%	94.1%

Several different trends are noted from this data. As expected, the particulate loadings from the combustor (cyclone inlet) increase with the use of ash recycle and limestone addition. Ash recycle caused a doubling of particulate loading in both the baseline case and the case with limestone. Limestone addition also doubled the particulate loading from the combustor. The addition of ash to the system through recycle means more is available for elutriation, increasing the particulate loading. When limestone is added to the system, some attrition of the limestone is expected and its elutriation will increase the loadings from the combustor as the data indicate.

The trend that is of particular interest is the difference in efficiencies of the collection devices for the runs with and without limestone addition. In both the cyclone and the baghouse, efficiencies were higher for the tests with limestone addition. For the cases with and without ash recycle, the addition of limestone meant a doubling of the particulates being generated from the combustor, while the outlet from the baghouse has loadings almost an order of magnitude less for the tests with limestone addition when compared to similar tests without limestone addition. This may be due to agglomeration of the fine particles by the addition of limestone, although the multicyclones did not show any major differences in the particle size distribution at the inlet to the baghouse with limestone addition. The very low efficiencies for the Gibbons Creek runs are not unexpected when considering the low Na<sub>2</sub>O content in the coal ash, 0.5%.

Laboratory resistivity measurements were made on composite samples of fly ash collected by the baghouse during each of the runs made for each coal. Bulk ash electrical resistivity measurements were made with an apparatus which was designed and built according to the American Society of Mechanical Engineers (ASME) Power Test Code 28 and provides control of temperature and gas environment for the samples being tested. These resistivity measurements will be useful in evaluating the effectiveness of ESP systems to collect AFBC generated particles.

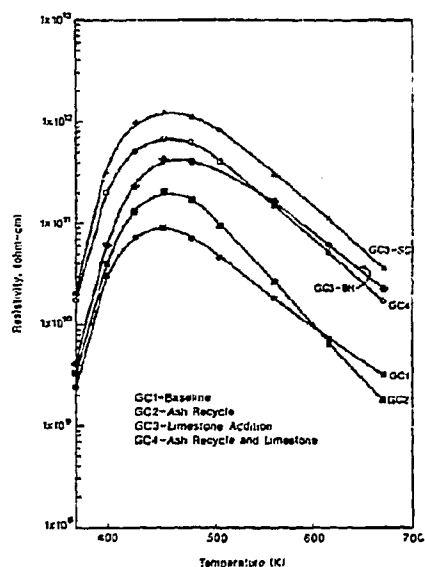
Resistivity curves generated from baghouse and secondary cyclone ash samples collected from the Gibbons Creek lignite runs are shown in Figure 9. A wide range of values is seen in the figure, with peak resistivities ranging from  $9 \times 10^{10}$  to  $1 \times 10^{12}$  ohm-cm. The resistivity curves indicate that the use of ash recycle and limestone addition significantly increase the resistivity of the fly ashes. This is particularly true in the temperature range where peak resistivities are occurring, 300 to 400°F. The difference in the resistivity curves is greatly reduced between 250 and 300°F, temperatures at which conventional ESP's are normally operated. The resistivity values in this lower temperature range are also substantially reduced from the peak values.

The differences in the resistivity curves are due to differences in the composition of the fly ash samples. Analyses of the bulk Gibbons Creek samples show higher concentration of CaO in the fly ash for runs with limestone addition. Little difference is seen between the runs with and without recycle, with possibly one exception. The SO<sub>3</sub> content of the ashes collected during runs with ash recycle are somewhat lower than runs without ash recycle. Resistivity is known to increase with increasing CaO and decreasing SO<sub>3</sub> content. Current data conform to these trends.



Data in Figure 9 also show a higher resistivity for ash collected in the secondary cyclone as compared to the baghouse ash. This is due to the higher CaO level (limestone) in the secondary cyclone. This indicates that the collection efficiency of a precleaning device could have a significant effect on the resistivity of the particulate entering the ESP and ultimately alter the performance of the ESP.

Figure 9. Laboratory Resistivity Measurements of Fly Ash from AFBC Gibbons Creek Lignite.



In interpreting and using this data, it should be noted that the resistivities reported here were based on extractive sampling using a laboratory resistivity measuring technique. Therefore, the absolute values of resistivities reported here may not be correct. However, the trends represented by the data are expected to be true of an actual operating system. Further research is needed to correlate the measured laboratory resistivities with actual ESP performance.

#### Waste Characterization

Representative samples of primary cyclone ash, secondary cyclone ash, baghouse ash, and drained bed material were collected from tests with ash reinjection and tests with limestone addition. A thorough characterization of these waste materials and their leachates was performed to give an indication of the potential impact on ground water and surface water. Each waste sample was subjected to ASTM and EP leachate tests. The leachates from these tests were analyzed for the RCRA elements (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) and several additional elements. Concentration of all RCRA elements in the leachates fell significantly below the established limits. Based on these results, fly ash and bed material wastes generated from the fluidized bed combustion of these Texas lignites would be classified as nonhazardous wastes according to current standards. Additional characterization results have been presented elsewhere (6).

### Corrosion and Erosion

After 1000-hours exposure in the AFBC, the tubes from the corrosion/erosion test using South Hallsville lignite were removed and examined. The main macroscopic feature of the samples from the test was a red color in most deposits, indicating a relatively high iron content in the deposits. There was also some evidence, albeit qualitative, that deposit formation on the inbed and splash zone tubes was extensive but most had spalled or eroded. The deposits on the convective pass tubes were tenacious.

Metallographic measurements, i.e., pit depth, deposit/scale thickness, and sulfide penetration, for each of the tubes is presented in Table 6. These measurements are the maximum observed from measurements made at eight locations around the circumference of the tube for each condition.

Figure 10 shows a comparison of the different metals tested in both the bed and convective sections of the combustor. A significant amount of metal attack (sulfide penetration plus depth of pits) was observed for all the in-bed tubes. The average value ranged from 35 to 81 microns attack during the 1000 hour test. If spalling of the corrosion products actually did occur as indicated by visual inspection of the tubes, metal wastage may have been greater than the values reported here. The 347 stainless steel performed better than the other metals tested under these conditions. For tubes located in the convective section, carbon steel was the only metal type showing significant metal attack due to corrosion or erosion. Sixty-one microns of metal wastage was measured. For the stainless steel tubes in the convective pass, metal wastage averaged below ten microns.

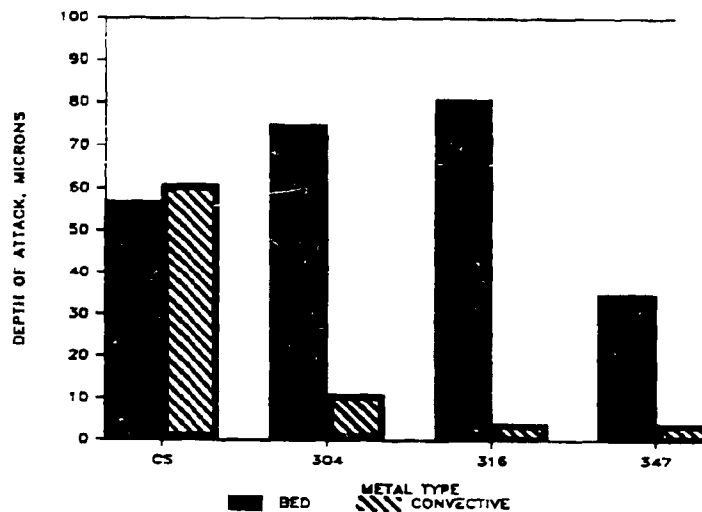


Figure 10. Depth of Fitting and Sulfide Attack as a Function of Metal Type-South Hallsville Lignite.

**TABLE 8**  
**RESULTS FROM EXAMINATION OF TUBES AND COUPONS FROM**  
**CORROSION/EROSION TESTING WITH SOUTH HALLSVILLE LIGNITE**

Tube No.	Material	Cooling Method	Average Surface Temp., °F	Metallographic Observations		
				Pits micron	Deposits micron	Sulfide Penetration micron
1	304	Air	1250	13	38	13
2	316	Air	1200	18	45	53
3	347	Air	1150	6	18	0
4	347	None	1550	24	40	40
5	304	None	1550	1	18	10
6	304	Air	1300	50	15	75
7	316	Water	350	20	75	13
8	CS	Water	350	18	12	50
9	347	Water	350	NA	NA	NA
10	304	Water	600	20	80	25
11	--	--	--	--	--	--
12	CS	Water	600	20	15	25
13	316	None	1550	20	12	120
14	304	None	1550	50	35	105
15	316	Air	1300	NA	NA	NA
16	347	Air	1300	8	13	38
17	316	Air	1200	35	15	0
18	304	None	1350	18	20	138
19	304	None	1350	14	2	0
20	347	None	1350	8	15	0
21	316	None	1350	35	25	18
22	CS	None	1350	38	75	5
23	CS	Air	800	38	108	25
24	316	Air	800	3	8	5
25	347	Air	800	0	50	0
26	304	Air	800	8	8	0
27	304	Water	250	NA	NA	NA
28	347	Water	250	3	5	0
29	316	Water	250	10	10	0
30	CS	Water	250	26	75	50

Tubes 1-15 located in the bed, 16-18 in the splash zone, and 19-30 in the convective section.

NA - Data not available

Metallographic observations are maximum values measured

The pit depth and amount of sulfide penetration are also affected by the tube surface temperature. As the tube surface temperature increased above about 1300°F, metal attack became more severe. A relatively constant rate of metal attack was noted at temperatures below 1300 (approximately 50 microns for the inbed tubes and 30 for convective pass tubes), but a marked increase in metal attack above this surface temperature (100 microns at 1550°F).

To relate this data to a meaningful real world situation, the corrosion criteria used by the Central Electricity Generating Board in the United Kingdom is discussed here. This criterion is equivalent to the loss of 7 mm of metal in 200,000 hours, corresponding to the total loss of the tube wall in the lifetime of the boiler. Assuming that the rate of metal loss varies with the square root of time (parabolic oxidation), an acceptable loss at 1000 hours would be 50 microns (7). At higher surface temperatures, greater than 1300°F, several of the stainless steel specimens exceeded this criteria. Most of the carbon steel also exceeded this criteria. Tubes located in the convective pass were all below the recommended criteria. This data indicates that below 1300 F, 304, 316, or 347 stainless steel would be suitable under for heat-exchanger tubes within the conditions tested. More detailed results of corrosion/erosion testing at UNDERC is presented elsewhere (2,8).

#### SUMMARY AND CONCLUSIONS

- o Bed temperature and alkali-to-sulfur ratio were found to be the two most important parameters affecting sulfur retention in the bed. The optimum temperature for sulfur capture occurred at temperatures less than 1450°F. Both coals tested will require added alkali-to-sulfur of approximately 3.5 to 4 to meet 1979 NSPS. Ash recycle and gas velocity had only a minimal effect on sulfur retention,
- o Emissions of NO<sub>x</sub> ranged from 0.12 to 0.40 lb/MMBtu, well below the NSPS of 0.60 lb/MMBtu. Increasing bed temperature was found to increase NO<sub>x</sub> emissions. The effect of gas velocity was dependent on the individual coal. NO<sub>x</sub> emissions increased with increasing velocity for the Gibbons Creek lignite, while with South Hallsville lignite an initial increase was followed by a decrease at higher velocities.
- o Very high combustion efficiencies typically greater than 98% were observed. Determination of combustion efficiencies for individual test conditions during the Gibbons Creek test showed that efficiency increased with increasing bed temperature and decreasing velocity. Ash recycle increased combustion efficiency slightly for the Gibbons Creek tests.
- o Baghouse collection efficiencies were low (92.8% to 97.0% for the Gibbons Creek tests, probably due to the low sodium content in the fly ash. Efficiencies improved when limestone was added as sorbent material, and the final emissions were lower than in the baseline tests, inspite of higher particulate loadings from the combustor.
- o Laboratory-determined resistivities increased over baseline values (inert bed material) as ash recycle and limestone addition were added to the test matrix. The additional CaO and SO<sub>3</sub> in the fly ash for these cases was determined to be the contributor to the higher resistivities.

- o More severe metal attack was measured for the inbed tubes versus those in the convective section. Corrosion/erosion increased with surface temperature, however, 304, 316, and 347 stainless steel would be suitable for heat-exchanger tubes at surface temperatures below 1300°F.

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ABSTRACT

**The Physical Model of Radiation  
Heat Transfer in Fluidized beds**

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A single particle model for estimating heat conduction, convection and radiation in high temperature fluidized beds has been developed. This physical model is clear and convenient for computation, especially since no empirically determined factors enter into the model. Using the model, the overall heat transfer coefficient and the radiation heat transfer have been calculated for different size particles at different bed temperatures. A satisfactory agreement between calculation and experiment has been obtained.

## FIRING LOW-RANK COAL/WATER FUEL IN A FLUIDIZED BED COMBUSTOR

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### ABSTRACT

Tests assessing the technical feasibility of burning hydrothermally-treated low-rank coal/water fuel (CWF) in an atmospheric, bubbling fluidized bed combustor (FBC) were performed at the University of North Dakota Energy Research Center (UNDERC). The fuel for the tests was prepared using UNDERC's hydrothermal coal dewatering process, a process for removal of liquid water from high moisture coal by heating the coal under pressure in a water medium. The inherent moisture of the coal particles is liberated and tars form closing coal micropores after cooling, preventing moisture reabsorption. The resulting hydrothermally-treated coal/water fuel has a significantly higher solids and Btu content than unprocessed slurry.

The fuel used for the testing was a Sarpy Creek (Absaloka Mine) Montana subbituminous CWF with approximately 60 percent dry solids. The CWF was prepared in a 200-lb/hr continuous hydrothermal process development unit. An 18 x 18 in. FBC was used for the combustion tests. The CWF was pumped directly into the dense-bed zone of the combustor through a simple, water-cooled pipe without the aid of a nozzle or atomizing air. Operation of the combustor was extremely stable when firing the CWF. Testing was also performed with a coal/water/limestone fuel (limestone added after hydrothermal treatment) which simplified the entire solids feeding system. Results from this testing are compared to previous results when feeding the same coal as received ("dry" coal screw fed into combustor).

### INTRODUCTION

Oil and gas are currently the predominant fuels for residential, commercial, and small-sized industrial energy markets. Coal, once the major fuel form for all energy use sectors, has lost considerable ground with smaller-scale energy users. Fluidized bed combustion (FBC) possesses great potential in capturing back some of these lost markets. The development of a simple, clean, efficient, and reliable coal feeding system will be necessary if coal-fired FBC's are to enter the commercial and residential energy markets. Pumping coal/water fuels into FBC's is a coal feeding method which could meet the above criteria.

Initial testing has been completed at the University of North Dakota Energy Research Center (UNDERC) assessing the technical feasibility of burning low-rank coal/water fuels (CWF) in a FBC. The objectives of the present low-rank CWF testing were twofold. The first objective was the design and

fabrication of a probe for the direct injection of slurry into the dense-bed zone of a bubbling FBC. The second objective was the actual combustion testing of a low-rank CWF in a FBC. Testing was performed with the 18 x 18 in. atmospheric, bubbling FBC at UNDERC. The low-rank CWF burned during the testing was prepared using UNDERC's hydrothermal coal dewatering process, a process for removal of liquid water from high moisture coal by heating the coal under pressure in a water medium. Conceptual economic studies on the UNDERC hydrothermal coal dewatering process have been reported by Bechtel National Inc. (sponsored by EPRI), Davey McKee Pacific Co. (sponsored by the Victorian Brown Coal Council), and UNDERC (sponsored by DOE) (1-3). The Bechtel study found the UNDERC process to be the most economical of several dewatering processes considered. Bechtel's cost estimate for a Wyoming subbituminous coal/water fuel was \$1.40/MMBtu. UNDERC's estimate for the same fuel (produced in a smaller plant) was \$2.00/MMBtu. Davey McKee estimated the cost of a hot-water dried Australian brown coal/water fuel to be \$2.00/MMBtu. These are the costs for processing the fuel and do not include the costs of the original coal.

#### PILOT PLANT FACILITIES

The low-rank CWF was prepared using UNDERC's 200-lb/hr continuous hydrothermal process development unit. An isometric view of the unit is shown in Figure 1. More detailed descriptions of the process has been made elsewhere (4-6). In the slurry preparation and pumping area, a 50/50 mixture (by weight) of deionized water and pulverized coal (80 percent less than 200 mesh) was mixed continuously in a stirred tank and circulated around the suction side of four high-pressure reciprocating pumps. In the slurry heating and coal dewatering area, the pressurized slurry was heated to about 300°F in a steam-heated exchanger, and was then heated to reaction temperature (625°F) in a series of coils immersed in condensing Dowtherm vapor. The heated and pressurized slurry then entered the top of a down-flow reactor where it was nominally retained at temperature for 5 minutes. In the slurry recovery and gas separation area, a combination high-pressure gas-liquid separator and level controller was used to separate evolved gases (mainly CO<sub>2</sub>) from the slurry and to keep the reactor flooded. Vapors and gases from the high-pressure separator were cooled; the condensate was recycled to the water tank; and the off-gas stream was incinerated in a thermal oxidizer. Parallel to the separator was a slurry letdown system which removed slurry continuously from the high pressure system at a rate commensurate with the slurry feed rate and always kept the reactor in a flooded condition. In the slurry concentration and process water recovery area, some process water was removed as steam from the hot, depressurized slurry in two atmospheric slurry flash concentrators. The overhead products from the flash concentrators were cooled; liquid was recycled to the water feed tank; and the off-gas stream was incinerated. Product slurry (40 to 50 weight percent dry solids) was collected from the bottom of the flash concentrators, cooled in a tank or drums, and then further concentrated by centrifugation. A high-speed, solid bowl, continuous centrifuge produced a cake which was reslurried with deionized water to the desired product concentration of 60 weight percent dry solids.

An isometric view of the 18 x 18 in. bubbling, atmospheric FBC is shown in Figure 2. The FBC facility consists of:



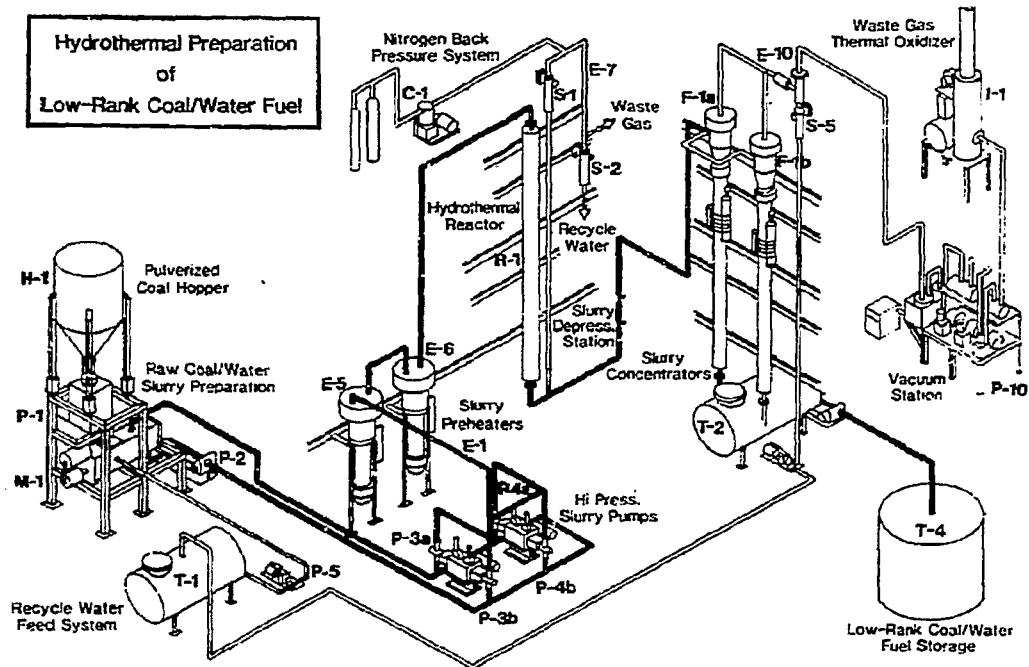


Figure 1. Isometric view of UNDERC's continuous hydrothermal process development unit.

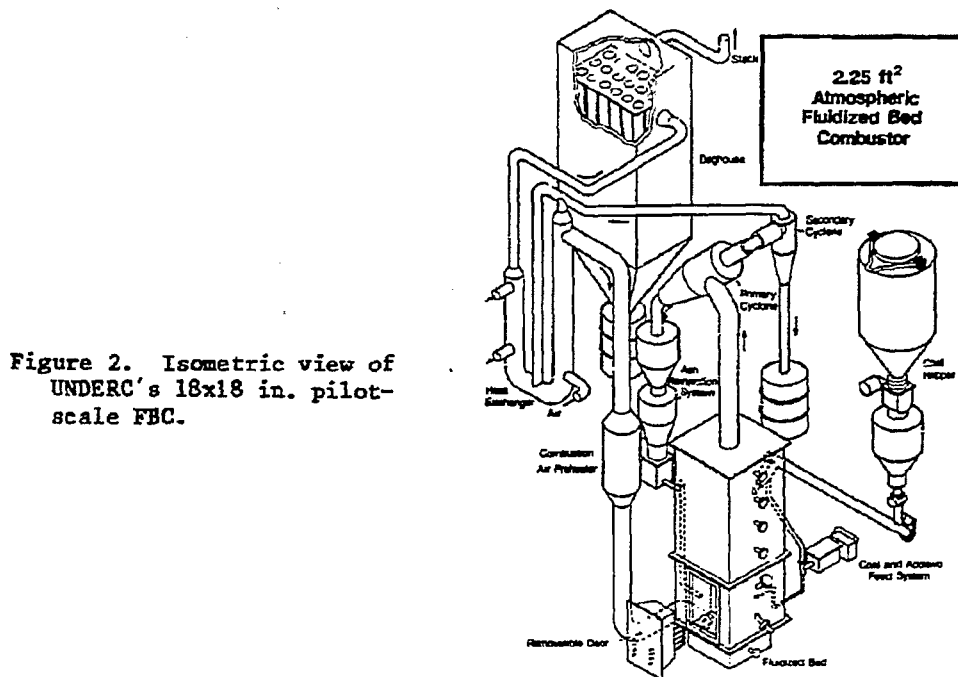


Figure 2. Isometric view of UNDERC's 18x18 in. pilot-scale FBC.

1. A refractory-lined, steel shell combustor;
2. A forced draft fan, a flue gas/combustion air heat exchanger, and a natural gas-fired preheater which provide combustion air and fluidize the bed;
3. A screw feed system for injecting coal and sorbent, and a pneumatic ash reinjection system;
4. A flue gas system consisting of two cyclones, two heat exchangers, a pulse jet baghouse, and an induced draft fan; and
5. A gas sampling system capable of continuously measuring and recording the  $O_2$ ,  $CO_2$ ,  $CO$ ,  $NO_x$ , and  $SO_2$  concentrations of the flue gas.

