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**Task 57 - Preparation and Combustion of Coal-Water Fuel
from the Sin Pun Coal Deposit, Southern Thailand**

**Topical Report
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Morgantown Site
P.O. Box 880
Morgantown, West Virginia 26507-0880

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By
Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street
P.O. Box 9018
Grand Forks, North Dakota 58202-9018

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Preparation and Combustion
of Coal–Water Fuel from the Sin Pun
Coal Deposit, Southern Thailand

Coal–Water Fuels

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PREPARATION AND COMBUSTION OF COAL-WATER FUEL FROM THE SIN PUN COAL DEPOSIT, SOUTHERN THAILAND

ABSTRACT

In response to an inquiry by the Department of Mineral Resources in Thailand, the Energy & Environmental Research Center (EERC) prepared a program to assess the responsiveness of Sin Pun lignite to the temperature and pressure conditions of hot-water drying. The results indicate that drying made several improvements in the coal, notably increases in heating value and carbon content and reductions in equilibrium moisture and oxygen content. The equilibrium moisture content decreased from 27 wt% for the raw coal to about 15 wt% for the hot-water-dried (HWD) coals. The energy density for a pumpable coal-water fuel (CWF) indicates an increase from 4500 to 6100 Btu/lb by hot-water drying. Approximately 650 lb of HWD Sin Pun CWF were fired in the EERC's combustion test facility. The fuel burned extremely well, with no feed problems noted during the course of the test. Fouling and slagging deposits each indicated a very low rate of ash deposition, with only a dusty layer formed on the cooled metal surfaces. The combustor was operated at between 20% and 25% excess air, resulting in a flue gas SO_2 concentration averaging approximately 6500 parts per million.

PREPARATION AND COMBUSTION OF COAL-WATER FUEL FROM THE SIN PUN COAL DEPOSIT, SOUTHERN THAILAND

EXECUTIVE SUMMARY

In Thailand, coal is the major source for both power and nonpower usages. Over the past 10 years, the Department of Mineral Resources (DMR) in Thailand has been evaluating the ability of the country's coal reserves to meet its increasing utility and industrial energy needs. DMR discovered over 750 million tons of measured coal and subbituminous reserves. Most of the reserves are the subject of additional exploration and development plans, which include applying clean coal technologies (i.e., coal preparation and beneficiation techniques) to reduce the impact of coal use on the environment.

The Energy & Environmental Research Center (EERC), which has for years been investigating the conversion of coal to energy-dense liquid fuels, was identified as a leading candidate to perform the development program. In response to the inquiry, the EERC prepared a four-task program to assess the responsiveness of the Sin Pun lignite to the temperature and pressure conditions of hot-water drying. The treated material was to be slurried in water and combusted in the EERC's combustion test facility (CTF). The remaining activity focused on Thai personnel training at the EERC in the area of clean coal technologies.

Approximately 400 kg of Sin Pun lignite was received at the EERC for testing. The lignite had a moisture-free sulfur content near 10 wt%, with over 95 wt% organic sulfur. HWD tests were conducted at 300° and 325°C using a bench-scale system. The coal-water fuel (CWF) produced from hot-water drying indicated a 10 wt% increase in attainable solids. Process gas and water analysis indicated that a portion of the coal's sulfur content was released during hot-water drying. In an effort to further reduce sulfur, hot-water drying tests were conducted at higher temperatures and pressures. The results indicated that over 50% of the sulfur may be extracted from the coal prior to combustion. Sin Pun ash chemistry does not initially appear to create a problem when the coal is combusted in boiler systems; however, regular sootblowing should be performed to reduce the chance of excessive sintering. Fluid-bed combustion was identified as a good technology to utilize the high-sulfur Sin Pun coal without creating an emission problem.