The nominal heat input for the unit is  $1 \times 10^6$  Btu/hr at a superficial gas velocity of 6 ft/sec and 20 percent excess air. A more detailed description of the unit has been previously presented (7). The coal feed system was modified before the start of testing to allow feeding the CWF into the combustor (modifications not shown in Figure 2).

Figure 3 shows the CWF feed system for the 18 x 18 in. FBC. The skid-mounted feed system includes a progressive cavity pump which is gravity fed from the feed tank. A variable speed drive on the pump controls the CWF feed rate. The CWF feed rate is measured by a Micromotion flow meter with digital indicator. The CWF is generally agitated before introduction to the feed tank. An air-operated mixer is also provided in the feed tank to continuously mix the CWF during the test. The atomizing air shown in the figure was not required for the current testing.

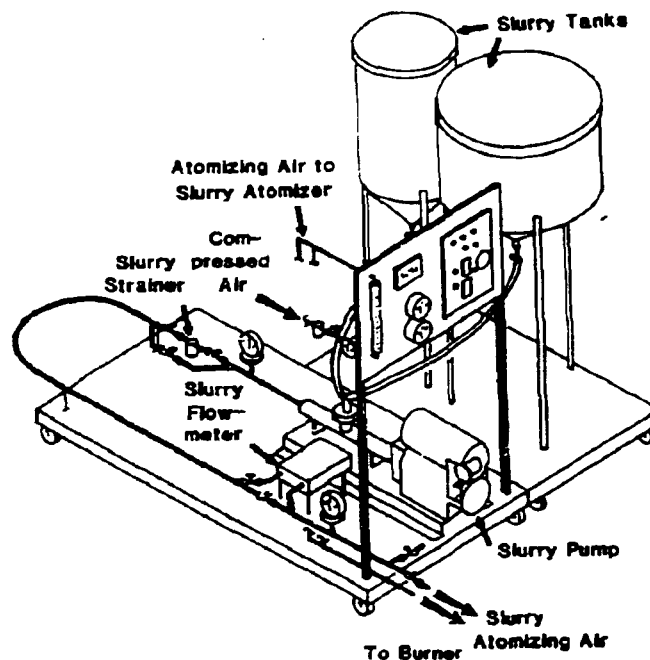


Figure 3. Coal/water fuel feed system.

A schematic of the CWF injection probe designed and fabricated for the testing is shown in Figure 4. The probe's simple design consisted of a straight, water-cooled, stainless steel pipe. The major difference between UNDERC's probe designed for low-rank CWF and probes used by other investigators for higher-rank coals is the absence of atomizing air (8-10). Atomizing air has been included in probes used for higher-rank coals because of their agglomerating properties. When high-rank coal/water fuels are fed into the hot bed, close proximity of fine particles within an evaporating droplet leads to their coalescence upon complete evaporation. The fine particles tend to agglomerate, forming solids lumps. Some agglomeration of the fine coal particles is beneficial in that fuel elutriation losses are decreased. However, severe agglomeration of the fine coal particles can cause unstable operation of FBC's because large agglomerates can sink to the bottom of the bed and gradually decrease fluidization quality. Low-rank CWF's apparently differ from fuels made from high-rank coals in that they are non-agglomerating. Therefore atomizing air should not be necessary and was not included in the design of the CWF injection probe.

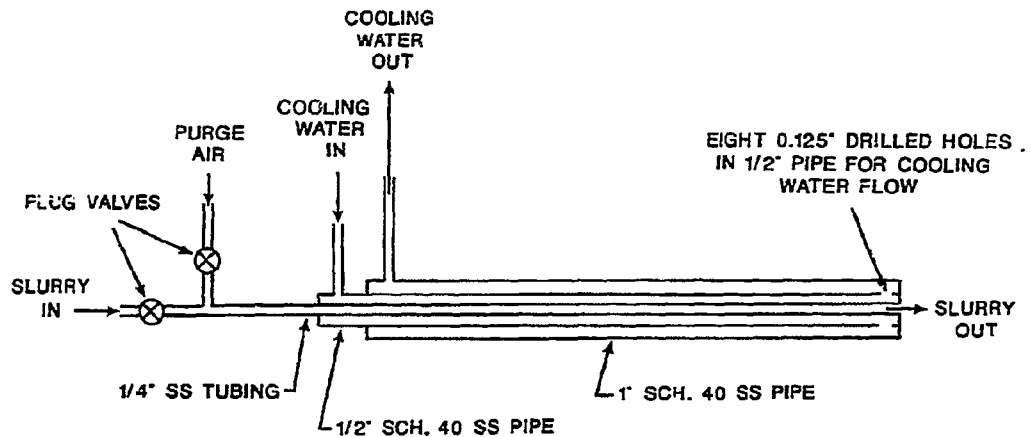


Figure 4. Schematic of CWF injection probe.

CWF was introduced into the FBC bed approximately 3 inches above the nozzle air distributor. Air was continuously supplied through the probe during start-up of the combustor (before feed initiated) to prevent any plugging of the probe by the bed material. Addition of this air was discontinued when CWF feed was started.

## TEST DESCRIPTION

A coal/water fuel produced from a Powder River Region subbituminous coal was used for the testing. The coal was obtained from the Absaloka Mine (Sarpy Creek field, Rosebud-McKay bed) which is located in the northeastern part of Big Horn county in Montana. This coal was chosen for the CWF testing because as-received Sarpy Creek coal (as-received coal screw fed into combustor) had been previously well characterized with the 18 x 18 in. FBC at UNDERC (11).

The CWF combustion test matrix is presented in Table 1. The test series consisted of five separate test periods. A superficial gas velocity of 5 ft/sec and 20 percent excess air were specified for all tests in the matrix. Silica sand (No. 10) was used for bed material (static bed depth of 2.8 ft used for all tests). Test Nos. 1 through 3 were run at three different bed temperatures, ranging from 1450° to 1650°F. Test Nos. 4 and 5 were set up to compare the effectiveness of adding sorbent (limestone) mixed with the CWF versus adding dry limestone separately to the bed.

TABLE 1  
CWF COMBUSTION TEST MATRIX<sup>1</sup>

<u>Test No.</u>	<u>Bed Temperature (°F)</u>	<u>Limestone Addition</u>
1	1450	None
2	1550	None
3	1650	None
4	1550	Pulverized limestone mixed with the CWF.
5	1550	Dry limestone (-8 x +20 mesh) added separately to bed.

<sup>1</sup>All tests were run at 5 ft/sec and 20 percent excess air. No. 10 silica sand was used as bed material. Static bed height was maintained at 2.8 ft.

## COAL/WATER FUEL PROPERTIES

Approximately 10,000 lbs of Sarpy Creek CWF (60 weight percent solids) were successfully prepared using the hydrothermal dewatering process. The coal was processed at 625°F and then centrifuged to a 65 to 70 weight percent dry solids cake for storage. Before combustion testing, the centrifuge cake was reslurried with deionized water to produce a 60 weight percent dry solids CWF. A coal/water/limestone fuel was prepared for Test No. 4 by adding pulverized limestone during the reslurrying process. This coal/water/limestone fuel was also mixed to produce a 60 percent solids fuel.

Analyses of the coal/water and the coal/water/limestone fuels are presented in Table 2. Size analyses for the fuels used during each test period are given in Table 3. An analysis of the limestone used in Test Nos. 4 and 5 is presented in Table 4. As stated above, pulverized limestone was added to the fuel in Test 4. In Test No. 5, coarser limestone (-8 x +20 mesh) was added directly to the bed separate from the CWF. The limestone was obtained from the Big Horn Limestone Co. in Montana.

TABLE 2  
FUEL ANALYSES

	Coal/Water Fuel		Coal/Water/Limestone Fuel	
	As Burned	Moisture Free	As Burned	Moisture Free
<u>Proximate Analysis:</u>				
Moisture	40.9	NA	41.8	NA
Volatile Matter	21.4	36.2	21.5	36.9
Fixed Carbon	29.6	50.2	27.9	47.9
Ash	8.1	13.6	8.9	15.3
Heating Value, Btu/lb	6,573	11,121	6,256	10,752
<u>Ultimate Analysis:</u>				
Hydrogen	7.13	4.38	7.12	4.25
Carbon	38.65	65.39	37.11	63.79
Nitrogen	0.48	0.81	0.51	0.87
Sulfur	0.53	0.90	0.55	0.95
Ash	8.05	13.63	8.88	15.27
Oxygen (Difference)	45.14	14.87	45.81	14.84
<u>Ash Analysis (% as Oxides):</u>				
SiO <sub>2</sub>	38.1		32.7	
Al <sub>2</sub> O <sub>3</sub>	17.4		15.3	
Fe <sub>2</sub> O <sub>3</sub>	4.8		4.6	
TiO <sub>2</sub>	1.1		0.9	
P <sub>2</sub> O <sub>5</sub>	0.7		0.6	
CaO	19.3		29.3	
MgO	3.0		2.6	
Na <sub>2</sub> O	0.1		0.0	
K <sub>2</sub> O	1.1		0.9	
SO <sub>3</sub>	14.5		13.1	

TABLE 3  
 SIZE ANALYSES OF AS-BURNED FUELS  
 (% ON SCREEN)

<u>Mesh</u>	<u>Microns</u>	<u>Test 1</u>	<u>Test 2</u>	<u>Test 3</u>	<u>Test 4</u>	<u>Test 5</u>
60	250	0.1	0.1	0.2	0.4	0.6
100	150	0.3	0.1	0.4	3.2	0.8
170	90	2.5	2.0	3.2	9.2	10.9
200	75	6.5	4.3	4.1	8.1	5.1
270	53	18.5	11.3	13.6	13.0	19.1
325	45	6.1	5.8	4.6	20.6	20.5
<325	—	66.0	76.3	74.0	45.6	43.2

TABLE 4  
 LIMESTONE ANALYSIS

<u>Constituent</u>	<u>Percent</u>
SiO <sub>2</sub>	3.3
Al <sub>2</sub> O <sub>3</sub>	0.2
Fe <sub>2</sub> O <sub>3</sub>	0.1
TiO <sub>2</sub>	0.0
P <sub>2</sub> O <sub>5</sub>	0.0
CaO	55.9
MgO	0.1
Na <sub>2</sub> O	0.0
K <sub>2</sub> O	0.0
SO <sub>3</sub>	0.1
Loss on Ignition	42.0
Moisture	0.02

A Haake Rotovisco RV100 viscometer was used to provide rheological data for the coal/water and coal/water/limestone fuels. Figure 5 shows apparent viscosity versus solids concentration for the CWF. A slurry with a solids content of 60 percent has a viscosity of 850 cP as calculated from the data after fitting to an exponential model. The fit resulted in a correlation coefficient of 0.9997 according to the equation:

$$\ln(Y) = \ln(A) + B(X)$$

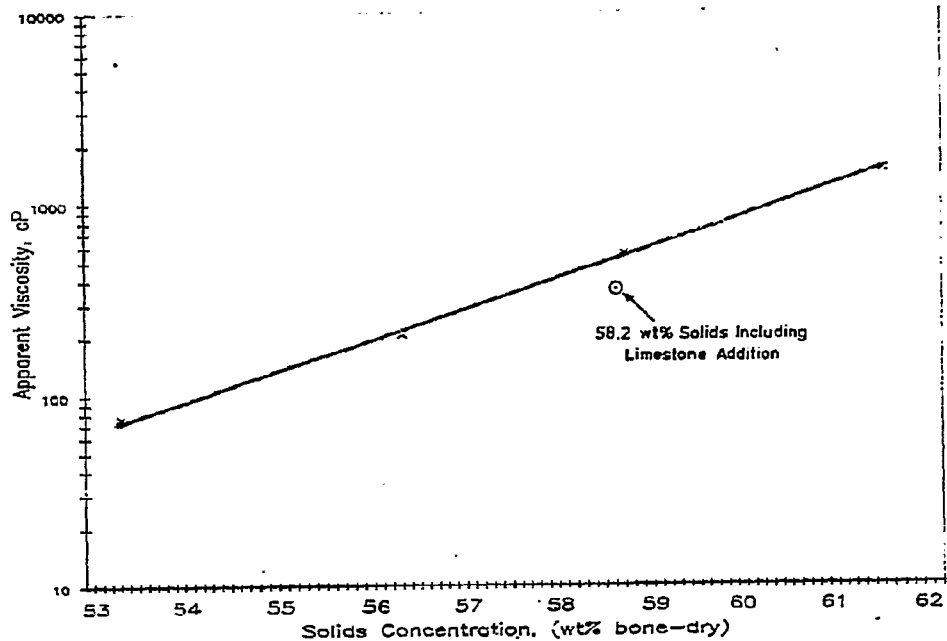


Figure 5. Apparent viscosity versus solids concentration at  $100 \text{ sec}^{-1}$  and  $77^\circ\text{F}$  for CWF.

where  $Y$  is the viscosity in cP,  $A$  is a constant,  $B$  is the regression coefficient, and  $X$  is the dry solids content in weight percent.

Pulverized limestone (approximately 80 percent minus 200 mesh) was added to the CWF to increase sulfur capture during Test No. 4. The molar ratio of calcium in the added limestone to sulfur in the coal was 1.5 to 1 which amounts to 0.04 lb of limestone to 1 lb of dry coal. This coal/water/limestone fuel had a viscosity of 373 cP at 58.2 percent dry solids (2.3 percent limestone and 55.9 percent dry coal). This point is shown in Figure 5 and its rheological characteristics compare favorably with the data without limestone addition at same total solids content. Any limestone added reduces the energy density of the slurried fuel. Therefore, consideration must be given to the energy density loss versus the benefits of additional sulfur capture with each particular coal.

A rheogram plotting shear stress versus shear rate is shown in Figure 6 for both the CWF's with and without limestone. The behavior for both fuels was similar to a Bingham plastic fluid. A Bingham plastic fluid has an initial yield stress (force necessary to set a fluid into motion) and essentially Newtonian flow behavior (constant viscosity with increased shear rate) after being set in motion. However, the fuels did show some viscosity reduction with increased shear rate, or pseudoplastic flow behavior, as exhibited by the slight bend in the rheograms.

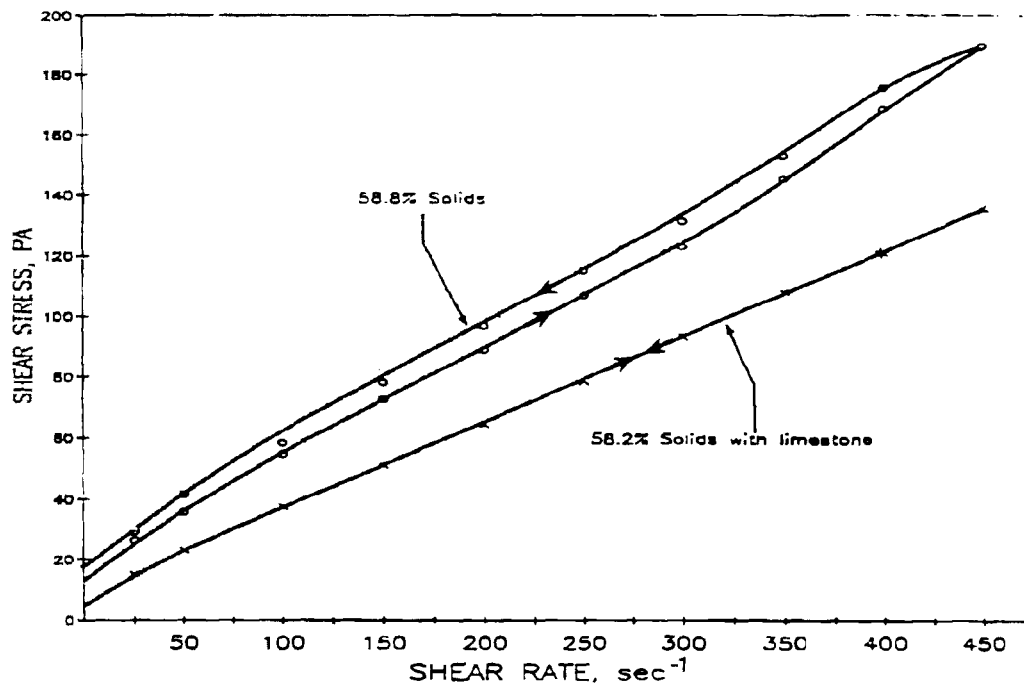


Figure 6. Shear stress versus shear rate for CWF with and without limestone.

The amount of viscosity reduction as a function of time with constant shear rate, or thixotropy, is qualitatively measured as the amount of negative hysteresis between the up and down curves of the rheograms. A positive hysteresis indicates rheopexy, or viscosity increase with constant shear. As shown in the rheograms (Figure 6), no thixotropic behavior was noted for the CWF with limestone. However, the small positive hysteresis for the CWF without limestone shows rheopexy behavior. Therefore, the viscosity of the CWF without limestone will increase with time the longer the material is sheared. Theoretically, the slurry would recover its original flow behavior if shearing of the fuel was discontinued.

Both fuels showed up to 8 hours stability during handling and have been stable for as many as 5 days in some cases. The fuel with added limestone was slightly more stable than the CWF without. These fuels were prepared without chemical additives to enhance flow behavior or stability. Therefore, any favorable flow behavior or stability of the fuels as compared to fuels made from similar sized and quality as-mined coals, were a result of the UNDERC hydrothermal dewatering process or the limestone addition.

## RESULTS AND DISCUSSION

After design and fabrication of the slurry feeding probe, the entire CWF feed system was tested during a short shakedown run. The bed was preheated to approximately 800°F before introduction of the CWF. During preheat the probe



was continuously purged with air to insure that it did not get plugged with bed material. When CWF feed was initiated, the purge air was discontinued. The CWF ignited easily and the combustor was brought up to normal operating temperatures and conditions. The unit was then operated on CWF (60 percent dry solids) for several hours without any problems with the slurry feeding system. Operation of the unit was very stable as evidenced by a steady bed temperature and good O<sub>2</sub> stability in the flue gas. Only infrequent and minor adjustments were required with the CWF feed rate. Inspection of the slurry feeding probe and the drained bed material after the shakedown run did not reveal any problems with the CWF feeding. The bed material was very similar in appearance to the original silica sand added to the bed during startup. Apparently all the ash was removed from the bed as fly ash.

After the successful shakedown of the slurry feeding system, the unit was restarted the following week and testing performed according to the test matrix previously outlined in Table 1. A summary of the data from the five test periods is presented in Table 5. The data for each test period was collected and averaged during steady state operation of the FBC unit.

TABLE 5  
AVERAGE TEST CONDITIONS AND RESULTS

	Test No. 1	Test No. 2	Test No. 3	Test No. 4	Test No. 5
Bed Temperature (°F)	1450	1547	1654	1553	1550
Freeboard Temperature (°F)	1670	1734	1797	1788	1735
Gas Velocity (ft/sec)	5.0	5.1	5.1	5.0	5.1
Excess Air (%)	19.9	19.6	20.6	20.7	21.1
Static Bed Depth (ft)	2.8	2.8	2.8	2.8	2.8
Slurry Feed Rate (lb/hr)	146.1	140.5	135.8	147.6	141.2
Total A/S Mole Ratio	1.68	1.66	1.84	2.69	3.01
Sulfur Retention (%)	47.5	34.0	22.9	51.8	59.9
Total Alkali Utilization (%)	28.3	20.5	12.5	19.2	19.9 ✓
SO <sub>2</sub> Emissions (lb/MMBtu)	0.84	1.06	1.17	0.85	0.69
NO <sub>x</sub> Emissions (lb/MMBtu)	0.18	0.21	0.26	0.22	0.22
Combustion Efficiency (%)	99.4	99.7	99.7	97.4	99.3

Combustion efficiencies were determined for each test period using the input-output method (7). This method of calculation determines the amount of uncombusted carbon in the fly ash as a fraction of the total carbon input with

the fuel. Combustion efficiencies of the first three test periods (all without limestone addition) were very high, ranging from 99.4 to 99.7 percent. The efficiency appeared to increase slightly with increasing bed temperature. These values are equal to or somewhat higher than combustion efficiencies previously determined when testing Sarpy Creek coal as received (as-received coal screw fed into combustor). More freeboard burning than normal was noted during the CWF testing as evidenced by high freeboard temperatures. The freeboard temperature was generally between 140° and 230°F higher than the average bed temperature, with less temperature difference at the higher bed temperatures. The freeboard burning is probably not a significant problem, but will shift additional heat transfer into the convective passes of an actual boiler. For previous testing with as-received coal (-1/4 in.) screw fed into the bed, freeboard temperatures were generally less than 100°F higher than the average bed temperature.

Combustion efficiencies, although determined for tests with limestone addition (Tests Nos. 4 and 5), should not be compared to the tests without limestone addition. Uncalcined limestone ( $\text{CaCO}_3$ ) can add significant quantities of  $\text{CO}_2$  to the uncombusted carbon in the fly ash, thereby "artificially" lowering the combustion efficiency.

Carbon monoxide (CO) emissions were low during the CWF testing, generally less than 200 ppm. Some small intermittent CO spikes were seen throughout the testing. The low CO levels at excess air levels of approximately 20 percent were another indication of good fluidization and combustion stability.

Emissions of  $\text{NO}_x$  were very low when burning the CWF's, ranging from 0.18 lb/MMBtu at 1450°F to 0.26 lb/MMBtu at 1650°F. These emissions are significantly lower than those when burning the same coal as received into the FBC which resulted in  $\text{NO}_x$  emissions ranging from 0.24 to 0.58 lb/MMBtu. The emissions of  $\text{NO}_x$  when burning the CWS are well below limits set by the 1979 New Source Performance Standards (NSPS's) of 0.6 lb/MMBtu.

In Test Nos. 1 through 3, the emissions of  $\text{SO}_2$  were investigated when burning CWF at various bed temperatures. Additional sorbent was not used during these three tests in order to quantify the sulfur capturing capacity of Sarpy Creek's alkaline ash. As shown in Figure 7, sulfur retention was highest at 1450°F (47.5 percent) and decreased as bed temperature was increased, dropping to 22.9 percent retention at 1650°F. These results are not significantly different than those observed previously when testing as-received Sarpy Creek coal. In the previous testing, the maximum sulfur retention also occurred at 1450°F.

To meet NSPS's, additional sulfur capture is required when burning Sarpy Creek coal. Therefore, Test Nos. 4 and 5 were included to compare the efficiencies of two different methods of adding limestone to the bed. In Test No. 4, pulverized limestone was added directly to the CWF during the slurring process. Pumping this coal/water/limestone fuel into the bed resulted in a very simple feed system for both the coal and limestone. In Test No. 5, dry limestone (-8 x +20 mesh) was added to the bed pneumatically, separate from the CWF. The sulfur retention data from Test Nos. 4 and 5 are also plotted in

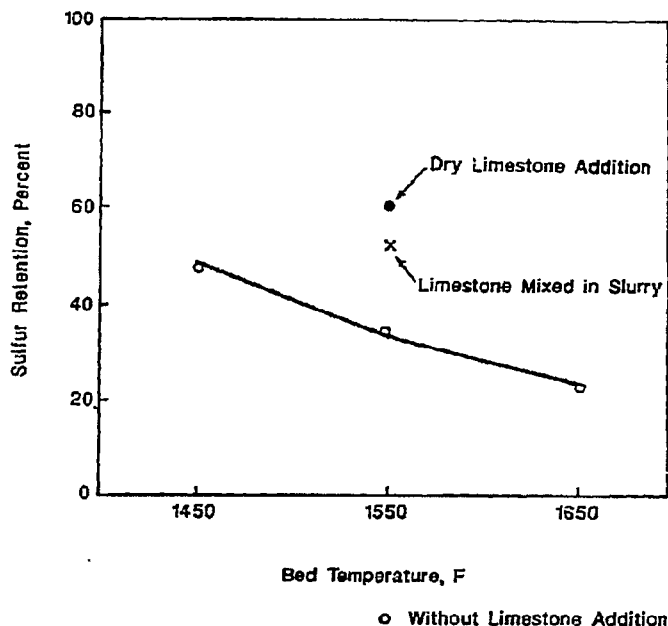


Figure 7. Sulfur retention as a function of bed temperature.