Pilot-scale hot-water drying tests were performed at 300° and 325°C. Slurry feed rates for the 300° and 325°C hot-water drying tests were approximately 500 lb/hr. The overall solids recoveries for the two tests were approximately 93 wt%. The results indicate that hot-water drying made several improvements to the Sin Pun coal, including an equilibrium moisture reduction of 40%, sulfur reduction of 10%, and a modest increase in heating value. Comparison of energy density (slurry basis) for fuels with similar viscosity showed an increase from 4500 to 6070 Btu/lb at 300°C and 6090 Btu/lb at 325°C. Approximately 360 kg (800 lb) of CWF with a target viscosity of nominally 500 cP was prepared for combustion testing.

The fuel burned extremely well, with no feed problems noted during the course of the test. Fouling and slagging deposits each indicated a very low rate of ash deposition, with only a dusty layer formed on the cooled metal surfaces. The combustor was operated between 20% and 25% excess air, resulting in a flue gas SO₂ concentration averaging approximately 6500 ppm. This level

indicates between 20% and 25% of the input sulfur content was captured by alkaline species, such as calcium, in the fly ash.

Personnel from Thailand's DMR arrived in Grand Forks and completed interactive training by observing bench- and pilot-scale hot-water drying demonstrations, CWF preparation and evaluation, and CWF combustion.

PREPARATION AND COMBUSTION OF COAL-WATER FUEL FROM THE SIN PUN COAL DEPOSIT, SOUTHERN THAILAND

CHAPTER 1. INTRODUCTION

1.1 Background

Low-rank coals (LRCs), which include lignite and subbituminous coals, constitute almost half of the vast reserves of coal that exist worldwide. Typically, deposits of these LRCs occur in thick seams with relatively thin cover; consequently, mining operations are generally inexpensive. Further, although at the bottom end of the quality range in coal classification, they are usually more homogeneous in their as-mined condition than high-rank coals. This feature is especially characteristic of lignite. However, despite their excellent combustion characteristics and other attractive properties, utilization of lignite and subbituminous coal has, to date, been largely confined to generating electrical power at or close to the mine site. The high moisture content and instability of LRCs have until now prevented their transport to distant coal markets.

The widespread use of LRCs in traditional coal markets is constrained by the following factors:

- High inherent moisture content
- High degree of risk for spontaneous combustion
- Weathering and resultant dust nuisance
- Fouling and slagging problems caused by high sodium content

Although their high inherent moisture content lowers their heating value and thus increases the cost of transportation and handling, the positive features of LRCs, such as their low cost per Btu and excellent combustion characteristics, have, to date, been ignored. No commercial drying process is currently available that can economically produce a conventional, dried bulk coal product that will withstand the rigors of storage, handling, and transportation. Traditional thermal drying methods used to dry bituminous coal are not effective on subbituminous coal and lignite because of the resulting decrepitation of these coals.

This situation encouraged researchers at the Energy & Environmental Research Center (EERC) to investigate alternative methods for drying such high-moisture coals economically. Their pioneering efforts led to the successful development of a hot-water-drying process for coal slurries at the EERC facility in Grand Forks, North Dakota, the world's largest research and development complex for investigating LRCs. This novel, nonevaporative drying technique is ideally suited for producing a coal-water fuel (CWF). As a consequence, subbituminous coal and lignite have now become more economically attractive for the production of CWF.

1.2 Objectives

The specific objectives of the project were as follows:

- To investigate the hot-water drying conditions for the selected southern Thai lignite at the bench and pilot scale
- To evaluate the combustion performance of the hot-water-dried (HWD) Thai lignite slurry

CHAPTER 2. EXPERIMENTAL PROCEDURES AND RESULTS

2.1 Coal Preparation and Analysis

Approximately 450 kg of Sin Pun lignite from Southern Thailand was shipped to the EERC. The coal, received as lumps up to 0.25 m (estimated), was crushed with a roll crusher, producing nominal 4- × 0-cm coal and then processed with a roller mill to 6.35 × 0 mm. Approximately 350 kg was pulverized for bench- and pilot-scale testing. 100 kg of "as-received" lignite was stored for future experimentation. Table 1 represents the particle size for the Sin Pun coal sample, which will be used for most of the hot-water drying tests at the EERC. Approximately 50 kg of coal sample was separated and stored for future work. A representative coal was submitted for proximate, ultimate, heating value, sulfur forms, and x-ray fluorescence analysis and ash fusion determinations. Analytical equipment and methods are presented in Table A-1 (Appendix A).