Figure 7. A higher retention is seen for the separately injected limestone (59.9 percent) than for the limestone mixed with the slurry (51.8 percent). This difference is due to the fact that more limestone was added in Test No. 5 (dry limestone feed) than Test No. 4 (limestone mixed in slurry). The total molar alkali-to-sulfur ratio (A/S) for Test No. 5 was 3.01, which is somewhat greater than 2.69 for Test No. 4. The total A/S takes into account the calcium and sodium contributed by both the inherent coal ash and the added limestone. To compare the sulfur capture in Test Nos. 4 and 5 on an equal basis, it is necessary to look at the alkali utilization rather than simple sulfur retention. Alkali utilization is calculated by dividing the sulfur retention by the alkali-to-sulfur ratio. Alkali utilization is plotted as a function of bed temperature in Figure 8. It is clear from the figure that utilization, like sulfur retention, increases with decreasing bed temperature over the range of temperatures studied. Figure 8 also shows that the form of calcium (there was no detectable sodium in the limestone and only very little in the coal ash) or the method by which it was added had little effect on its utilization. All three tests run at the same bed temperature (1550°F), which included the two methods of limestone addition and a test without limestone addition, had essentially identical alkali utilizations: 19.2, 19.9, and 20.5 percent.

Samples of bed material drained from the FBC after each test period were submitted for element 1 and size analysis. From the sieve analysis, little particle growth was evident. Visual observation of the bed material particles and elemental analysis indicated very little ash deposited on the surface of

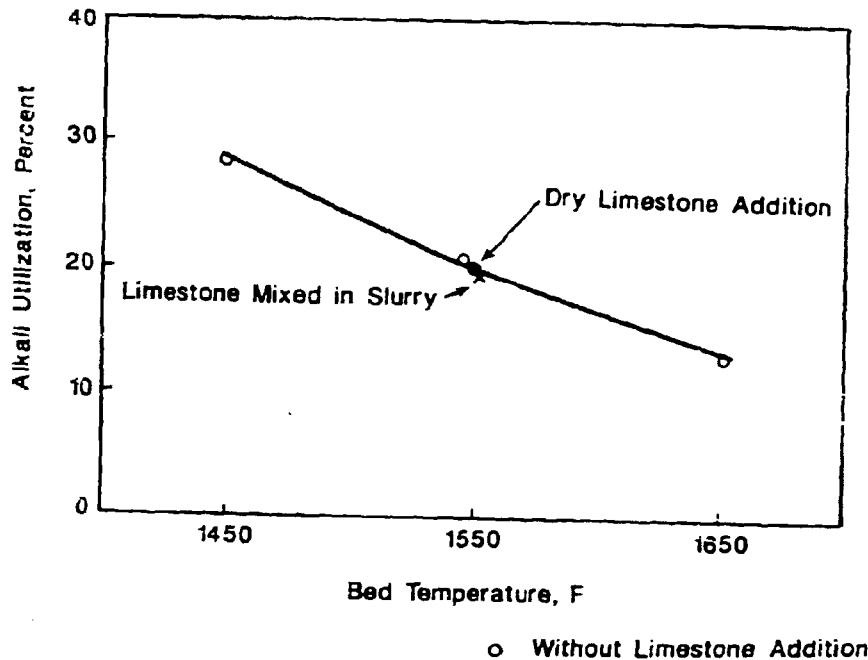


Figure 8. Alkali utilization as a function of bed temperature.

these particles. The fine ash was elutriated from the bed before it was able to react with the silica sand bed material. Since ash does not collect in the bed, it is probable that a continuous bed removal system will not be required when burning CWF's of the Sarpy Creek coal.

#### SUMMARY

A low-rank coal/water fuel prepared from a Powder River Region subbituminous coal using UNDERC's hydrothermal coal dewatering process was successfully burned in a 18 x 18 in. atmospheric, bubbling FBC. The 60 weight percent dry solids CWF was pumped directly into the dense-bed zone through a simple, water-cooled pipe without the aid of a nozzle or atomizing air. Significant results from the testing include:

- o The CWF exhibited flow behavior that was acceptable for short-term handling and ease of feeding. In addition, there was no detrimental rheological effect to hydrothermally-treated low-rank CWF from the addition of limestone for sulfur capture.
- o Limestone utilization for the reduction of SO<sub>2</sub> emissions was equal for pulverized limestone added directly to the CWF versus dry limestone added separately to the bed (-8 x -20 mesh). The utilization appeared significantly dependent on bed temperature.
- o Combustion efficiency as measured by carbon burnout was very high, ranging from 99.4 to 99.7 percent. These efficiencies are equal to or slightly greater than efficiencies previously obtained for the as-received Sarpy Creek coal when screw fed into the same FBC.

- o Emissions of NO<sub>x</sub> when burning CWF were significantly lower than previously seen when burning the same coal as received. Emissions ranged from 0.18 to 0.26 lb/MMBtu, increasing slightly with increasing bed temperature.
- o Little growth in bed particle size or increase in bed weight was noted during the CWF testing. Therefore a continuous spent bed removal system may not be required when burning CWF's produced from similar coals.

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THE INFLUENCE OF INORGANIC MATTER ON THE FLASH PYROLYSIS  
OF SOME CANADIAN COALS

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ABSTRACT

In low rank coals much of the inorganic matter is present as cations associated with organic carboxyl groups in the coal rather than as discrete mineral phases. By treating the coal with acid the inorganic content is reduced by cation exchange as well as by acid leaching of discrete minerals.

Whole and acid treated samples of pulverized lignite were pyrolyzed in pilot-scale (1-3kg coal/hr) and bench scale (60-160g coal/hr) fluidized bed reactors at atmospheric pressure, 0.45 second vapour residence time, and temperatures of 550° to 730°C. Yields of char, tar, water, and light gases were determined. Removal of inorganic matter from a Saskatchewan lignite resulted in increased yields of tar and total volatile matter, with little effect on the yields of light gases.

Increased yields of tar are largely a result of an increased asphaltene fraction in general and specifically an increased catechol content. Char from acid washed coal is less reactive to carbon dioxide.

## Introduction

Work on coal pyrolysis was initiated at the University of Waterloo in 1979 using a small bench scale fluidized bed apparatus patterned after that developed by CSIRO (Tyler, 1979). The focus of the early work was to determine the optimum pyrolysis conditions for the maximum yield of organic liquids for a variety of coals ranging in rank from lignite to bituminous.

This present paper is concerned with the influence of inherent inorganic matter in lignites on its pyrolysis behaviour and specifically the yield of products, the composition of the tar, and the reactivity of the char.

Lignites represent an early stage of the coalification process and are thus relatively rich in humic substances compared to higher rank coals. The distinguishing features of this organic matter of lignite are the lower aromaticity compared to bituminous coal and the prevalence of oxygen-containing functional groups consisting of carboxylates, phenols and ethers. The inorganic elements in lignite are found in three principal forms: as discrete mineral phases, dissolved in the pore water, or combined chemically with the organic materials. The most significant feature of the inorganic matter in lignites is the large amount of alkali and alkaline-earth metal cations thought to be associated with the carboxyl groups in the coal.

Many studies have reported the effects of these inorganic cations on the utilization processes for low rank coal. Several of these investigations have reported that removing these cations from the coal prior to flash pyrolysis results in increased yields of tar.

To investigate this phenomenon, a Saskatchewan (Estevan) lignite was acid treated to remove varying amounts of inherent cations and subsequently pyrolyzed using a bench scale fluidized bed pyrolyzer to determine the effects on the yields of char, tar, water, carbon oxides, hydrogen, and light hydrocarbon gases. In addition, a second sample of Saskatchewan (Coronach) lignite was acid washed and pyrolyzed using a pilot scale fluidized bed pyrolyzer to confirm the results from the bench scale unit and to collect sufficient amounts of tar for detailed analysis.



## Experimental

As-received coals were ground and sieved to provide samples with a particle size range of 74 - 250 $\mu$ m for the bench scale unit and 62 - 600 $\mu$ m for the pilot plant.

Acid washed coals with a range of cation contents were prepared from the raw coal by extraction with HCL at five different acidities (pH = 4.0, 3.5, 2.5, 1.5, 0.8). Another acid washed sample was also prepared by extraction with sulphuric acid at a pH of 3.0. During the extractions the pH of the coal-acid slurry was maintained at the desired acidity by incrementally adding acid until the exchange was complete.

Both the bench scale and pilot scale fluidized bed pyrolyzers have been described in detail by Scott (1986). A schematic comparison of the two units is shown in Figure 1. Briefly, in each case an entrained flow feeder injected a stream of coal particles directly into an electrically heated fluidized sand bed. Coal was fed to the bench scale nitrogen fluidized bed at rates of 60 - 100g/h in nitrogen for an average run time of 30 minutes. In the pilot scale unit circulating pyrolysis gas fluidized the sand bed and carried coal to the reactor at rates of 1 - 3kg/h, approximately 2kg of coal being pyrolyzed in each experiment. Both char and volatile matter were entrained out the top of the reactor and collected downstream. In the bench unit char was collected in a char pot which was kept at reaction temperature while in the pilot plant unit the char was collected in a char pot at ambient temperature. Vapour product collection consisted of a system of two condensers and a cotton wool filter connected in series. Vapour products were washed from the condensers using tetrahydrofuran (THF). The solvent was evaporated at about 65°C and 20 inches Hg vacuum, and the liquid product was then weighed and stored in a refrigerator prior to further analyses.

Raw and acid washed coals were characterized by proximate and ultimate analysis as well as by the analysis of their inorganic cations (Ca, Mg, Na, and K). Gaseous pyrolysis products were analyzed by gas chromatography. Char and tar products were analyzed for their carbon, hydrogen, and nitrogen contents. The tar was further characterized by solvent fractionation and the oil and asphaltene fractions were analyzed by GC-MS. Finally, the reactivity of the char to carbon dioxide was determined by thermogravimetric analysis (TGA).

Two methods of analysis were attempted to determine the total amounts of specific inorganic elements in Estevan lignite (i.e., the combined amount in the mineral matter and in the organic matrix). The inorganic content of the raw coal was determined by first demineralizing a coal sample using the method of Bishop and Ward (1958) and then analyzing the extracted acidic solution for the desired elements by atomic absorption spectrophotometry. A second method tested was the ash digestion procedure described by Perkin-Elmer Corp. (1978) followed by analysis of the extract solution. Thirdly, a procedure for the determination of exchangeable cations was adapted from the study of Morgan, Jenkins, and Walker (1981) in which the coal was subjected to ion exchange with ammonium acetate in order to selectively remove only the exchangeable cations and leave essentially intact the discrete mineral matter.

## Results

### Composition of Coals

Proximate and ultimate analysis of the raw and acid washed lignite samples are given in Table 1. It is significant that acid washing does not appear to have any effect on the organic portion of the lignites. It is apparent however that the inorganic matter, as indicated by the ash content, is reduced with increasing severity of acid treatment.

Table 2 gives the inorganic cation content of the raw and acid washed coals. The Ca and Mg contents of raw Coronach lignite are nearly twice those of Estevan lignite however the sodium content of Estevan lignite is about 13 times that of the Coronach sample. The cation contents of the two coals both washed in HCL at a pH of 2.5 are very similar with the exception of sodium. For the acid washed Estevan lignite sample it is apparent that the cation contents decrease with increasing severity of acid treatment.

### Pyrolysis of Raw and Acid Washed Coals

Earlier studies have established that the maximum tar yield for low rank coals occurs on flash pyrolysis at about 600 - 650°C and short residence times of about 0.2 - 0.5 seconds. Since the main objective of the present investigation was to determine the influence of inorganic matter on pyrolysis yields, and particularly the optimum tar yield, tests were confined to temperatures in the range 550° - 730°C and vapour residence times of about 0.4 - 0.5 seconds.

The raw and acid washed Estevan lignite samples were each pyrolyzed in the bench scale pyrolyzer at 650°C and 0.55 second vapour residence time. The major effect of acid washing was the higher tar yield with a corresponding reduction in gas yield. The tar yield for an Estevan sample washed at a pH of 0.8 was 150 percent that of the raw Estevan while the gas yield was only 85 percent as great. The trend, as shown in Figure 2, is to higher tar yields and lower gas yields with stronger acid washing. Char yields are very slightly reduced. A lower CO<sub>2</sub> yield accounts for most of the reduction in gas yield with stronger acid washing. Hydrogen and methane also decrease slightly whereas carbon monoxide increases slightly.

Table 3 gives results of pyrolysis runs on the pilot scale pyrolyzer of raw and acid washed Coronach lignite. Results from the pyrolysis of raw Coronach at 650°C indicate that this lignite decomposes to yield more tar than that of Estevan lignite. Gas and water yields are lower and char yields higher than those of Estevan lignite pyrolyzed on the bench scale unit. However, some of these differences can be attributed to the hot char pot of the bench scale pyrolyzer which promotes more complete devolatilization of the char resulting in slightly higher gas yields and lower char yields compared to the pilot scale pyrolyzer. Results shown in Table 3 suggest that acid washing produces higher tar yields. Also, somewhat lower gas yields are obtained which are principally due to lower CO<sub>2</sub> yields, in agreement with results from the bench scale unit.

Figure 3 illustrates the results of tar yields from raw and acid washed Coronach lignite over the temperature range 550° - 730°C. The results indicate that maximum tar yields are obtained at about 650°C in all cases, which agrees with results from earlier work using the bench scale unit. Tar yields from acid washed Coronach were higher than those from raw Coronach at the temperatures tested.

From the results in Table 3 it is obvious that char yields are reduced by acid washing. This reduction is increased at lower temperatures and this trend coincides with the increased tar yield on acid washing which is also greater at lower temperatures.

The decrease of gas yields due to acid washing Coronach lignite, shown in Table 3, are not as great as those due to acid washing Estevan lignite. Gas yields from the Coronach sample are slightly reduced with acid washing for pyrolysis at 650°C, but are very similar at lower temperatures for raw and acid washed coal.

Tyler (1980) reported an empirical correlation for acid washed coals in which the maximum tar yields were related to the atomic H/C ratios of the parent coals. This correlation is illustrated in Figure 4 together with the results from Coronach lignite. Figure 4 also shows the higher tar yields of raw Coronach compared to those of raw Estevan lignite. It appears that the maximum tar yields from both the raw and acid washed coals can be approximately predicted from this correlation for these Canadian lignites.

### Composition of Tar

The results of solvent fractionation of tars from raw and acid washed Coronach lignite are illustrated in Figure 5. The yield of methanol insoluble fractions of the preasphaltenes from acid washed Coronach lignite are slightly lower than those from the raw Coronach. The methanol insoluble fractions are black agglomerates in appearance. Hence it is likely that these methanol insoluble fractions consisting of polymer-like matter could be formed by the direct decomposition of coal and/or by the repolymerization of highly reactive volatile fragments. Generally, these polymerized compounds are undesirable in practical use since they potentially cause some difficulty in supplying tar to potential users. From this point of view, it is indicated that the acid washing of Coronach lignite might be effective in reducing the methanol insoluble fractions comprising these polymer-like components.

Although Runs P-83 and P-80 have very similar tar yields, the tar from acid washed Coronach (P-83) contains a larger asphaltene fraction than the tar produced from the raw lignite (P-80). Even the asphaltene fraction obtained from acid washed coal at the lowest temperature of 553°C is slightly higher than that from the raw coal pyrolyzed at 652°C. Thus it is concluded that acid washing Coronach lignite results in higher asphaltene yields.

The preasphaltene fraction of the acid washed lignite pyrolyzed at 553°C is larger than that of the raw coal pyrolyzed at 581°C, however this difference disappears for the runs at 650°C. There was no observed effect on the oil yield due to acid washing.

Consequently, it can be concluded that the increased tar yields by acid washing treatment are primarily due to the increase in the yields of asphaltene fractions.

Figure 6 shows some results from the GC-MS analysis of the asphaltene fraction of a raw and an acid washed Coronach lignite tar sample. The results show that the concentrations

of catechol and of methyl catechol increase remarkably when pyrolyzing the acid washed lignite, while the concentrations of phenol and related compounds are less affected by the acid washing treatment. This suggests that the removal of cations from Coronach lignite in some way affects the catechol precursors such that the production and evolution of catechol is enhanced. Secondary vapour-phase reactions are not assumed, therefore, to be responsible for the significant increase in catechol content in the asphaltene fraction of pyrolysis tar from Coronach lignite.

#### Char Reactivity

The effect of the cation content of the parent coal on char reactivity in carbon dioxide was also studied using thermogravimetric analysis. Figure 7 shows the results of four separate TGA runs with samples of Estevan lignite given different cation removal pretreatments but with identical devolatilization steps which conform to the TGA proximate analysis method. This procedure ensures that devolatilization is complete at the reaction temperature and that the reaction of  $\text{CO}_2$  with the fixed carbon is the only significant weight-loss mechanism occurring.

The results shown in Figure 7 clearly illustrate the differing char reactivities for different coal pretreatment. The numerical values given in Figure 7 are the initial rates of reaction of the Estevan lignite chars in  $\text{CO}_2$  at  $950^\circ\text{C}$ . Clearly the initial reaction rates varied directly with the inorganic content of the parent coal. The demineralized sample was virtually unreactive with  $\text{CO}_2$ . An acid washed sample ( $\text{pH}=0.8$ ) reacted at  $0.8(\text{g/gh})\text{maf}$  while a char sample from raw lignite in which the exchangeable cations were replaced with ammonium ions reacted at  $1.47(\text{g/gh})\text{maf}$  or 1.8 times as fast as the acid washed sample. The raw lignite char had the highest reactivity, as expected, at  $8.46(\text{g/gh})\text{maf}$ . Apparently, the inorganic cations associated with the organic part of the coal are able to catalyze the char- $\text{CO}_2$  reaction and therefore removing these cations reduces the char reactivity. It is difficult to suggest why the ammonium-form coal, in which it is assumed that all the exchangeable inorganic cations were removed, reacted faster than the acid washed coal. Possibly the discrete mineral phase also plays a role in the catalysis of the reaction, or possibly the remaining catalysts in the acid washed coal were affected by residual acid.

### Acknowledgments

The work was carried out with the financial support of the Energy Research Laboratories, Canada Centre for Mineral and Energy Technology (CANMET) of Energy, Mines and Resources Canada. One of the authors (S. Miyawaki) also wishes to express his thanks to the Nippon Mining Co. for the award of a scholarship for graduate study.

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Table 1: Ultimate and Proximate Analysis  
of Raw and Acid Washed Saskatchewan Lignites

	As Pyrolyzed		moisture and ash free basis						
	moisture	ash	volatile matter	fixed carbon	C	H	N	Diff. (O+S)	Atomic H/C
Coronach, raw	27.77	12.52	50.22	49.78	66.54	4.38	0.83	28.25	0.79
Coronach, pH=2.5	20.91	6.98	45.99	54.01					
Estevan, raw	6.66	6.24	47.83	52.15	68.75	4.36	1.80	25.10	0.70
Estevan, pH=4.0	12.64	5.25			70.99	4.54	1.84	22.63	0.77
Estevan, pH=3.5	10.41	4.59			69.22	4.67	1.58	24.53	0.81
Estevan, pH=3.0 <sup>1</sup>	0.84	5.24			70.06	4.38	1.41	23.25	0.74
Estevan, pH=2.5	0.0	2.63			66.07	4.08	1.66	28.60	0.86
Estevan, pH=1.5	1.34	2.74			64.53	4.44	0.96	30.10	0.83
Estevan, pH=0.8	0.17	2.58	49.30	50.58	68.22	4.63	1.44	25.70	0.81

1. acid washed in H<sub>2</sub>SO<sub>4</sub>

Table 2 : Inorganic Contents of Raw and Acid Washed Lignite

	gram equivalents/ kg dry coal				Total
	Ca	Mg	Na	K	
Coronach, raw	1.01	0.40	0.04	0.03	1.48
Coronach, pH=2.5	0.16	0.01	0.01	0.02	0.20
Estevan, raw	0.53	0.21	0.53	0.02	1.29
Estevan, pH=4.0	0.47	0.16	0.30	0.01	0.94
Estevan, pH=3.5	0.40	0.12	0.28	0.01	0.81
Estevan, pH=3.0 <sup>1</sup>	0.37	0.06	0.19	0.01	0.63
Estevan, pH=2.5	0.16	0.03	0.20	0.01	0.40
Estevan, pH=1.5	0.07	0.02	0.19	0.01	0.29
Estevan, pH=0.8	0.04	0.02	0.19	0.003	0.25

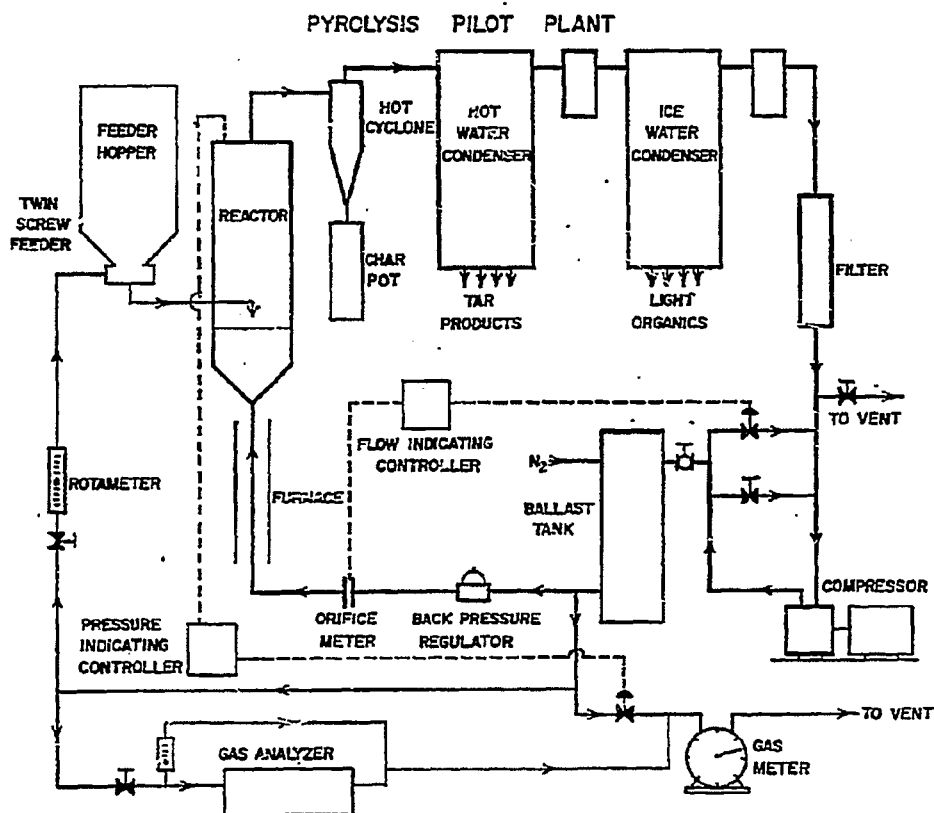
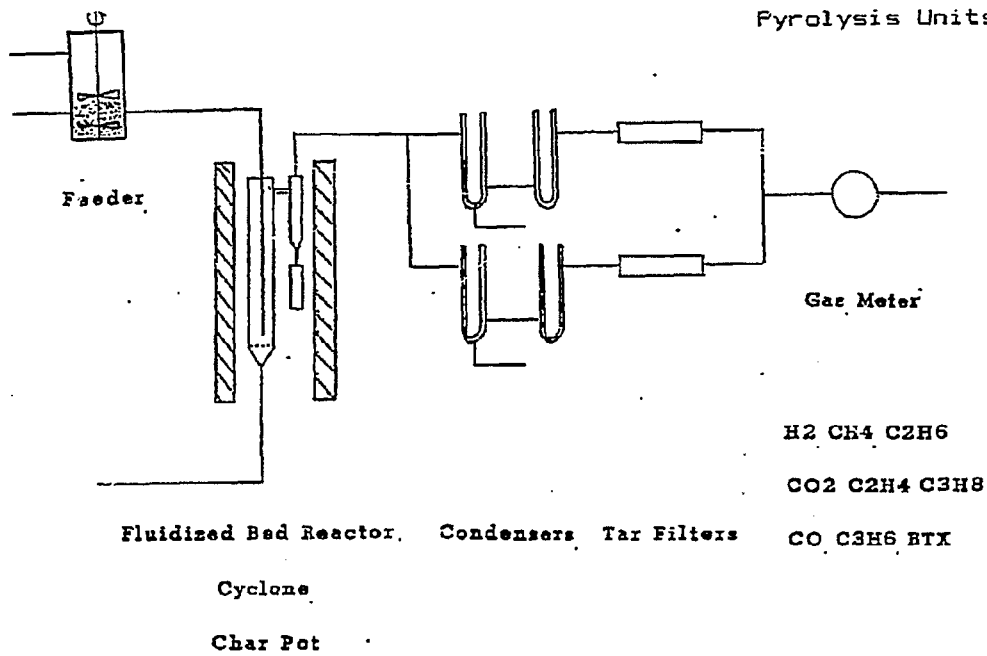
1. acid washed in H<sub>2</sub>SO<sub>4</sub>

Table 3. Effect of acid washing on product yields, pilot plant pyrolysis, Coronach lignite #3, pH=2.5, HCl.

	Acid washed			Original	
	P-84	P-82	P-83	P-85	P-80
Temperature(°C)	553	652	732	581	652
Residence time(s)	0.50	0.46	0.41	0.46	0.45
Feed rate(kg/h)	1.657	1.535	1.577	1.635	1.590
Moisture(wt %)	20.91	20.91	20.91	22.77	22.77
Ash(dry wt %)	8.83	8.83	8.83	16.21	16.21
Product yields, wt % maf coal					
Gas	13.35	16.55	21.07	13.87	17.06
Tar	15.20	19.95	17.53	12.47	17.32
Char	63.18	57.31	55.69	67.99	58.97
Water	9.25	7.41	12.22	6.37	8.50
Total	101.48	101.22	106.51	100.70	101.85
Gaseous products, wt % maf coal					
H <sub>2</sub>	0.07	0.11	0.17	0.08	0.14
CO	4.14	5.93	9.69	3.26	5.81
CO <sub>2</sub>	7.39	8.38	8.29	8.80	8.83
CH <sub>4</sub>	1.31	1.59	2.05	1.25	1.77
C <sub>2</sub> H <sub>4</sub>	0.54	0.33	0.57	0.23	0.32
C <sub>2</sub> H <sub>6</sub>	0.17	0.08	0.12	0.12	0.09
C <sub>3</sub>	0.14	0.07	0.09	0.08	0.06
C <sub>4</sub>	0.09	0.06	0.09	0.06	0.04
Total	13.85	16.55	21.07	13.87	17.06



Figure 1 : The Waterloo Bench Scale and Pilot Scale Flash Pyrolysis Units



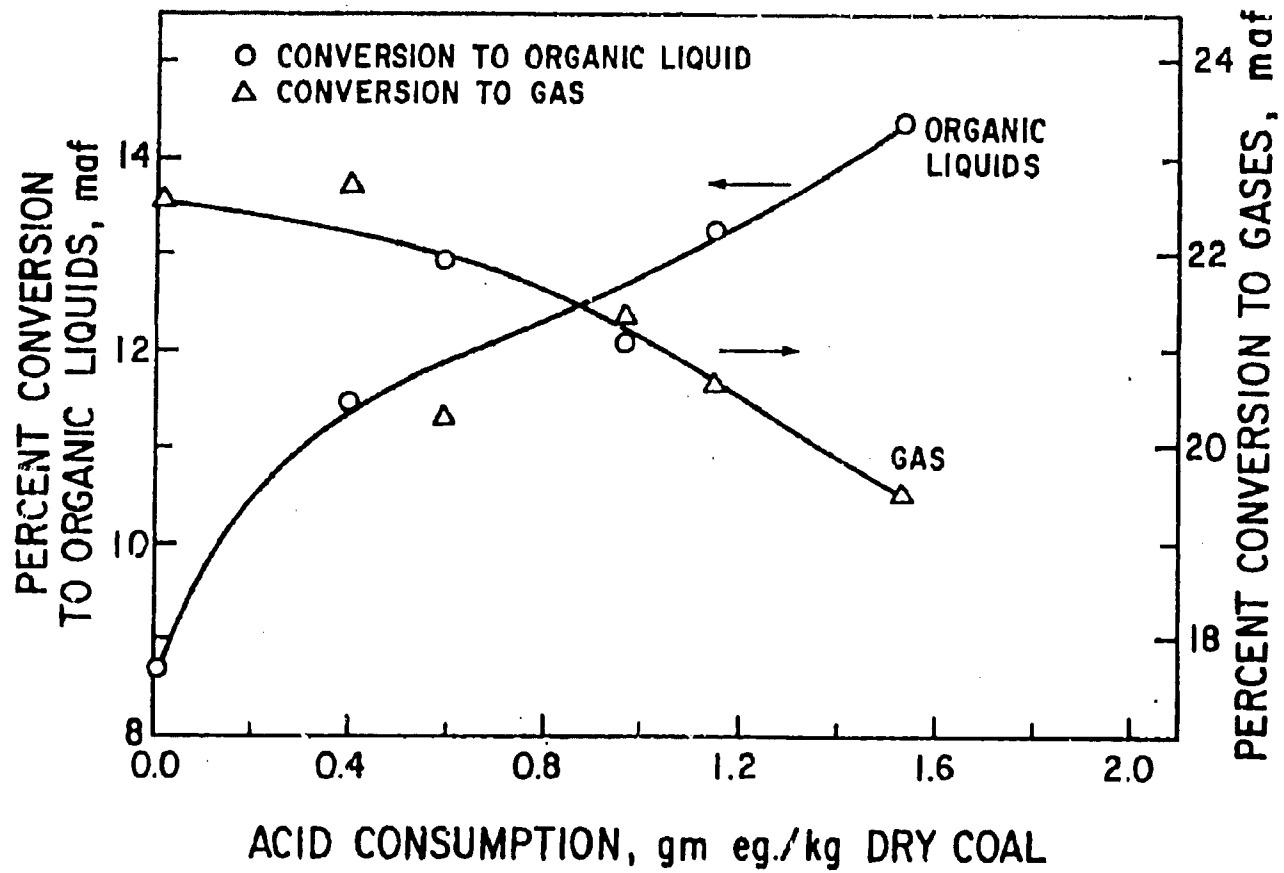


Figure 2 : Tar and Gas Yields vs. Acid Consumption for Estevan Lignite

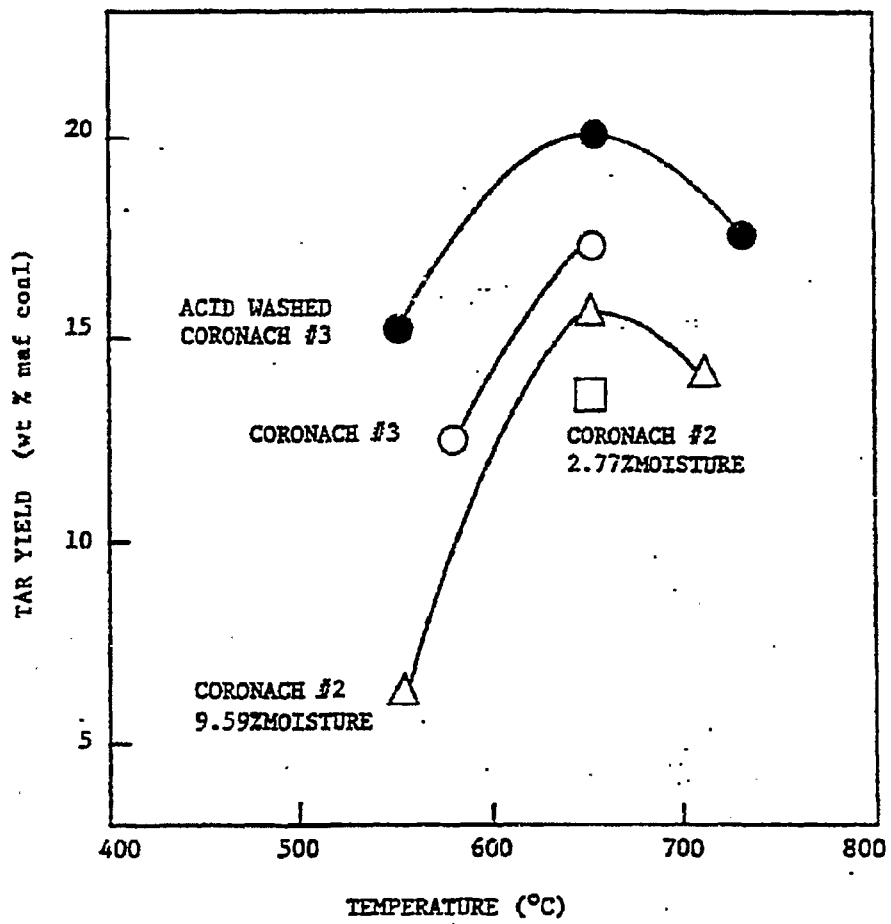


Fig. 3. Tar yields from Coronach lignites, pilot plant pyrolysis.

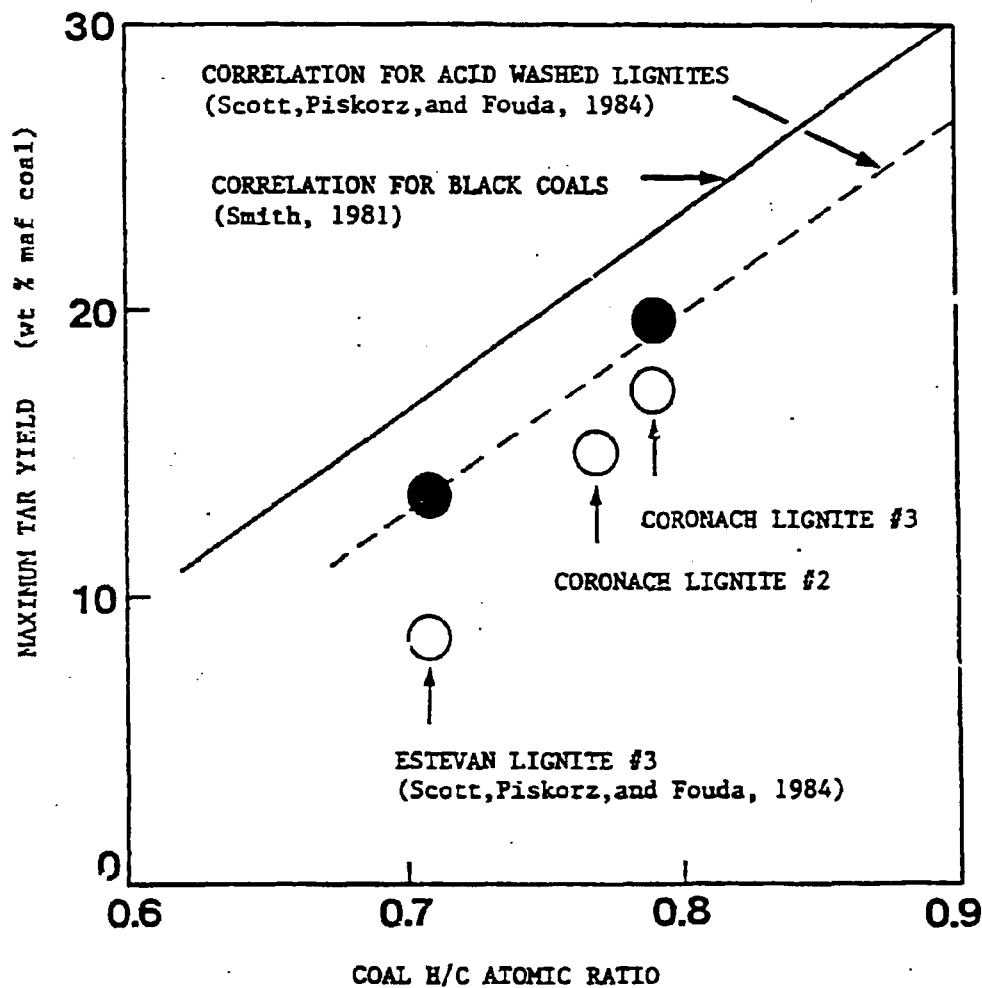


Fig.4. Correlation for acid washed lignites

- acid washed lignites
- original lignites

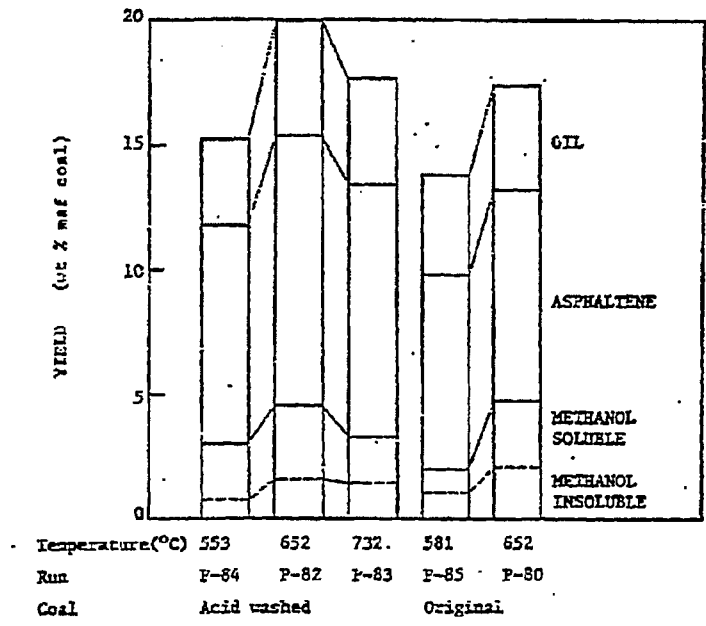


Fig. 5. Solvent fractionation of tars, effect of acid washing, pilot plant pyrolysis, Coronach lignite #3.

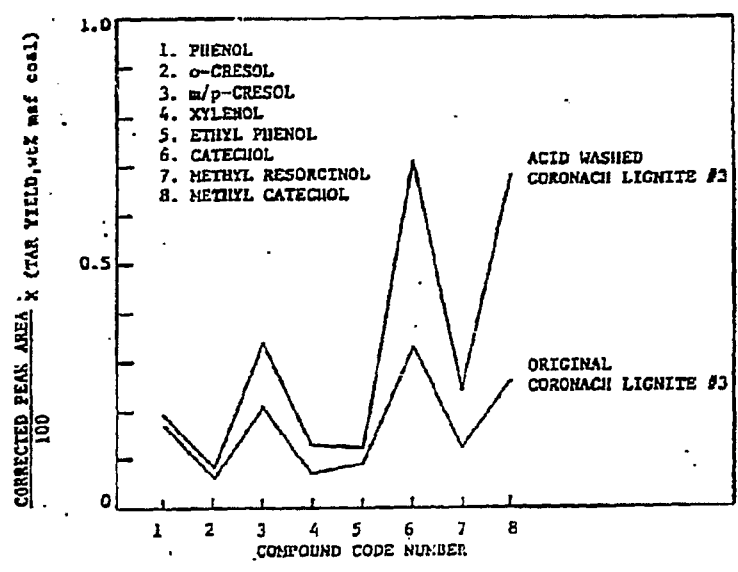


Fig. 6. Concentration of major compound in toluene soluble fraction, pilot plant pyrolysis, low rank coal.

Note: Compounds are labeled with numbers 1 to 8 in order of retention time.

EFFECT OF EXCHANGEABLE CATIONS ON THE REACTIVITY  
OF SASKATCHEWAN LIGNITE CHAR IN CO<sub>2</sub> AT 950°C

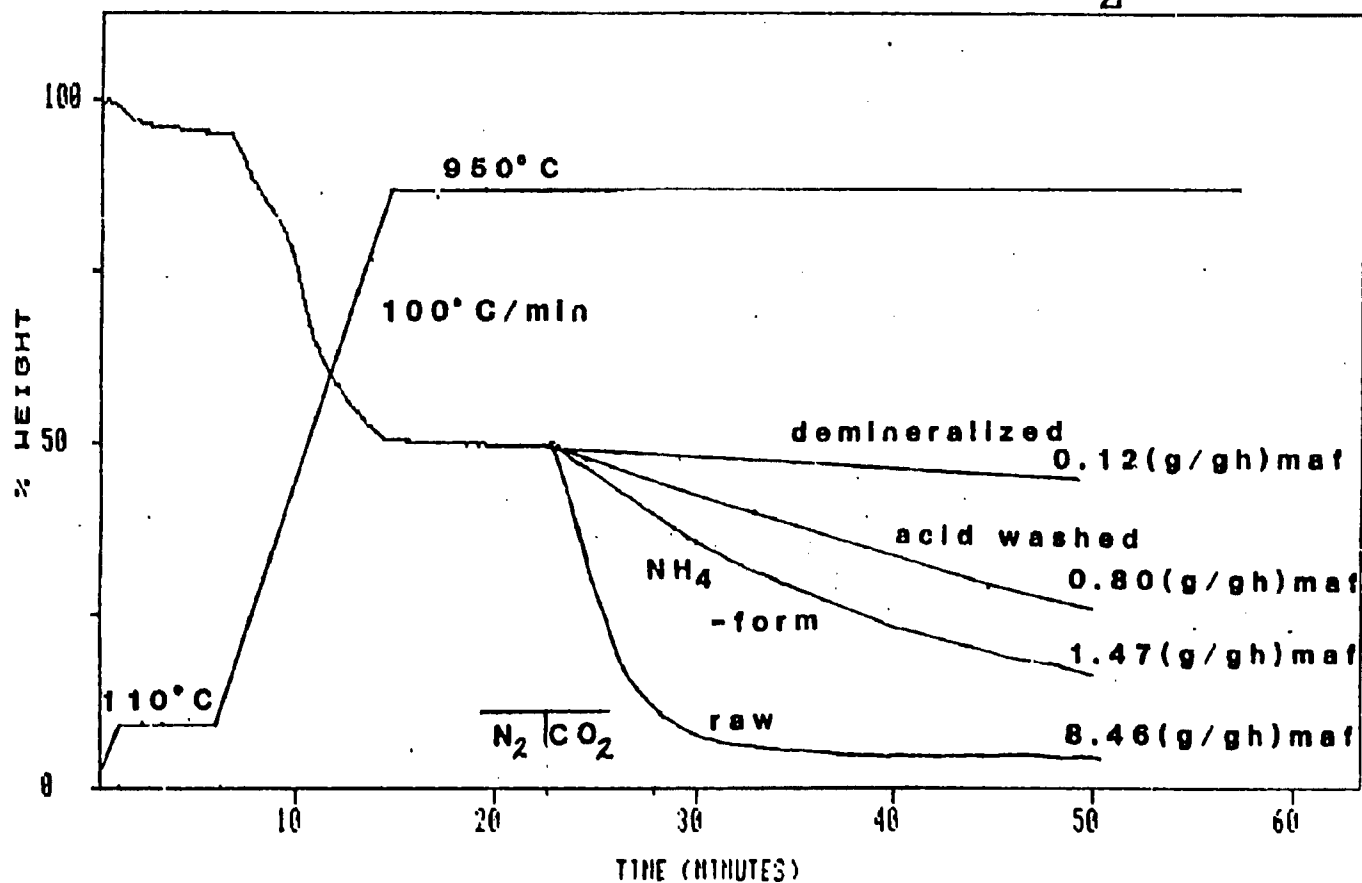


Figure 7 : The Effect of Exchangeable Cations on the Reactivity of Saskatchewan Lignite Char in Carbon Dioxide

THE EFFECT OF COAL CLEANING ON THE COMBUSTION  
PERFORMANCE CHARACTERISTICS OF BIG BROWN LIGNITE

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ABSTRACT

Texas Utilities Electric Company (TU Electric) and the Electric Power Research Institute (EPRI) co-sponsored a comprehensive research program to assess the feasibility of physically cleaning Wilcox Formation lignite to improve power plant performance. Under this program, lignite from the Big Brown Mine and cleaned lignite produced at EPRI's Coal Cleaning Test Facility were studied. The impacts of coal cleaning on boiler fireside performance were evaluated during a series of bench-scale and pilot-scale combustion tests conducted by Combustion Engineering at their Kreisinger Development Laboratory.

Results of this evaluation show that coal cleaning has beneficial effects on several areas of fuel-related performance. Mill wear potential and grinding energy requirements were reduced for the cleaned lignite. Contrary to predictions based on commonly used bench-scale indicators, pilot-scale combustion results showed improved ash slagging and fouling behavior. Fly ash erosion potential decreased significantly due to cleaning. The performance benefits of the cleaned lignite can be translated into potential operating savings from maintenance cost reductions due primarily to longer component life. Additional benefits can come from improved plant heat rate due mainly to lower pulverizer power consumption, and reduced sootblower medium consumption, and from estimated increases in unit availability.

INTRODUCTION

Coal cleaning offers a means of improving fuel quality which can reduce plant operating costs and improve plant availability. It is necessary to quantify impacts of fuel performance in order to accurately assess the expected plant-side benefits that coal cleaning may offer toward electrical generating costs. To evaluate and demonstrate the merits of coal cleaning, Combustion Engineering (C-E) was contracted by the Electric Power Research Institute (EPRI) to conduct a comprehensive research program to assess and compare the combustion performance characteristics of run-of-mine (ROM) coals with their cleaned counterparts.

A Texas lignite from the Wilcox formation, burned at TU Electric's Big Brown Steam Electric Station in Fairfield, Texas, and its cleaned coal, prepared at EPRI's Coal Cleaning Test Facility (CCTF) at Homer City, Pennsylvania, were evaluated under this project. The test program was developed to determine key fuel performance characteristics affecting boiler operation. The evaluation program consisted of both bench-scale and pilot-scale testing. Specific test areas addressed included:

- o Relative pulverizer power consumption and relative mill component wear rates.
- o Relative flame stability and carbon conversion efficiencies.
- o Ash slagging potential through determination of waterwall deposit cleanability as a function of firing conditions.
- o Ash fouling potential through determination of convection tube deposit cleanability as a function of firing conditions.
- o Effect of ash deposition on waterwall and convection tube heat transfer.
- o Convection tube fly ash erosion rates.
- o Gaseous and particulate emissions.
- o Electrostatic precipitator performance characteristics through measurement of relative ash collection efficiencies, relative power consumption, and fly ash electrical resistivity.

Results of the combustion tests were used in conjunction with C-E's Boiler Performance Program (BPP) to predict the performance of the cleaned lignite in the Big Brown boiler.

#### METHODOLOGY

##### Bench-Scale Characterization

A series of standard ASTM coal analyses were performed on composite pulverized fuel samples collected during the pilot-scale combustion tests. Supplemental C-E bench-scale tests were conducted to provide additional information on the combustion and mineral matter characteristics of each fuel. These were:

- o Abrasion index - Measure of relative mill wear potential.
- o Gravity fractionation analysis - Indication of propensity for selective deposition of iron - relative ash slagging potential.
- o Weak acid leaching - Measure of the "active alkali" concentration - relative ash fouling potential.
- o Quartz content - Indication of both coal and fly ash abrasion and erosion characteristics.
- o Thermo-gravimetric analysis (TGA) - Measurement of relative fuel reactivity and carbon burnout properties of chars generated in C-E's Drop Tube Furnace System (DTFS).
- o Pore surface area (BET) - Measurement of DTFS char specific surface area.

In addition to the above bench-scale tests, various advanced analytical techniques such as Mossbauer analysis, X-Ray Diffraction (XRD) and Computer-Controlled Scanning Electron Microscopy (CCSEM) and other techniques were used to provide detailed fundamental data on the mineral composition and mineral size distribution within each fuel. Similar data is also being obtained on in-flame solid samples as well as ash deposits collected during combustion (



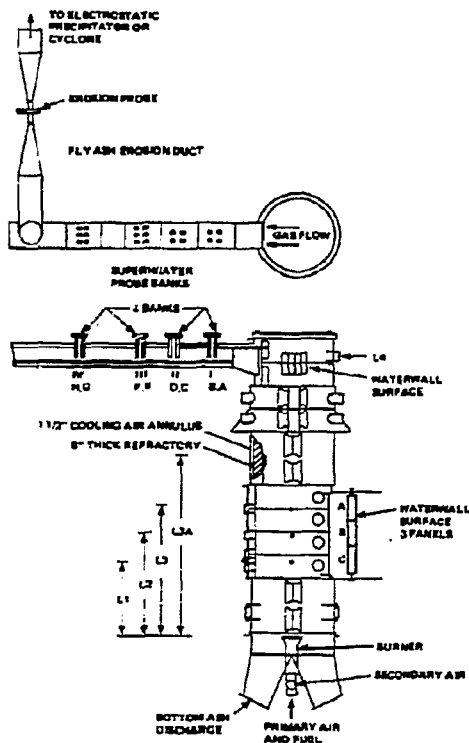


FIGURE 1. FIRESIDE PERFORMANCE TEST FACILITY

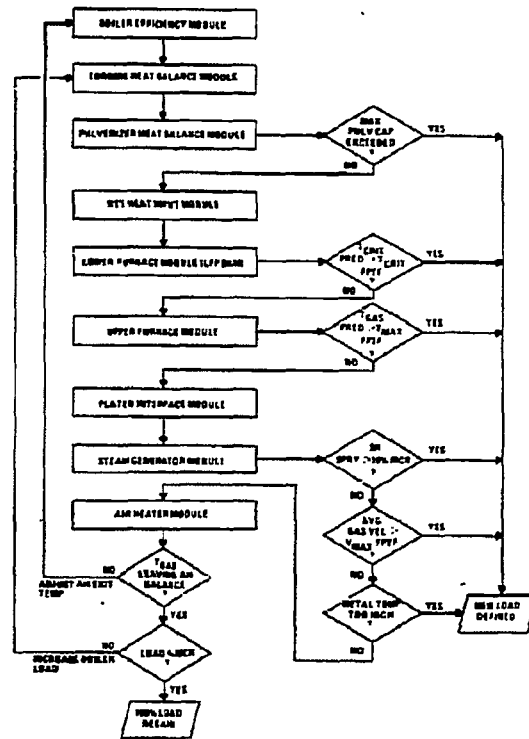


FIGURE 2. BOILER PERFORMANCE PROGRAM FLOWCHART FOR CLEANED COAL PREDICTIONS

testing C-E's Fireside Performance Test Facility (FPTF), shown in Figure 1 (1). Results of these advanced methods are currently being correlated to FPTF combustion performance to improve the understanding of the influence of critical fuel properties and ultimately improve the reliability of performance predictions based upon fundamental fuel properties.

#### Pilot-Scale Pulverization Tests

The pulverization characteristics of each lignite were evaluated in a C-E Model RB-271 bowl mill. Tests were conducted at coal feed rates of 1500 lb/hr, 1000 lb/hr, and 750 lb/hr. Coal feed rates were controlled by a weigh-belt gravimetric feeder. Coal particle size was controlled through adjustment of mill classifier vanes, to obtain a coal fineness of 70 percent  $\pm$  3 percent passing 200 mesh (75 micron). Grinding energy requirements were determined by measuring mill motor power consumption with a recording wattmeter.

#### Pilot-Scale Combustion Tests

Combustion testing was conducted at fuel firing rates between 3.4 MBtu/hr and 3.8 MBtu/hr, and furnace temperatures between 2850°F and 2975°F allowing ash deposit characteristics to be determined over a range of typical boiler operating conditions. The furnace gas temperatures and radiative heat flux were measured periodically during each test with a high velocity suction pyrometer and a 2 $\pi$  ellipsoidal radiometer.

Initially, test furnace conditions (i.e., fuel heat input, furnace temperature, excess air, and fuel fineness) were established to simulate the general operating conditions of the Big Brown Station, Unit No. 1, firing Wilcox seam ROM lignite. Based upon the baseline test results, increasing furnace loads were evaluated for the cleaned coal. Subsequent firing rates were adjusted based upon observed fireside performance, with the objective of converging on the maximum conditions at which each fuel could be burned without ash deposition problems. From a slagging standpoint, these maximum conditions were defined as the highest thermal loading (firing rate) and flame temperature (defined as critical furnace temperature) at which the FPTF could operate and still generate cleanable waterwall deposits. Each lignite was evaluated for over 60 hours of continuous test firing.

Ash slagging potential was assessed from deposit cleanability (soot blower effectiveness) and the effect of ash deposits on waterwall heat transfer. The higher the thermal loading at which the coal could be fired and still maintain cleanable deposits, the lower the slagging potential. Deposit cleanability was determined both by visual assessment and by comparison of the waterwall heat absorption before and after sootblowing at the end of each test run.

The fouling potential was assessed by determining the convection deposit cleanability and the deposit buildup rates. Deposit cleanability was determined by on-line deposit-to-tube Bonding Strength Measurements (BSM's) and subjective assessment during soot blowing. Bonding strength measurements were taken after a 2 to 3 inch deposit accumulated. Following these measurements, the remaining deposits were removed to initiate another deposit buildup cycle. This sootblowing frequency was used to measure the rate of deposit buildup.

Convection tube fly ash erosion characteristics were studied in a high velocity test section downstream of the convection tube banks. Tube specimens were exposed to the particulate laden flue gas at gas velocities of approximately 200 ft/sec. High gas velocities were used to accelerate erosion and provide measurable wear within the test period. The amount of erosion was determined using a radioactive surface measurement technique (2). Erosion data were normalized for gas velocity and ash loading.

#### Boiler Modeling

C-E's Boiler Performance Program (BPP) was used to model the study boiler. The BPP is a computational tool that was developed to select various boiler components for new boiler designs and then predict the performance of the system. Calculations are performed for the steam generator envelope and related auxiliary equipment to provide information required for detailed component design.

The BPP was calibrated using field performance data from Big Brown No. 1 prior to the cleaned coal performance calculations. This calibration was conducted to improve the accuracy and confidence level of the BPP predictions by reducing the number of assumptions about the fireside heat transfer characteristics and to develop laboratory-to-field scale-up factors specific to the study unit. The calibration procedure begins with the input of all known temperatures, pressures and flowrates from the steam and gas sides of the study boiler. Fundamental fuel kinetic data and high temperature fuel swelling factors required in calibrating the lower furnace combustion model were selected from C-E's

comprehensive DTFS data bank based upon results of the TGA and BET surface area analyses performed on the lignite chars generated in the DTFS (3). The BPP was then used to back-calculate several unknown parameters that affect boiler heat transfer. Some of the important parameters established included:

- o Furnace gas and wall radiative properties
- o Lower furnace average slag conductance
- o Boiler tube surface effectiveness
- o Air preheater leakage and gas side efficiency

Once these values were determined, the BPP was run in the forward sequence with these calculated parameters used as input along with the FPTF and bench-scale test data on the baseline lignite to establish specific scale-up factors. These scale-up factors were then applied using the cleaned lignite test results to predict boiler performance. Figure 2 shows the flow chart for the BPP cleaned coal prediction procedure. The BPP was run in an iterative mode until fireside and steamside performances balanced. Boiler operating limits (listed below) for the cleaned lignite were based upon FPTF test results and C-E's engineering standards.

<u>Operating Limit</u>	<u>Source</u>
o Pulverizer Capacity (lb/hr)	C-E Standard
o Critical Slagging Temp (°F)	FPTF
o Critical Fouling Temp (°F)	FPTF
o Max. Gas Velocity (erosion) (ft/sec)	FPTF
o Superheat Spray Water Flow (lb/hr)	C-E Standard
o Reheat Spray Water Flow (lb/hr)	C-E Standard
o Tube Metal Temp (°F)	C-E Standard

#### BENCH-SCALE RESULTS

##### ASTM Methods

Bench-scale analytical results for the baseline and cleaned lignite are summarized in Table 1. The baseline lignite is fairly typical of a high ash, low sulfur Gulf state lignitic coal. Coal cleaning reduced the ash content from 19.1 lb ash/MBtu for the baseline coal to 10.1 lb ash/MBtu for the cleaned coal. Sulfur content was reduced by approximately 10%, from 1.1% on a dry basis (DB) for the baseline coal to 1.0% (DB) for the cleaned coal, primarily through the reduction in pyrite. The sulfur present in this coal is predominantly in an organically associated form which limits sulfur removal through physical cleaning. The heating value increased from 10,135 Btu/lb (DB) to 11,235 Btu/lb (DB), reflecting the reduction in mineral matter due to cleaning.

Silica and alumina contents in the baseline ash decreased with cleaning while iron, calcium and magnesium contents increased reflecting the removal of coarse quartz particles and fine clay minerals. Ash fusion temperatures decreased with cleaning, reflecting the higher basic constituents in the cleaned coal ash. Ash fusion temperatures, determined under both reducing and oxidizing atmospheres, show that ash fusibilities are not affected by the oxidation state of the iron present in the ash indicating that the low ash fusion temperatures are not caused by the fluxing effects of iron.

Table 1

## FUEL ANALYSES OF TEXAS LIGNITES\*

	<u>Baseline</u>	<u>Cleaned</u>		
<b>Proximate (wt.%)</b>				
Volatile Matter	42.3	45.7		
Fixed Carbon	38.3	43.0		
Ash	19.4	11.3		
Total	100.0	100.0		
<b>Ultimate (wt.%)</b>				
Carbon	60.8	67.8		
Hydrogen	5.2	4.7		
Sulfur	1.1	1.0		
Nitrogen	1.5	1.5		
Oxygen	11.9	13.7		
Ash	19.4	11.3		
Total	100.0	100.0		
<b>Sulfur Forms (wt.%)</b>				
Pyritic	0.2	0.1		
Sulfate	0.1	0.1		
Organic	0.8	0.8		
HEV (Btu/lb)	10135	11235		
<b>Ash Composition (wt.%)</b>				
	<u>Ash Basis</u>	<u>Coal Basis</u>	<u>Ash Basis</u>	<u>Coal Basis</u>
SiO <sub>2</sub>	54.5	10.6	39.8	4.5
Al <sub>2</sub> O <sub>3</sub>	15.9	3.1	13.8	1.6
Fe <sub>2</sub> O <sub>3</sub>	5.5	1.1	7.3	0.8
CaO	11.3	2.2	18.0	2.0
MgO	1.9	0.4	2.8	0.3
Na <sub>2</sub> O	0.5	0.1	0.6	0.1
K <sub>2</sub> O	0.7	0.1	0.4	<0.1
TiO <sub>2</sub>	1.1	0.2	1.7	0.2
SO <sub>3</sub>	8.9	1.7	15.7	1.8
Total	100.0	19.4	100.1	11.3
<b>Ash Fusion Temperatures (°F)</b>				
	<u>Reducing</u>	<u>Oxidizing</u>	<u>Reducing</u>	<u>Oxidizing</u>
IDT	2030	2050	2010	2030
ST	2120	2120	2050	2060
HT	2260	2280	2100	2110
FT	2310	2320	2110	2120

\*dry basis

Supplemental Methods

The results of the supplemental bench-scale tests are shown in Table 2. In general, these results indicate that coal cleaning should improve overall fuel and ash performance characteristics. Weak acid leaching results show that both coals have low concentrations of active alkalis indicating low fouling potentials(4). The gravity fractionation analysis indicates a lower slagging potential with a reduction in segregated iron content in the cleaned coal(5). Mossbauer spectra of these lignites show that the iron is primarily present as pyrite. Cleaning reduced the pyrite content in baseline lignite by approximately 50% from 0.6 wt.% (dry coal basis) for the baseline lignite to 0.3 wt.% (dry coal basis) in the cleaned lignite.

Table 2

## FURNACE SLAGGING AND FOULING INDICES OF THE BASELINE AND CLEANED TEXAS LIGNITES

## SLAGGING INDICATORS

<u>Bench-Scale Indicators(1)</u>	<u>Baseline</u>		<u>Cleaned</u>		<u>Ref.</u>
	<u>Index</u>	<u>Potential</u>	<u>Index</u>	<u>Potential</u>	
Fusion Slagging Index, °F(2)	2110	high	2180	high	(7,8)
Base-Acid Ratio	0.3	moderate	0.5	high	(9)
Iron-Calcium Ratio	0.5	high	0.4	high	(7,9)
Slag Viscosity Temperature (T250), °F					
method of Sage and McIlroy (3)	2550	low-to-moderate	2300	low-to-moderate	(10)
method of Duzy (4)	2500	low-to-moderate	2130	moderate-to-high	(10)
Ash Fluid Temperature (Red. Atm.), °F	2310	high	2110	severe	
Gravity Fractionation (wt. % Fe <sub>2</sub> O <sub>3</sub> in 2.8 sink)	60	moderate	48	low	(5)
Overall Slagging Potential		moderate		high	
<u>Pilot-Scale Results</u>					
Slagging Potential		moderate		low-to-moderate	

## FOULING INDICATORS

Bench-Scale Results

Na <sub>2</sub> O in ash, wt. %	0.5	low	0.6	low	(7,10)
Weak Acid Leaching (wt. % Active Na <sub>2</sub> O-ash basis)	0.3	low	0.6	low	(4)
Ash Initial Deformation Temp (Red. Atm.), °F	2030	moderate	2010	moderate	
Overall Fouling Potential		low		low	

Pilot-Scale Results

Fouling Potential		moderate-to-high		low-to-moderate	
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(1) Indices calculated from ash analysis by ASTM D-3174, Table 1

(2) From Ash Fusion Data in Table 1

(3) Valid for Lignitic Ash Type, Having an Acidic Content greater than 60%

(4) Valid for Lignitic Ash Type, Having an Acidic Content less than 60%

Results of CCSEM mineralogical analysis identifying major discrete minerals in the two fuels are shown in Table 3, and the particle size of the discrete minerals are shown in Table 4. These data, obtained on the pulverized fuel, indicate that coal cleaning reduced the discrete mineral content of the baseline lignite by predominantly removing the coarse (>20 microns) quartz particles and the fine (<2.5 microns) clay minerals. However, the discrete minerals identified by CCSEM analysis represent approximately 63% of the total ash in the baseline lignite and 46% of the total ash in the cleaned lignite. These results indicate that a considerable amount of the inorganic constituents are within the coal possibly as submicron mineral particles or chemically bound in the organic matter of the coal and are undetected by this CCSEM technique.

Table 3

## MAJOR MINERALS (BY CCSEM) OF THE BASELINE AND CLEANED LIGNITES

	Baseline		Cleaned	
	Z MM <sup>a</sup>	Z Coal	Z MM	Z Coal
Quartz, SiO <sub>2</sub>	47	5.74	48	2.56
Kaolinite, Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub>	2	0.24	9	0.47
Illite, KAl <sub>2</sub> (AlSi <sub>3</sub> ) <sub>2</sub> O <sub>10</sub> (OH) <sub>2</sub>	3	0.37	3	0.16
Montmorillonite, Al <sub>2</sub> Si <sub>4</sub> O <sub>10</sub> (OH) <sub>2</sub> ·xH <sub>2</sub> O	5	0.61	2	0.10
Minor Minerals <sup>b</sup>	8	0.98	14	0.73
Mixed Clay Minerals	29	3.54	18	0.94
Miscellaneous	6	0.73	5	0.26
Total	100	12.21 <sup>c</sup>	100	5.22 <sup>c</sup>

(a) Z MM = Discrete Minerals

(b) Minor minerals consist of gypsum, pyrite and its various oxidized forms, calcite, and rutile.

(c) Mineral matter in the coal was calculated based upon the total quartz content in the coal measured by XRD methods as a basis.

Table 4

SIZE DISTRIBUTION (by CCSEM) OF MAJOR MINERALS  
IN THE BASELINE AND CLEANED LIGNITE

Size Range (microns)	Discrete Minerals (Wt. %)				Quartz (Wt. %)			
	Baseline		Cleaned		Baseline		Cleaned	
	Z MM <sup>a</sup>	Z Coal	Z MM <sup>a</sup>	Z Coal	Z MM <sup>a</sup>	Z Coal	Z MM <sup>a</sup>	Z Coal
>40	23	2.8	13	0.7	31	1.8	16	0.4
20-40	21	2.6	14	0.7	31	1.8	13	0.3
10-20	14	1.7	16	0.8	13	0.7	15	0.4
5-10	13	1.6	18	0.9	10	0.6	21	0.5
2.5-5	7	0.9	17	0.9	5	0.3	16	0.4
<2.5	21	2.6	22	1.2	10	0.6	18	0.5
TOTAL		12.2		5.2		5.7		2.5

(a) MM = Discrete Minerals

The CCSEM results agree with XRD data on the crushed (3/8 x 0) fuels indicating the reduction of greater than 100 micron quartz particles in the cleaned lignite. Fewer large quartz particles is consistent with the Abrasion Index indicating lower fuel abrasiveness; large quartz particles contained in the fuel are believed to significantly contribute to pulverizer wear (6).

Analysis of the Big Brown lignites by extended x-ray absorption fine structure (EXAFS) spectroscopy and energy dispersive x-ray (EDX) spectra indicate the calcium and sulfur are dispersed throughout the coal matrix and are not subject to removal by physical cleaning. This largely explains the enrichment of calcium (11% to 18% CaO, Table 1) in the cleaned lignite ash and the subsequent increase in its base-acid ratio and also sheds some light on the apparent discrepancies between the CCSEM minerals analysis and ASTM ash analysis.

The bench-scale ash performance indices have been summarized in Table 2, along with various coal ash performance indices tabulated from various workers (4, 5, 7, 8, 9, 10). In general, ASTM-based and supplemental indicators predict that the slagging and fouling performance of the baseline fuel will worsen with cleaning, contrary to pilot-scale combustion results.

#### PILOT-SCALE RESULTS

Pilot-scale pulverization and combustion test results are summarized in Table 5. Test results show that coal cleaning had a beneficial effect on many areas of fuel performance. Both mill wear potential and grinding energy requirements were reduced for the cleaned lignite. Contrary to most bench-scale indices, combustion test results showed improved ash deposition behavior. The cleaned coal also showed a significant reduction in fly ash erosion potential.

##### Pulverization

Pulverization characteristics of the baseline coal were improved by cleaning in terms of reduced mill power requirements. Results given in Table 5 show that pulverizer power consumption decreases with cleaning due primarily to the lower coal throughput associated with the increase in heating value of the cleaned coal. Grinding energy on a unit weight basis was similar, reflecting the similar Hardgrove grindability indices of both fuels at equivalent moisture.

##### Furnace Slagging Characteristics

Furnace slagging characteristics of the Big Brown lignites were assessed by determining deposit buildup rates, the cleanability of deposits by sootblowing (Figure 3), and the impact of slag deposits on heat transfer through a waterwall panel (Figure 4). Furnace slagging results are summarized in Table 5. In general, both the baseline and cleaned coals exhibited moderate slagging potentials. Panel deposits were cleanable up to the maximum furnace temperature tested (2920°F), which corresponds to more severe conditions than those predicted by the BPP at full load in Big Brown No. 1.

Waterwall deposits produced from the cleaned lignite were generally thinner and more sintered in appearance than those produced at similar conditions from the baseline lignite. Comparative photographs on waterwall deposits taken during testing are shown in Figure 3. The effect of ash deposition on waterwall heat transfer rates was typically less for the cleaned lignite reflecting the lighter deposit buildup. An example of this difference is illustrated in plots of waterwall heat flux versus time shown in Figure 4. At flame temperatures of

Table 5

## FPTF RESULTS FROM THE BASELINE AND CLEANED COAL COMBUSTION TESTS

	<u>Baseline</u>	<u>Cleaned</u>
<u>PULVERIZATION</u>		
Relative Grinding Energy, KWh/Mbtu (a),(b)	0.81	0.68
Quartz Particles greater than 100 microns, wt.% (a)	1.46	0.71
Relative Wear - Abrasion Index	76	12
Hardgrove Grindability (HGI) (a)	64	64
<u>ASH SLAGGING</u>		
FPTF Critical Furnace Temperature for Cleanable Deposits, °F	>2900	>2900
FPTF Wall Deposit Emissivity (at 1650°F)	0.95	0.94
FPTF Gas Emissivity Operator(F)	1.20	1.18
Slagging Potential	moderate	low-to-moderate
<u>ASH FOULING</u>		
FPTF Critical Gas Temperature for Cleanable Deposits, °F	2220	2330
FPTF Deposit Bonding Strength (at 2200°F)	14	9
FPTF Sootblowing Frequency, hr (at 2200°F)	8	12
Fouling Potential	low	low
<u>EMISSIONS</u>		
Theoretical SO <sub>2</sub> (measured), lb/MBtu	2.2(2.0)	1.9(1.6)
In Situ Fly Ash Resistivity, ohm-cm x 10 <sup>-12</sup>	2.0	5.0
<u>EROSION</u>		
FPTF Erosion Rate, mils/10 <sup>6</sup> lb ash (c)	1.87	1.81
FPTF Erosion Rate, mils/10,000 hr (c)	1.28	0.68

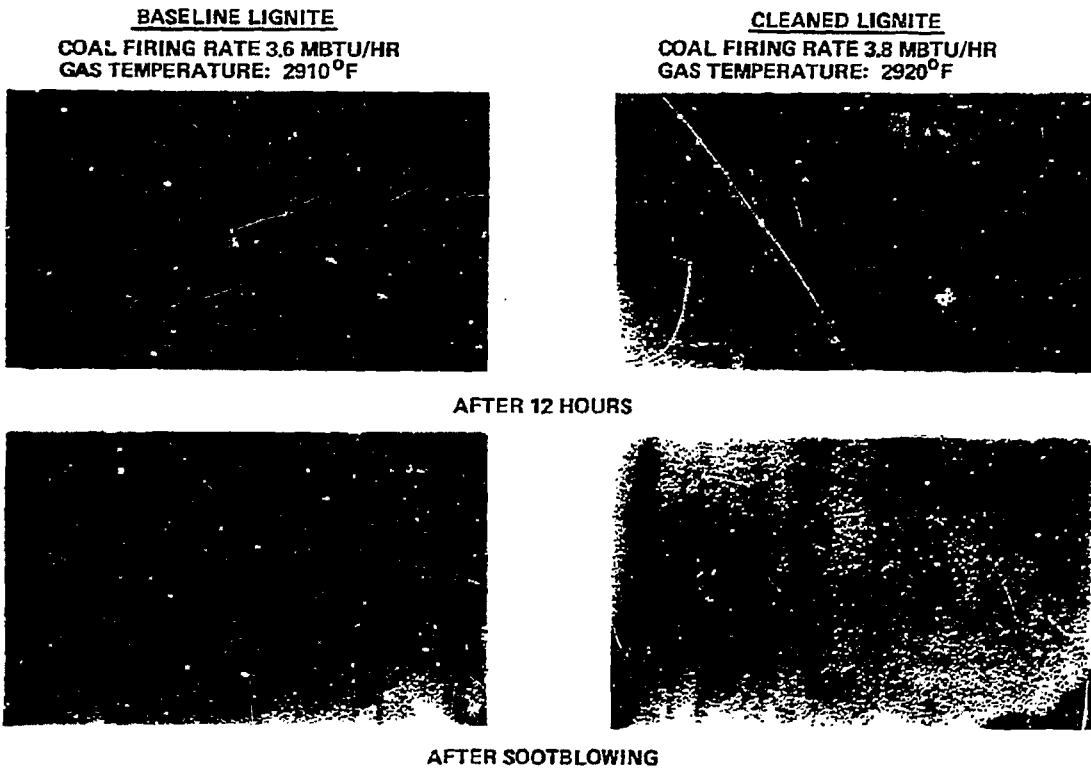
(a) at 30% coal moisture

(b) at 1,500 lb/hr coal feedrate to a Model RB-271 Bowl Mill;  
coal fineness is 70%-200 mesh

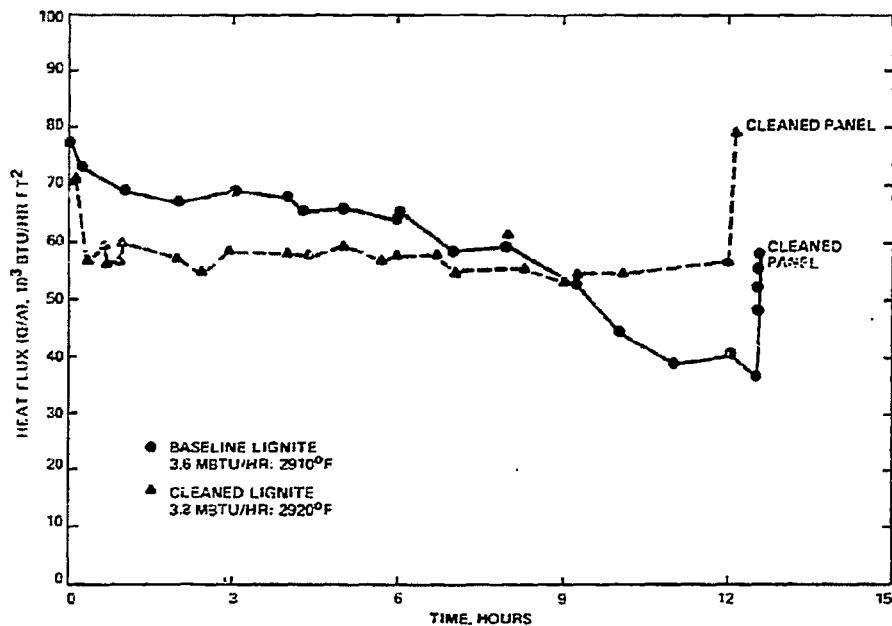
(c) normalized to a gas velocity of 60 ft/sec.

approximately 2920°F, waterwall heat flux gradually decreased to lower values when firing the baseline lignite compared to the heat absorption rate with the cleaned fuel. The spike in the heat flux plots at the end of the test (at approximately 12 hours) is the result of deposit removal (heat flux recovery) during the sootblowing evaluation. Waterwall deposits generated by both fuels were considered cleanable by sootblowing over the range of conditions studied.





**FIGURE 3. SLAG DEPOSITION ON WATERWALL PANEL C DURING TESTING AT MAXIMUM LOWER FURNACE CONDITIONS FOR THE BASELINE AND CLEANED LIGNITES**



**FIGURE 4. HEAT FLUX (Q/A) THROUGH WATERWALL PANEL C AT MAXIMUM LOWER FURNACE CONDITIONS FOR THE BASELINE AND CLEANED LIGNITES**

The improvements in slagging characteristics for the cleaned lignite observed during combustion testing were not clearly predicted by the indices determined from the ASTM data. In fact, most of the commonly used indices indicated that cleaning should have a detrimental effect on ash slagging potential. This anomalous behavior illustrates that conventional bench-scale methods are not always reliable, and emphasizes the importance of subtle changes in mineral matter content and mineral size distributions that can be determined from pilot-scale testing.

#### Convective Pass Fouling Characteristics

Convective pass deposit characteristics were assessed in the FPTF by determining deposit build-up rates, sootblowing frequencies and deposit-to-tube bonding strengths. Convective pass fouling results from the combustion tests are summarized in Table 5. Results indicate that the fouling potentials can be assessed as moderate-to-high for the baseline coals, and low-to-moderate for the cleaned coal.

Contrary to bench-scale indices that predicted similar fouling performance, the fouling characteristics of the baseline lignite improved substantially with cleaning. Both the rate of deposit buildup and the nature of the deposits accumulating improved with cleaning. Time-sequenced photographs, Figure 5, illustrate the relative deposit build-up rates between the baseline and cleaned lignites. Coal cleaning reduced the convective pass ash deposition rates and the required soot blowing frequency from approximately every 8 hours for the baseline coal to greater than 12 hours for the cleaned coal.

Convective pass deposits produced during the combustion of the cleaned coal had lower bonding strengths than deposits produced from the baseline coal under similar conditions. On-line deposit-to-tube bonding strength measurements for each fuel are shown in Figure 6 as a function of gas temperature. The maximum gas temperature to maintain soot blower effectiveness was established at 2220°F for the baseline coal, and 2330°F for the cleaned coal. These results indicate that the cleaned lignite could be fired at higher loads before fouling would limit operation.

#### Fly Ash Erosion

Fly ash erosion decreased significantly with coal cleaning. Normalized results show approximately 50% reduction in metal erosion rates from 1.28 mil/10,000 hours for the baseline coal to 0.68 mil/10,000 hours for the cleaned coal at 60 ft/sec gas velocity (Table 5). The combination of reduced ash loadings in the flue gas and reduced fly ash erosivities (due mainly to reduced quartz content) appear to account for the decrease in erosion rates between the baseline and cleaned coals. These results indicate that switching to the cleaned lignite would contribute to increased convection tube life and that the cleaned lignite can be fired at higher rates without significantly decreasing boiler tube life.

#### PREDICTED UTILITY BOILER PERFORMANCE USING CLEANED LIGNITE

The commercial benefits associated with using the cleaned lignite were quantified by using FPTF test results along with C-E's Boiler Performance Program (BPP). The BPP was used to model and predict the performance of TU Electric's Big Brown Unit No. 1. Big Brown No. 1 is a supercritical combined

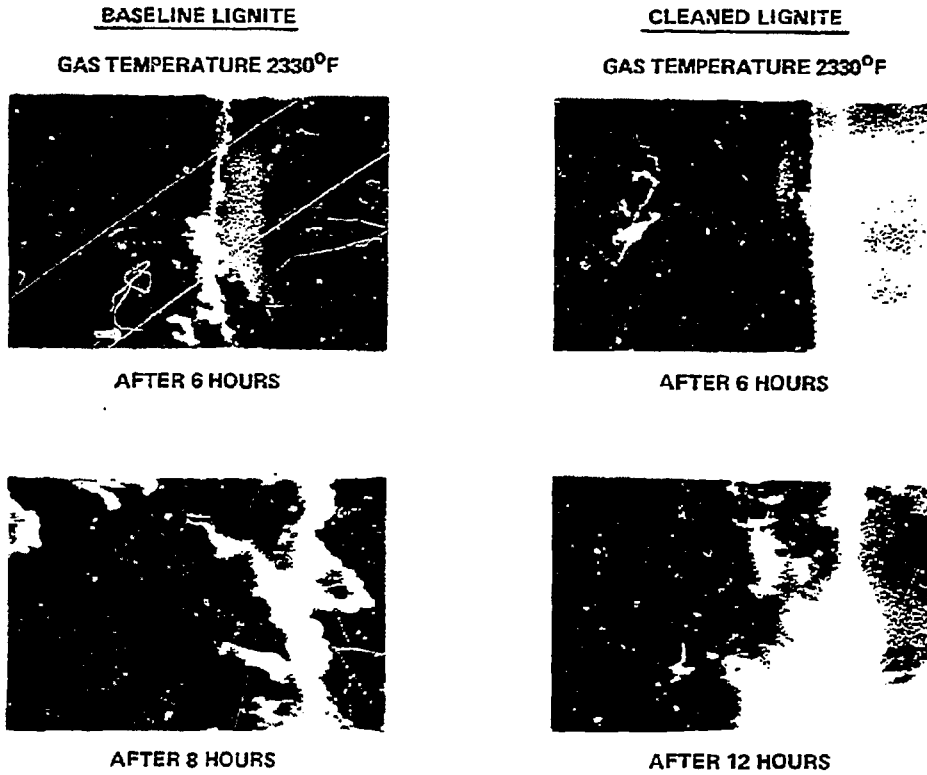


FIGURE 5. FOULING DEPOSITS ON SUPERHEATER PROBE IA FOR THE BASELINE AND CLEANED LIGNITES

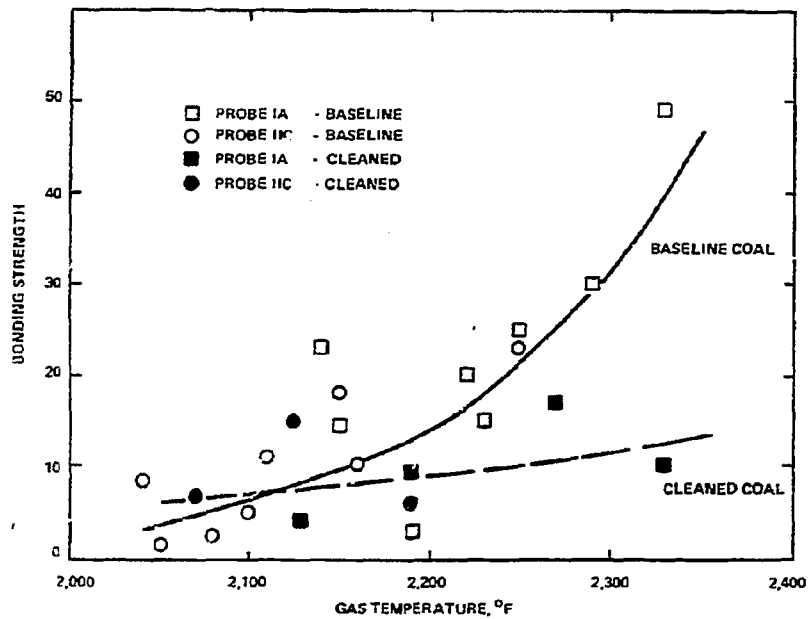


FIGURE 6. DEPOSIT-TO-TUBE BONDING STRENGTH AS A FUNCTION OF CONVECTIVE PASS GAS TEMPERATURE

circulation balanced draft boiler with a divided furnace. The unit has a nameplate rating of 575 MW and a maximum continuous rating (MCR) of 4,025,000 lb/hr main stream flow at 1005°F/3825 psig and 3,520,000 lb/hr reheat steam flow at 1005°F/647 psig. Table 6 summarizes the significant differences in boiler operation which can be expected when firing the cleaned lignite.

A review of operating data from the Big Brown station revealed that an increase in coal heating value could have a favorable impact on several areas of boiler performance. Periods of reduced generating capacity have occurred due to coal handling problems in the pulverizer feed system. Increasing the heating value of the coal would reduce the required coal feed rate by approximately 11%. Greater pulverizer capacity would reduce the impact coal pluggage and feeder problems have on total generating capacity. In addition, reductions in mill abrasion will contribute to greater pulverizer availability and reduced pulverizer maintenance. When firing the cleaned coal at a similar boiler loading, the ash quantity introduced into the furnace would be reduced by approximately 50%, reducing ash handling and disposal costs.

The calculated furnace exit gas temperature is expected to be slightly higher with the cleaned coal than the baseline (2632°F vs 2604°F) due to less total moisture having to be evaporated from the coal being fired. The differences in gas temperatures will diminish as the gas progresses through the unit to the air heater outlet.

For the purposes of this analysis, the coal moisture contents were normalized to a value typical for the baseline coal (31%). Given this, the cleaned coal boiler efficiency will be almost one percent higher than the baseline coal. The reduction in total moisture due to the 11% lower coal feedrate, and a reduced air heater outlet temperature resulted in lower latent heat and dry gas losses respectively. The difference in carbon heat loss was minimal. Each percent increase in cleaned coal moisture would reduce the boiler efficiency by 0.25%.

Test results indicated that the baseline and cleaned lignite would have similar slagging performance in terms of cleanability and deposit thermal conductance at full load conditions in the Big Brown radiant furnace region. The convective tube bonding strengths and deposition rates measured in the FPTF demonstrated that neither the baseline nor cleaned coal would cause a fouling problem at the maximum convective pass gas temperatures predicted (2200°F) at MCR.

Consequently, fouling was not considered to be an operating limitation. Field observations confirmed that the presently installed sootblower system at Big Brown could control furnace and convection pass deposits satisfactorily at these conditions. However, the reduction in deposit buildup rate for the cleaned lignite would reduce sootblowing requirements.

The projected boiler tube erosion rates with the cleaned coal are 49% lower compared to the baseline coal. The greatest amount of erosive wear is anticipated in the horizontal reheater section due to the higher average gas velocity. Average metal loss in this area was projected to be 1.93 mil/10,000 hours for the baseline lignite and 0.99 mil/10,000 hours for the cleaned lignite.

Table #

## BIG BROWN BOILER COMPARISON USING CLEANED LIGNITE

	<u>Baseline</u>	<u>Cleaned</u>
Gross Output (nominal), MW	550	550
Boiler Efficiency, %	81.67	82.58
Excess Air, %	14.4	14.4
Coal Feedrate, 10 <sup>3</sup> lb/hr	843	752
Carbon Conversion, %	99.65	99.56
Carbon Heat Loss, %	0.30	0.39
Main Steam Flow, 10 <sup>3</sup> lb/hr	4090	4090
R.H. Steam Flow, 10 <sup>3</sup> lb/hr	3706	3706
S.H. Temp./Pressure, °F/psig	989/3730	995/3730
R.H. Temp./Pressure, °F/psig	972/631	1005/634
S.H. Spray Flow, 10 <sup>3</sup> lbs/hr	25	25
R.H. Spray Flow, 10 <sup>3</sup> lbs/hr	133	133
Furnace Outlet Temp. (Horizontal), °F	2604	2632
Furnace Outlet Temp. (Vertical), °F	2180	2209
Air Heater Gas Outlet Temp., °F	371	369
Max. Average Gas Velocity (V <sub>max</sub> ), ft/sec	58	60
Erosion Rate (Horizontal Reheater & V <sub>max</sub> ), mil/10,000 hrs	1.99	0.99

## ECONOMIC BENEFITS OF USING CLEANED LIGNITE

Switching to firing cleaned lignite can, in general, impact the cost of power generation by improving boiler island performance in the following areas:

- o Generating Capacity
- o Boiler Availability
- o Boiler Maintenance
- o Net Plant Heat Rate

The actual costs benefits for the given plant are dependent on many site specific variables such as unit operating requirements (baseloading), replacement power costs, and current fuel related limitations. Overall, baseloaded plants experiencing fuel-related operating limitations will realize the greatest benefits by using higher quality fuel, providing that additional capacity or availability can be absorbed economically.

Results of the boiler performance analysis for Big Brown No. 1 indicated that improvements could be expected in boiler availability, reduced maintenance requirements, and net plant heat rate (NPHR). Lower fuel and ash abrasion, and erosion rates were the primary contributors to reduced maintenance costs. Lower auxiliary power consumption and higher boiler efficiency were the primary contributors to an improved NPHR. Although improved availability was indicated, unit availability is highly dependent on site specific factors and was beyond the scope of this study. Since Big Brown currently operates at design capacity, increased generating capacity was not addressed.

The total NPHR benefit realized by switching to cleaned lignite was estimated to be 133 Btu/kWh at an assumed baseline NPHR of 9810 Btu/kWh or a 1.36% improvement. The increase in boiler efficiency (1%) accounted for 88% of the NPHR improvement. Auxiliary power consumption savings contributed the remainder. Pulverizer power consumption would be reduced 9% due to lower fuel feedrate. Sootblower air compressor load was estimated to be one-third less based upon the laboratory data on ash deposition rates. The total reduction in auxiliary power consumption would be 2.9% resulting in 0.16% improvement in NPHR.

The reductions in boiler maintenance requirements were predicted using the laboratory results and engineering field correlations as opposed to direct statistical analysis. The coal characteristics which affect boiler maintenance costs are primarily erosion, abrasion, corrosion, and calorific value. Equipment abrasive and erosive wear is caused by both the coal and its ash. Correlations for the most troublesome boiler wear mechanisms have been developed by C-E and were used to estimate maintenance cost reductions at Big Brown.

The heating value of the coal can have a first order impact on plant maintenance costs. Plant equipment processing a higher calorific value fuel (of similar wear characteristics) will operate on shorter duty cycles and experience lower wear rates due to the lower mass throughput. If two fuels have similar abrasion and erosion characteristics, wear rates and associated maintenance costs will be proportional to the quantity of fuel fired. Test results showed that cleaning the Big Brown lignites resulted in substantial improvements in both fuel abrasion and ash erosion characteristics of the cleaned lignite, indicating further reductions in component wear.

The combined impacts of coal/ash characteristic (quality) and the total material throughput (quantity) were expressed as "maintenance factors." These maintenance factors, shown in Table 7, can be used to estimate savings associated with improvements in fuel-related maintenance.

Table 7

Big Brown Maintenance Factors for Cleaned Big Brown Lignite

<u>Maintenance Account</u>	<u>Fuel Characteristics</u>	<u>Quality Factor</u>	<u>Quantity Factor</u>	<u>Maintenance Factor</u>
<b>Fuel Handling System</b>				
Crushers/Conveyors	Coal Abrasion	0.78	0.89	0.69
Dust Control	Coal Quantity	1.00	0.89	0.89
<b>Fuel Firing System</b>				
Pulverizers	Coal Abrasion	0.78	0.89	0.69
Fuel Piping	Coal Erosion	0.78	0.89	0.69
<b>Boiler and Auxiliaries</b>				
Pressure Parts	Ash Erosion	0.97	0.53	0.51
Sootblowing System	Ash Deposition Rate	1.00	0.67	0.67
Air Heater	Acidic Corrosion	1.00	1.00	1.00
<b>Ash Handling System</b>				
Fly Ash	Ash Erosion	0.97	0.53	0.51
Bottom Ash	Ash Quantity	1.00	0.53	0.53

Additional benefits from using cleaned lignite may include improved availability and potential ash disposal cost savings, both of which are highly sensitive to site specific factors and operational requirements.

#### CONCLUSIONS

The results of this study demonstrated the potential for utility steam plant operating and maintenance cost savings by utilizing a higher quality, cleaned fuel. Physical coal cleaning improved fuel performance characteristics in nearly all areas of boiler operation. Benefits derived from utilizing higher quality fuel fall into four general categories: increased generating capacity, increased unit availability, reduced maintenance costs and improved plant heat rate. The greatest potential for savings exists for baseloaded units currently experiencing capacity derating and/or poor unit availability due to fuel-related problems.

More specific conclusions drawn from this study are:

- o The removal of mineral matter and subsequent increase in fuel calorific value due to coal cleaning results in the reduction of coal and ash passing through the pulverizer and the boiler. Thus pulverizer capacity increases, pulverizer power consumption is reduced and pulverizer and ash handling equipment life is extended. Additional benefits are generally derived in the area of pulverizer wear due to a reduction in fuel abrasiveness from the selective removal of large abrasive minerals such as quartz and pyrite during cleaning.
- o Convection tube wear is also significantly reduced due to the reduction in ash loading and lower erosivity of the cleaned lignite fly ash. Test results indicate that utilizing cleaned lignite would increase erosion related convective tube life by approximately 50%.
- o Pilot-scale combustion results showed improved ash slagging due to cleaning. Waterwall deposits produced from the cleaned lignite were generally thinner and more sintered in appearance than those produced at similar conditions from the baseline lignite. Waterwall deposits generated by both fuels were cleanable by sootblowing over the range of conditions typically encountered in lignite-fired utility boilers.
- o The fouling characteristics of the Big Brown lignite improved substantially with cleaning. Both the rate of deposit build-up and the nature of the deposits improved with cleaning. Combustion test results indicate that the fouling potential is moderate-to-high for the baseline coal, and low-to-moderate for the cleaned coal. Results show that the maximum gas temperature to maintain cleanable deposits (by sootblowing) was 2220°F for the baseline coal and 2330°F for the cleaned coal.

- o Commonly used bench-scale performance indicators based upon ASTM analyses did not reliably predict the ash slagging and fouling behavior of both the baseline and cleaned lignites. Use of these indicators to provide assessment of performance changes resulting from coal cleaning is suspect as opposite trends (predicted degradation in performance while actual combustion performance improved) were indicated. Results of specialty bench-scale tests and advanced analytical techniques provide more fundamental data on the fuels which can help to explain apparent fuel behavior. However, additional research is required before reliable bench-scale correlations are developed.
  
- o Results of the boiler performance analysis for the Big Brown Unit indicated that improvements could be expected in boiler availability, reduced maintenance requirements, and net plant heat rate (NPHR). Lower fuel and ash abrasion, and erosion rates were the primary contributors to reduced maintenance costs. Lower auxiliary power consumption and higher boiler efficiency were the primary contributors to improved NPHR. Additional benefits from using a cleaned lignite include improved availability and potential ash disposal cost savings, both of which are highly sensitive to site specific factors and were not addressed.

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## ASH DEPOSITION STUDIES OF LOW-RANK COALS IN A LABORATORY FURNACE

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### ABSTRACT

The objective of this work was to gain a better fundamental understanding of the initiation and growth of ash deposits formed from pulverized coal firing in utility boilers. A vertical externally-heated tube furnace was used to form ash deposits from low-rank coals under conditions similar to those in a utility boiler. In tests with this apparatus, a thin stream of coal was combusted in a muffle tube with a maximum hot zone temperature of 1500°C. The residence time of coal particles within the muffle tube was estimated to be between one and two seconds. Near the furnace exit a deposit was formed when the fly ash and products of combustion were accelerated by a nozzle up to 16 meters per second and then impinged on a pre-oxidized boiler steel substrate held at 500°C. A variety of low-rank coals were tested in the tube furnace including western U.S. subbituminous coals, Fort Union lignites and Gulf Coast lignites. The effects of ion-exchangeable cations and oxygen partial pressure on deposit formation rate and strength were evaluated. Many of the low-rank coals combusted in 20% excess air produced strongly bonded deposits. However, a marked difference in deposit characteristics was noted for the Gulf Coast lignites compared to the other low-rank coals after combustion at high oxygen partial pressure (60% oxygen). The Gulf Coast lignites formed strongly bonded deposits while the other low-rank coals formed deposits with little mechanical strength. As expected, most of the sodium and calcium was removed from the low-rank coals by ion-exchange with ammonium acetate. The ion-exchanged Gulf Coast lignites combusted in 20% excess air formed fused, strongly bonded deposits while the ion-exchanged subbituminous and Fort Union lignites formed much weaker deposits. The difference in deposition behavior between the Gulf Coast lignites and other low-rank coals may be attributed to a different type of alkali bonding within the coal mineral matrix.

### INTRODUCTION

A series of papers (1-4) has described a laboratory test for evaluating the fundamentals of coal ash deposition relative to utility boilers. In this test a thin ray of pulverized coal is burned in a tube furnace heated to simulate the temperature of a utility boiler. The resultant fly ash is then impacted on an oxidized steel substrate held at a controlled temperature similar to that of a boiler tube surface. To form a deposit the fly ash is accelerated through a simple refractory nozzle to a velocity similar to that in a boiler before impacting on the substrate. The rate of growth and structure of the deposit are examined. In addition, the compressive strength of the deposits is determined at room temperature after removal from the furnace. A coal feed

rate of about 0.3 grams/minute is sufficient to build a deposit within 30 minutes; therefore a sample size of 50 grams can be tested several times. The advantage of such a small-scale test compared with test rigs burning 7-50 kg/hour is that many tests can be performed under closely controlled conditions at a much lower cost. The disadvantage is that it is an accelerated test which may not give results completely comparable to the slow growth of deposits in a utility boiler furnace. In addition, the partitioning of ash in a boiler to give bottom ash, wall slag and fly ash cannot be simulated in this test.

Ash deposits from a variety of high- and low-rank coals and synthetic coals were characterized in previous test work with the muffle tube furnace (2). The results of these studies indicated that deposits were similar in structure and composition to those in a full-scale utility boiler, with fusion or strong sintering occurring at the top of the deposit exposed to the highest gas temperature. The rate of deposit growth with time was found to be more accelerated for high-rank coals as compared to an even rate for low-rank coals. In the work presented here the deposition characteristics of low-rank coals from different regions in U.S. are compared in tests with the tube furnace. The effects of ion-exchangeable cations and oxygen partial pressure on deposit formation rate, strength and composition are shown in this study.

#### EXPERIMENTAL TECHNIQUES

The general arrangement of the test system is shown in Figure 1. The main muffle furnace tube of 99.8% fused alumina (6.35 cm internal diameter by 90 cm long) has a maximum temperature zone of about 50 cm long. It is heated by three tangentially-fired natural gas-air burners and the temperature is controlled by adjusting the air-to-fuel ratio. An electrical resistance heater can be attached to the main furnace to allow a longer particle residence time. The hot zone of this heater is 43 cm long and can achieve a maximum temperature of 1250°C.

The coal feed system consists of a spouting-bed feeder which entrains pulverized coal (-60 mesh) in a primary air stream of less than 0.5 liter/minute. The feeder assembly rests on an electronic balance to continuously monitor the coal feed rate. This mixture of coal and air is injected into the furnace through the brass water-cooled injector probe. Preheated (900°C) secondary air or air-oxygen mixture enters the furnace through a mullite flow straightener. Estimated particle residence times within the hot zone of the main furnace are between 1 and 2 seconds. The extension heater can increase the particle residence times by about 1.5 seconds. At the exit of the furnace, the gas stream and fly ash are accelerated by a nozzle prior to impingement on the substrate which is held at a controlled temperature by a water-cooled probe. Exit gases are removed by a vacuum pump to prevent back-pressure build-up in the furnace tube. Gaps between the collector probe and the bottom of the furnace were sealed with high temperature fiber packing. A detailed diagram of the deposition section of the furnace is shown in Figure 2.

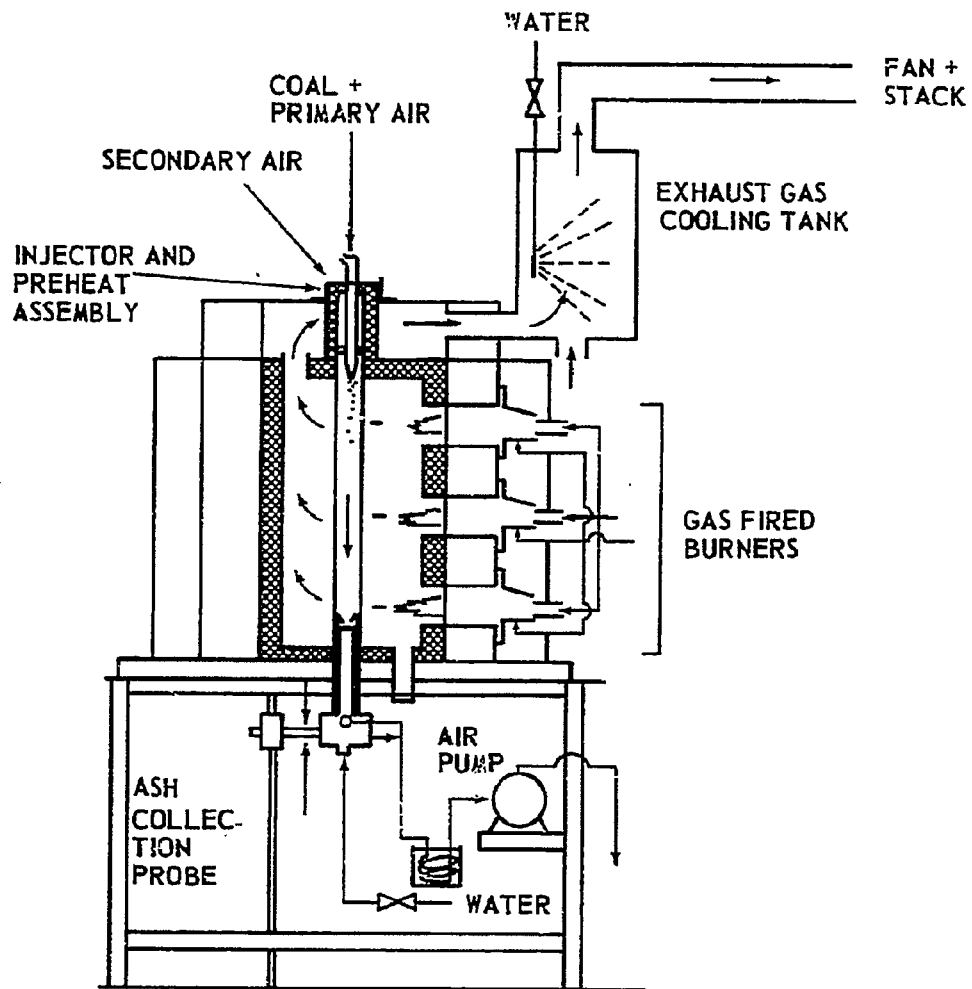


Figure 1. Drop-Tube Furnace System.

The low-rank coals were prepared by drying them at 110°C for 24 hours. The coals were then ground to less than 60 mesh with approximately 60 to 80 wt% of the coal less than 200 mesh. These coals were also treated with ammonium acetate solution to remove ion-exchangeable cations (Na, Ca, Mg). This treatment involved stirring 50 grams of dried coal in 800 mL of 1M ammonium acetate at 70°C for 24 hours. The slurry was filtered, washed and then treated for another 24 hours. After drying, the ion-exchanged coals were tested in the tube furnace to evaluate the effect of cation removal on deposit characteristics.

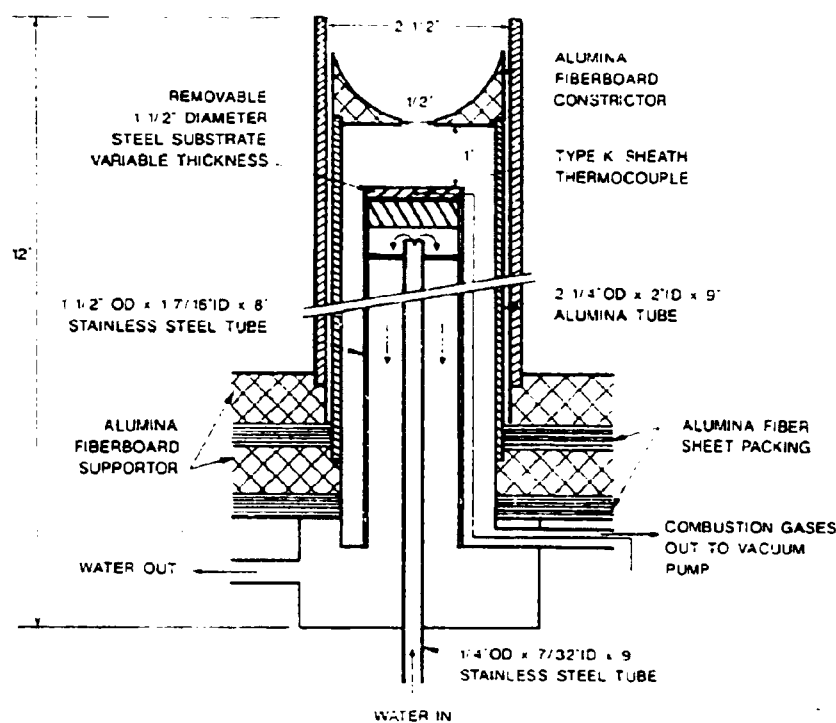


Figure 2. Bottom of Drop Tube Furnace, Constrictor and Test Substrate.

Substrates of 1.5 inch diameter and 0.2 inch thickness were made of mild carbon boiler steel supplied by Babcock and Wilcox Company, Ohio. These discs were polished sequentially with 240, 320, 400 and 600 grit SiC on a polishing wheel and then oxidized in a muffle furnace at 400°C for 20 hours. A small hole was drilled from the edge through to the center of each substrate to allow placement of a type-K thermocouple.

The gas-fired tube furnace was normally operated with a hot zone of 1500°C (wall temperature). The gas temperature at the acceleration nozzle was 1260°-1280°C as determined by pyrometric cones which may simulate the heat transfer conditions of a deposit. The gas particle temperature history for these conditions are similar to those encountered in a boiler radiant section (slagging) as shown in Figure 3. The gas temperature history similar to that of a boiler convection section (fouling) can be achieved by placing the extension heater under the main tube furnace. The velocity of the fly ash impinging upon the substrate could be varied to simulate that in both the radiant (4 m/s) and convective (16 m/s) sections of a boiler. The velocity was varied by changing the diameter of the ceramic acceleration nozzle near the bottom of the furnace.

Air or air/oxygen mixtures preheated to 900°C were utilized for combustion. The total combustion air was approximately 4 liters/minute, giving 30% excess air for the pulverized coal feed rate of 0.33 grams/minute. High oxygen partial pressure (approximately 0.6) for the combustion gas could be

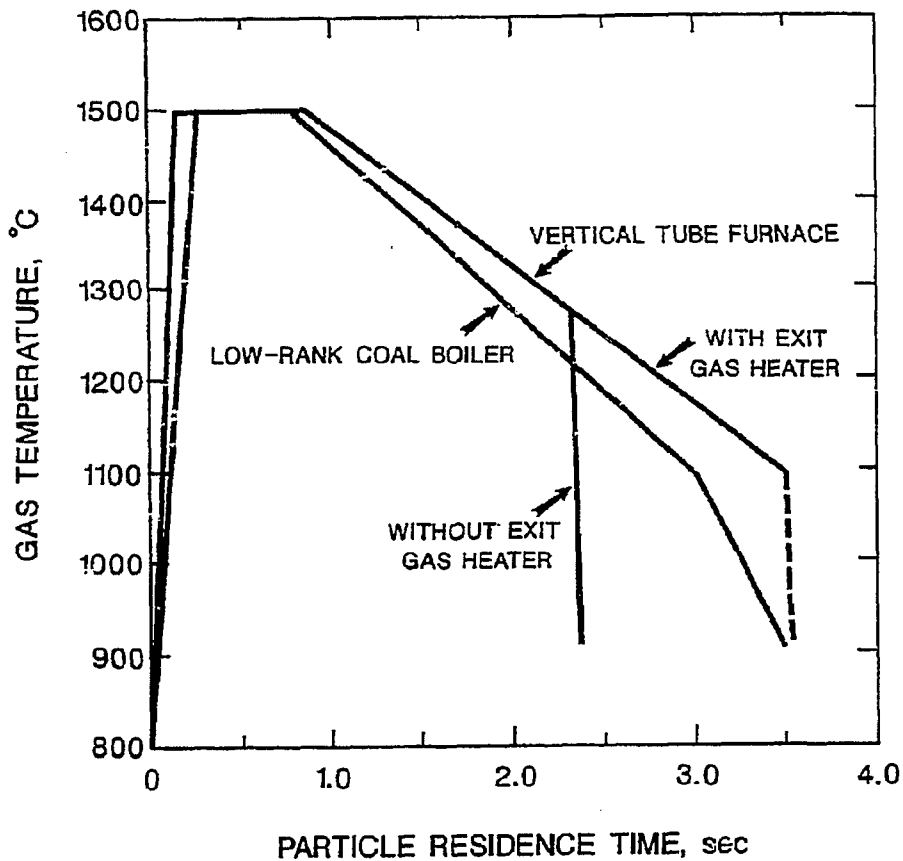


Figure 3. Particle Residence Time Versus Gas Temperature for the Vertical Tube Furnace With and Without the Exit Gas Heater. Hot Zone Temperature in Main Furnace was Maintained at 1500°C and Temperature in Exit Gas Heater was 1250°C.

achieved by mixing 2 liters/minute of each oxygen and air. These tests were conducted to evaluate the effect of high oxygen partial pressure on the mineral matter transformations and ash deposition.

Chemical characterization of the deposits was performed on the deposits after removal from the tube furnace. A scanning electron microscope, combined with energy dispersive x-ray spectrometry (SEM-EDS) was used for quantitative chemical analysis. Examination was made of some of the deposits cross-sectioned through the deposit and substrate. X-ray diffraction analysis (XRD) was also performed on selected samples of deposits to identify specific crystalline species.

A device was developed to measure the strength of deposits after they were removed from the test furnace. It consists of two primary components shown in Figure 4, a miniature horizontal translator (Oriel Corporation, Stamford, CN) and a miniature pressure transducer (Precision Measurement Company, Ann Arbor, MI). The output of the transducer is read from a strain and transducer indicator and has a maximum value of 5.5 MPa (approximately 750 psi). The strength of the deposits were determined by compressing them between the end of a steel rod and an aluminum block attached to the translator/transducer base plate. The deposits from the drop tube furnace are quite small (approximately 20 mm high and 5 mm diameter) and strength measurements can be made at approximately 3 mm intervals. The deposit strengths measured cold may not be the same as those which would be present in a deposit inside a boiler; however, they may be an indication of the degree of sintering and fusing of the deposit.

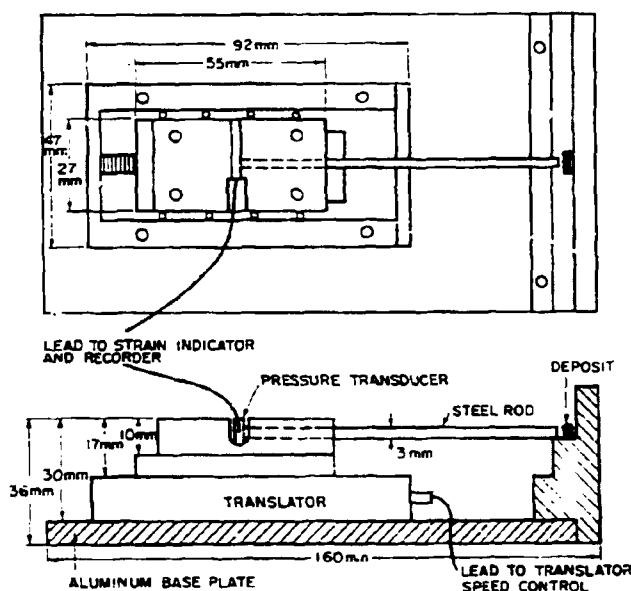


Figure 4. Translator/Transducer Assembly with Deposit Strength Measurement Device.

## RESULTS AND DISCUSSION

Low-rank coals from the following regions of the U.S. were tested in the tube furnace: Fort Union, Powder River, Green River Basin and Gulf Coast. The ash analysis of the Gulf Coast lignites that were tested in the drop tube are shown in Table 1. These coal ashes contained relatively low to moderate

TABLE 1

ASTM ASH ANALYSES AND FUSION TEMPERATURES  
FOR SELECTED GULF COAST LIGNITES FROM TEXAS

	Darco		Martin Lake		San Miguel		Wildcat	
	Raw <sup>+</sup>	I/E*	Raw	I/E	Raw	I/E	Raw	I/E
<u>% Ash, dry</u>	11.3	7.1	12.9	8.6	12.6	9.2	14.2	7.2
<u>Ash Analysis</u>								
<u>% wt equiv. oxide</u>								
SiO <sub>2</sub>	33.0		19.9		52.8	70.4	27.5	
Al <sub>2</sub> O <sub>3</sub>	13.1		11.9		14.6	17.1	13.6	
Fe <sub>2</sub> O <sub>3</sub>	10.8		16.1		4.8	5.5	9.3	
TiO <sub>2</sub>	1.1		0.9		0.8	0.8	1.1	
P <sub>2</sub> O <sub>5</sub>	0.1		0.7		0.3	0.1	0.1	
CaO	18.3	9.7	16.2	10.2	7.9	2.6	24.0	5.1
MgO	4.2	1.1	7.5	3.1	0.8	0.3	3.4	0.4
Na <sub>2</sub> O	0.9	0.1	3.2	0.1	4.8	0.1	0.4	0.0
K <sub>2</sub> O	0.3		0.3		2.4	0.5	0.3	
SO <sub>3</sub>	15.2		23.5		10.9	2.4	20.0	
<u>Ash fusion</u>								
<u>temp., °C (red)</u>								
IT	1135	1253	1182	1292	1176	1260	1172	1279
ST	1150	1263	1189	1298	1190	1280	1210	1289
HT	1160	1300	1197	1313	1200	1310	1215	1331
FT	1180	1350	1199	1327	1370	1420	1216	1342

<sup>+</sup> = Raw - untreated coal.

\* = I/E - Ion-exchanged with ammonium acetate to remove cations.

sodium contents and moderate to high calcium contents. The ion-exchange treatment with ammonium acetate was found to remove between 58 to 91% of calcium and greater than 90% of the sodium from these coals. The ASTM ash softening temperatures were about 100°C higher for the ash produced from the ion-exchanged versus raw untreated lignites as shown in Table 1. The ash analyses of low-rank coals from other regions that were also tested are shown in Table 2. These coal ashes contained varying amounts of sodium and calcium. Ion-exchange with ammonium acetate removed between 48 and 65% of the calcium and greater than 90% of the sodium from these coals. The ash fusion temperatures were considerably higher for the ion-exchanged versus raw coal ashes in some cases.

Examination of deposits collected on the probe showed negligible carbon content, indicating a high degree of burn-out. No fly ash was collected on the furnace tube and negligible amounts were found on the nozzle. The amount of deposit collected has been found to be reproducible to within +10 percent for duplicate tests with low-rank coals (2,3).

Ash deposits from the tube furnace were usually composed of several distinct regions: (1) a thin layer of dust on the substrate; (2) a weak layer of loosely sintered spheres and (3) a higher layer ranging from sintered to partially molten at the top. The degree of fusing of the deposit depended upon the melting behavior of the fly ash as a function of the temperature gradient between the constrictor and the substrate. A diagram of a typical deposit is shown in Figure 5. Figure 6 shows the amount of ash deposition with time for some of the untreated and ion-exchanged coals burned in 20% excess air at 1500°C for a 1 to 2 second residence time. The sticking coefficient is defined as the deposit formation rate divided by the rate of firing of ASTM ash. The sticking coefficient is determined by differentiating the weight versus time curve and dividing by the rate of ash fired. As expected, the rate of addition of ash constituents generally increases as the deposit grows since the top of deposit will become hotter as it approaches the nozzle. The compressive strengths of some of the untreated and ion-exchanged coal ash deposits as a function of height are shown in Figure 7. The strength of the deposits increased as a function of height since increasing temperature had produced sintering and fusing within the deposits. A summary of test results for the untreated and ion-exchanged low-rank coals is shown in Table 3. The ion-exchanged coals generally had lower ash sticking coefficients than the raw coals. However, the ion-exchanged Gulf Coast lignites all formed strongly bonded deposits, whereas most of the other ion-exchanged coals formed weak loosely bonded deposits. In general, the maximum strength of the deposit formed from the ion-exchanged Texas lignites was weaker than the deposit formed from the untreated coal. The maximum deposit strengths shown in Table 3 were measured at the top of the deposit. Strengths in excess of 5.5 MPa usually indicated a high degree of fusion of the deposit and were greater than the rating of the pressure transducer.

Deposits were also produced from the low-rank coals after combustion in a stream of 60% O<sub>2</sub>. The hot zone temperature of 1500°C, exit gas temperature of 1260°-1280°C, exit gas velocity of 4 m and residence time of 1 to 2 seconds were approximately the same as those for the tests conducted in air.



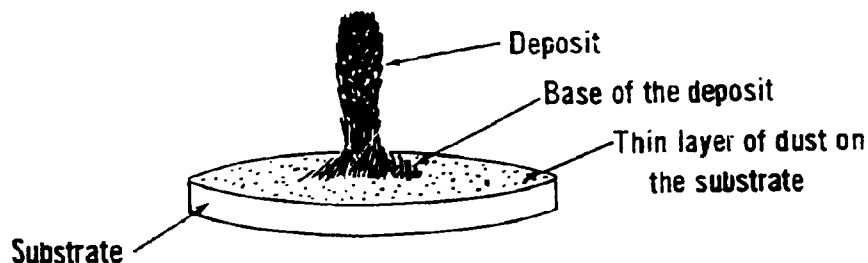
TABLE 2

 ASTM ASH ANALYSES AND FUSION TEMPERATURES  
 FOR SELECTED WESTERN LOW-RANK COALS

	Beulah-Zap N.D. lignite		Center N.D. lignite		Rosebud MT Sub-C		Colo-H Sub-A	
	Raw <sup>+</sup>	I/E*	Raw	I/E	Raw	I/E	Raw	I/E
% HTA, dry	9.36	5.01	9.68	6.54	9.47	6.77	8.06	6.53
Ash Analysis								
% wt equiv. oxide								
SiO <sub>2</sub>	14.0		21.6	31.4	39.0		44.7	
Al <sub>2</sub> O <sub>3</sub>	11.1		11.9	17.5	19.8		19.7	
Fe <sub>2</sub> O <sub>3</sub>	10.4		11.3	16.7	6.0		6.7	
TiO <sub>2</sub>	0.4		0.4	0.6	1.3		0.7	
P <sub>2</sub> O <sub>5</sub>	0.5		0.1	0.2	0.7		2.0	
CaO	21.6	15.1	20.7	16.4	13.9	9.1	10.3	5.2
MgO	5.6	1.5	7.6	2.9	5.7	1.3	2.9	0.5
Na <sub>2</sub> O	10.4	1.1	2.9	0.2	0.5	0.1	0.6	0
K <sub>2</sub> O	0.5		0.6	0.5	0.3		1.1	
SO <sub>3</sub>	22.8		20.4	10.6	14.9		9.1	
Ash fusion								
temp., °C (red)								
IT	1295	1323	1243	1253	1210	1467	1195	1337
ST	1295	1336	1273	1268	1237	1486	1205	1367
HT	1300	1358	1278	1307	1310	1511	1260	1425
FT	1300	1359	1276	1351	1331	1550	1340	1440

<sup>+</sup> = Raw - untreated coal.

<sup>\*</sup> = I/E - Ion-exchange with ammonium acetate to remove cations.



### DESCRIPTION OF THE DEPOSITS

Figure 5. Typical Ash Deposit Formed During the Combustion of a Lignite.

As shown in Table 3, high  $O_2$  partial pressure reduced the ash sticking coefficients of all the coals tested with a much lower reduction for the Gulf Coast lignites. However, the deposits from the Gulf Coast lignites all had high strengths at the top while none of the deposits from the other low rank coals had any measureable strength. High oxygen partial pressure may decrease the amount of low-melting point liquid phase that can aid in viscous flow sintering. In addition, increasing the  $O_2$  partial pressure would be expected to increase the char reaction rate and particle temperature of coals during combustion. Other researchers (5) measured particle temperatures (by optical pyrometry) at similar conditions in a tube furnace. They observed nearly  $400^{\circ}C$  higher particle temperatures for 75-90  $\mu m$  Rosebud (MT) coal in 60% versus 20%  $O_2$  and a much greater vaporization of alkalis.

Deposits were also produced from both groups of coals with a furnace temperature history similar to that encountered in boiler convective section fouling. An extension heater was used with the main gas-fired furnace to provide a longer residence time and an exit gas temperature of  $1200^{\circ}C$ . As shown in Table 4, the ash sticking coefficients were similar to those when the coals were tested at slagging conditions. The Gulf Coast lignites formed deposits of moderate to high strength at fouling conditions, while the other low rank coals formed only weakly bonded deposits.

X-ray diffraction analysis was also performed on some of the ash deposits to identify specific crystalline species. Quartz was the only crystalline species that could be identified in the ash deposits of San Miguel lignite after combustion in both air and 60%  $O_2$ . A comparison of the XRD analyses of selected lignite ash deposits produced is shown in Table 5. The chemistries of the crystalline phases identified are summarized in Table 6. Alkali and alkaline earth aluminosilicates such as melilite, plagioclase and pyroxene were found to be the major crystalline species identified in the deposits from the Fort Union lignite and Martin Lake Texas lignite. Only a trace of pyroxene is found in the Center deposit at high  $O_2$  partial pressure as shown

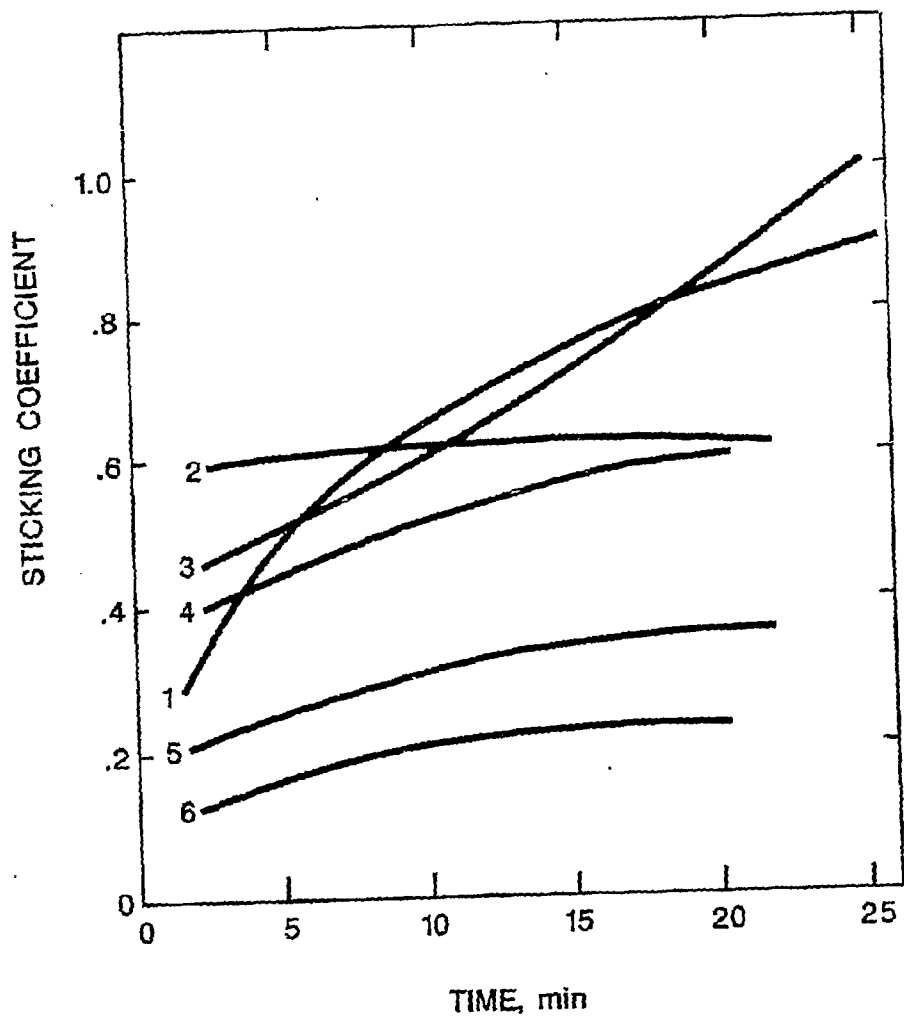


Figure 6. Ash Sticking Coefficient of Low-Rank Coals as a Function of Time (1-Center, 2-I/E Center, 3-San Miguel, 4-I/E San Miguel, 5-Beulah-Zap, and 6-I/E Beulah-Zap).

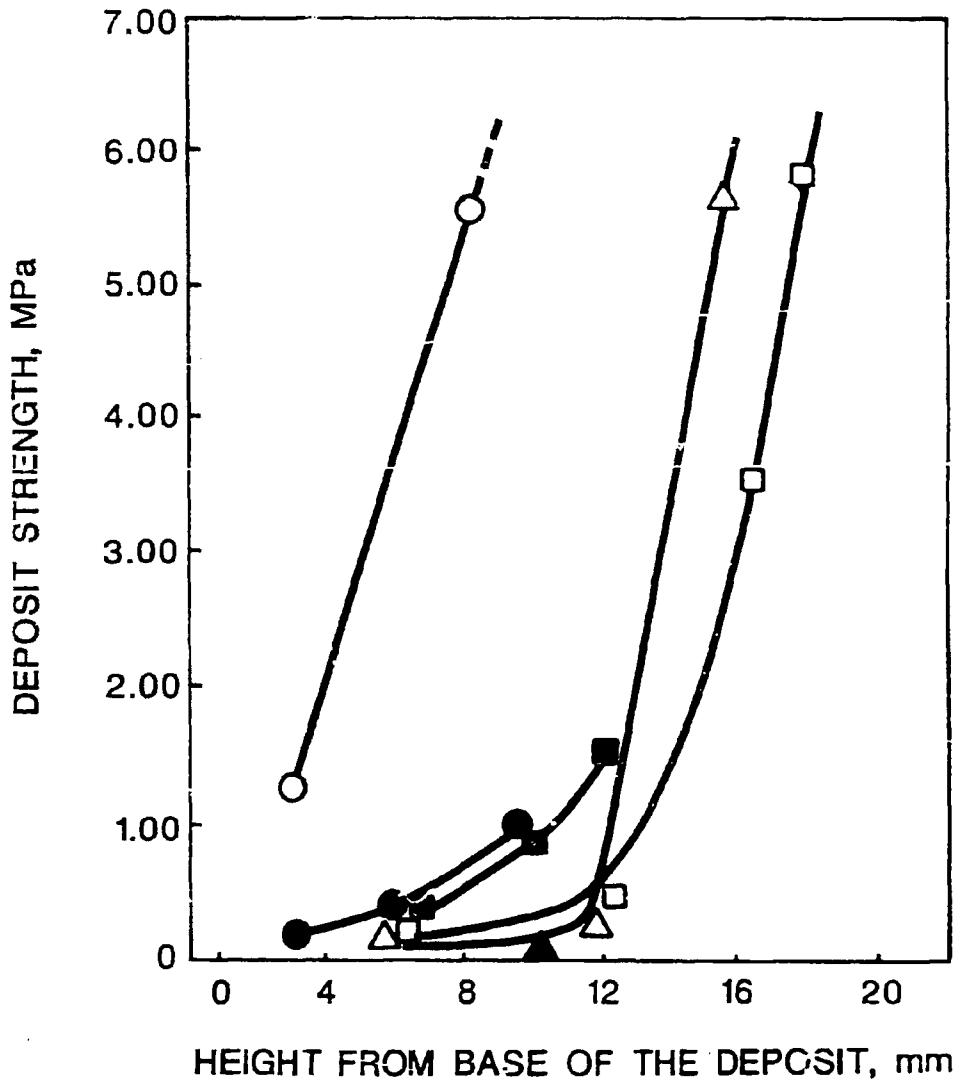


Figure 7. Deposit Strength as a Function of Height for Selected Low-Rank Coals for a 20-Minute Test (O = Center; ● = I/E Center; □ = San Miguel, ■ = I/E San Miguel; △ = Beulah-Zap, and ▲ = I/E Beulah-Zap).

TABLE 3  
EFFECT OF ION-EXCHANGE AND HIGH OXYGEN PARTIAL PRESSURE ON  
ASH DEPOSIT FORMATION AND STRENGTH (1500°C HOT ZONE, 1-2 SEC RESIDENCE  
TIME, 20 MINUTE RUN, 7 GRAMS COAL FED)

	Ash Sticking Coefficient			Maximum Deposit Strength, MPa		
	Untreated		Ion-Exchanged	Untreated		Ion-Exchanged
	Air	60% O <sub>2</sub>	Air	Air	60% O <sub>2</sub>	Air
<u>Gulf Coast Lignites</u>						
Darco	0.45	0.44	0.36	>5.5	>5.5	>5.5
Martin Lake	0.61	0.45	0.56	5.0	2.5	1.4
San Miguel	0.80	0.65	0.59	5.2	3.6	1.5
Wildcat	0.71	0.66	0.66	>5.5	>5.5	1.2
<u>Western Coals</u>						
Beulah-Zap	0.32	0.12	0.27	5.0	0.0	0.0
Center	0.80	0.17	0.61	>5.5	0.0	1.8
Colorado-H	0.51	0.30	0.45	3.5	0.0	0.0
Rosebud	0.48	0.31	0.42	2.2	0.0	0.0

TABLE 4  
EFFECT OF SLAGGING VERSUS FOULING CONDITIONS ON  
DEPOSIT FORMATION AND STRENGTH  
(20-MINUTE RUN, 7 GRAMS COAL FED)

Western Region Coals	Sticking Coefficient		Max. Deposit Strength, MPa	
	Slagging	Fouling	Slagging	Fouling
Beulah-Zap	0.32	0.29	5.0	0.0
Center	0.68	0.42	> 5.5	1.0
Rosebud	0.48	0.31	2.2	0.0
Colo-H	0.51	0.54	3.5	0.1
<u>Gulf Coast Lignites</u>				
Darco	0.45	0.42	5.5	2.6
Martin Lake	0.61	0.56	5.0	2.3
San Miguel	0.80	0.89	5.2	3.9
Wildcat	0.71	0.49	5.5	4.0

in Table 5. It appears that very high O<sub>2</sub> partial pressures may reduce the interaction of alkali and alkaline earth elements with other ash components such as silica and clays.

The microstructure of the ash deposits were examined using SEM-EDS. Many of the crystalline phases found using XRD could be identified using the SEM-EDS on polished cross-sections of deposits. SEM-EDS examination of a Center lignite deposit shown in Figure 8a illustrates a high degree of crystallinity with very little glass material. The crystalline and glass phases in the ion-exchanged lignite deposit are shown in Figure 8b. The ion-exchanged coal deposit does not exhibit the degree of crystallization and has higher porosity as compared to the untreated coal. Analysis of the crystalline and glassy phases in the deposits are summarized in Table 7. The glass material in the Center lignite deposit contains significantly more sodium than the crystals. X-ray diffraction indicates that the major crystalline phase present is pyroxene. The ion-exchanged coal has most of the sodium removed and the deposit formed did not have significant quantities of molten material in the deposit. Melilite is the dominant crystalline phase in the deposit from the ion-exchanged Center. The compositions of the crystalline and glass materials are similar for the Center and ion-exchanged Center except for the lack of sodium and potassium in the deposit from ion-exchanged Center.

### CONCLUSIONS

A laboratory-scale vertical externally-heated tube furnace was used to produce ash deposits from low-rank coals at conditions similar to those in a utility boiler. Deposits formed from Gulf Coast lignites revealed different

TABLE 5

## X-RAY DIFFRACTION ANALYSIS OF LIGNITE DEPOSITS

Deposit Location	Beulah	Center	I/E <sup>†</sup> Center	Center(60%O <sub>2</sub> *)	San Miguel	I/E San Miguel	Martin Lake
Deposit top half	major: melilite periclase minor: Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>	major: pyroxene plagioclase minor: quartz	major: pyroxene periclase minor: quartz melilite	major: lime hematite quartz minor: mullite anhydrite	major: amorphous  minor: quartz	major: amorphous melilite  minor: quartz	major: plagioclase pyroxene minor: quartz amorphous
Deposit lower half	major: melilite periclase minor: Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>	major: pyroxene  minor: quartz spinel	major: quartz  minor: pyroxene plagioclase melilite hematite spinel periclase	trace: pyroxene	major: amorphous  minor: quartz	major: amorphous lime minor: quartz	major: periclase  minor: hematite quartz amorphous
Base and dust	major: lime Na <sub>2</sub> SO <sub>4</sub> periclase Ca <sub>3</sub> Al <sub>2</sub> O <sub>6</sub>  trace: anhydrite	major: amorphous  minor: periclase hematite spinel anhydrite	major: quartz amorphous  minor: spinel		major: amorphous  minor: quartz	major: amorphous quartz  minor: quartz	major: periclase  minor: lime hematite amorphous

<sup>†</sup> = Ion-exchangeable cations removed.

\* = Layers could not be separated and the complete deposit was analyzed.

TABLE 6  
CHEMISTRY OF CRYSTALLINE PHASES IDENTIFIED IN DEPOSITS

<u>Phase</u>	<u>Chemical Formula</u>
Periclase	MgO
Lime	CaO
Quartz	SiO <sub>2</sub>
Hematite	Fe <sub>2</sub> O <sub>3</sub>
Anhydrite	CaSO <sub>4</sub>
Melilite <sup>+</sup>	
Gehlenite	Ca <sub>2</sub> Al <sub>2</sub> SiO <sub>7</sub>
Akermanite	Ca <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>
Pyroxene <sup>+</sup>	
Diopside	CaMgSi <sub>2</sub> O <sub>6</sub>
Augite	Ca(Fe,Mg)Si <sub>2</sub> O <sub>6</sub>
Plagioclase <sup>+</sup>	
Albite	NaAlSi <sub>3</sub> O <sub>8</sub>
Anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>
Spinel <sup>+</sup>	
Magnetite	Fe <sub>3</sub> O <sub>4</sub>
Magnesioferrite	MgFe <sub>2</sub> O <sub>4</sub>

<sup>+</sup> = Solid solution series - identification of the exact crystalline phase within the series could not be made.

deposition characteristics as compared to low-rank coals from other regions of the U.S. At tests simulating the particle temperature history of a boiler radiant section, most of the low-rank coals formed highly fused and strongly bonded deposits. Ion-exchange removed most of the sodium (>90%) and much of the calcium (>50%) from the coals tested. The Gulf Coast lignites formed strongly bonded deposits after the coals were ion-exchanged, but weaker than those formed by the untreated coal. Most of the low-rank coals from other regions that had the ion-exchangeable cations removed did not form strong deposits. Increasing the oxygen partial pressure from 0.2 to 0.6 greatly lowered the amount and strength of deposits for most of the low-rank coals except the Gulf Coast lignites. At tests simulating the particle temperature history of a boiler-convective section, the Gulf Coast lignites formed strongly sintered and fused deposits.



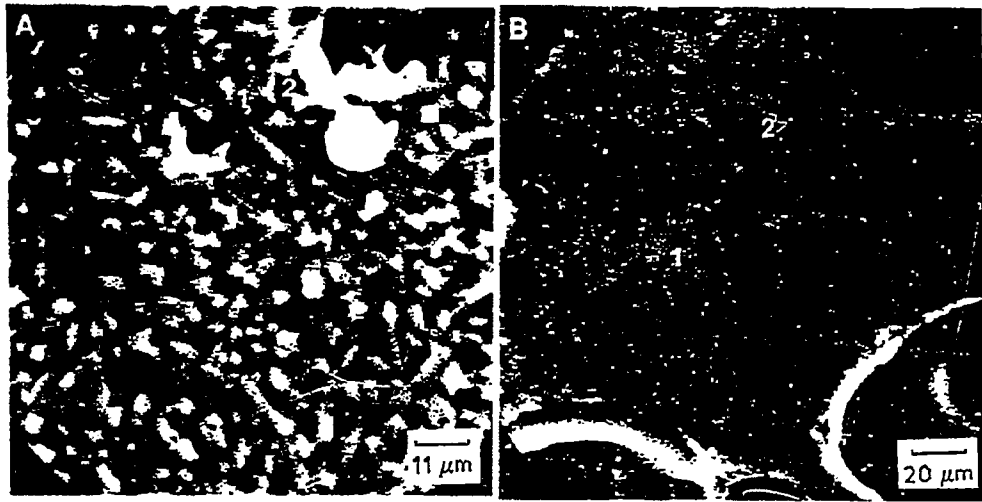


Figure 3. Backscatter Electron Images of Deposit Cross-sections (A) Untreated Center Lignite and (B) Ion-Exchanged Center Lignite Deposits.

TABLE 7

EDS ANALYSES OF SELECTED POINTS IN FIGURE 9.  
(WT. % AS EQUIVALENT OXIDE)

Oxide	A-1(Crystal)	A-2(Glass)	B-1(Crystal)	B-2(Glass)
SiO <sub>2</sub>	36.2	43.9	33.9	40.3
Al <sub>2</sub> O <sub>3</sub>	17.5	17.9	17.6	27.9
Fe <sub>2</sub> O <sub>3</sub>	14.1	3.8	18.8	13.7
TiO <sub>2</sub>	0.7	0.3	0.8	0.5
P <sub>2</sub> O <sub>5</sub>	0.0	0.0	0.0	0.0
CaO	20.3	20.8	20.1	13.1
MgO	10.6	5.8	5.4	3.3
Na <sub>2</sub> O	0.3	4.2	0.2	0.2
K <sub>2</sub> O	0.1	0.9	0.2	0.3
SO <sub>3</sub>	0.3	1.0	0.0	0.2
BaO	0.0	1.6	2.9	0.6

The difference in the ash deposition characteristics of the Gulf Coast lignites versus the other low-rank coals may be attributed to a difference in mineralogy of these coals. Although both groups of coals contained considerable amounts of alkali and alkaline earth elements (Na, Ca), the form in which they were found within the coal could be different.

The form in which alkali and alkaline earth elements were contained in the low-rank coals could have had a significant effect on their deposition behavior in the laboratory test furnace. For example, if calcium was present in mixed-layer clays in the Gulf Coast lignites, enough calcium could remain after ion-exchange with ammonium acetate to yield a relatively low-fusion ash after combustion in the furnace. Many of the low-rank coals from other U. S. regions have calcium in this form. This may account for great difference between the ash deposition behavior between the Gulf Coast lignites and the other coals at high  $O_2$  partial pressures. High  $O_2$  partial pressure would be expected to increase particle temperatures and vaporization of alkali species. Alkali and alkaline earth elements bound within clay structures would not be released as easily as those bound to the coal matrix and could still interact with the clays to form relatively low-melting point glasses. Alkali species which vaporize from the coal structure can condense and form sulfates at cooler regions at the exit of the hot zone. The formation of sodium-calcium-sulfates on the surface of small fly ash particles could lead to the viscous sintering of ash deposits and some development of strength. However, the glassy material from alkali/clay reactions may result in the formation of a much stronger deposit since more of a bulk melting occurs than during sintering. Future tests will be conducted to evaluate the interaction of alkali and alkaline earth elements with minerals.

#### ACKNOWLEDGMENT

This work was performed under U.S. DOE Contract DE-AC18-85FC10627 with Dr. H. Fred Bauer as contract monitor. We thank Dr. Bauer for his interest and encouragement in this work. Steven Benson acknowledges support from the University of North Dakota Energy Research Center under the UNDERC-DOE Cooperative Agreement while attending The Pennsylvania State University.

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