Table 2 summarizes the coal characteristics of the Sin Pun coal received by the EERC. The coal has a moderate ash content (11.3 wt% moisture-free [mf]), extremely high sulfur content (9.3 wt% mf), moderate nitrogen content (1.0 wt% mf), and as-received moisture content of 20.3 wt%. The as-received heating value was 7650 Btu/lb, which translates to a moisture-free heating value of 9600 Btu/lb.

TABLE 1

Particle-Size Distribution Analysis for Sin Pun Coal	
	Cumulative wt% Under Size
Particle Size, μm	Pulverized Coal
500	100.0
300	100.0
150	97.9
100	92.0
75	83.2
50	71.4
45	58.1
35	46.7
10	23.1
5	9.9
2	0.5
Estimated MMD ¹	40 μm

¹ Mass mean diameter or average particle size.

TABLE 2

Sin Pun Coal Analysis			
	As-Received	Moisture-Free Raw Coal	Moisture- and Ash-Free
Proximate Analysis, wt%			
Moisture	20.3	-	-
Volatile Matter	42.4	53.18	59.9
Fixed Carbon	28.3	35.55	40.1
Ash	9.0	11.27	-
Ultimate Analysis, wt%			
Carbon	46.3	58.14	65.5
Hydrogen	5.7	4.36	4.9
Nitrogen	0.8	1.04	1.2
Sulfur	7.4	9.32	10.5
Oxygen	30.7	15.87	17.9
Ash	9.0	11.27	-
Heating Value, Btu/lb	7650	9602	10,800

The ratio of fixed carbon to volatile matter is used by steam coal users as a barometer to determine whether a coal will burn well in a conventional boiler system. Typically, a ratio of less than 1.3 represents a good steam coal. At higher values, the coal may not completely combust, which leads to unburned fuel and adds carbon to the ash. The calculated fuel ratio for Sin Pun coal is 0.66, which means the coal is reactive and should burn completely in a boiler; however, it is likely to be prone to spontaneous heating when stockpiled.

Sulfur forms analysis, Table 3, indicated that over 95 wt% of total sulfur is present as organic sulfur. If the sulfur were in the pyritic form, conventional or advanced physical cleaning procedures could effectively reduce the sulfur content. However, the high organic fraction creates a greater problem. Within the United States, research efforts to reduce organic sulfur have focused on the addition of special chemicals and thermal processes to release the sulfur (1). These techniques and their effectiveness in removing sulfur are coal-specific and would have to be tried with the Sin Pun coal. These tests are considered outside the scope of the existing program. Table 3 reports a higher total sulfur value than Table 2, likely because of differences in laboratory procedures.

Based on ash chemistry, represented in Table 4, problems are not anticipated with fouling and slagging when Sin Pun coal is combusted in a boiler system. The high level of sulfur may, however, contribute to a sintering problem on boiler tubes if regular sootblowing is not performed.

TABLE 3

Sulfur Forms Analysis for Sin Pun Coal	
Analytical	Dry Basis, wt%
Proximate	
Total Sulfur	10.59
Sulfur Forms	
Organic	9.85
Pyritic	0.23
Sulfatic	0.51
Total Sulfur	10.59

TABLE 4

Raw Coal Ash Analysis, wt%		
Sample Analysis	Oxides	Elemental
Silica	34.5	27.2
Aluminum	14.9	13.3
Iron	19.4	22.9
Titanium	0.7	0.7
Phosphorus	0.3	0.2
Calcium	25.7	31.0
Magnesium	4.0	4.1
Sodium	0	0
Potassium	0.4	0.6

2.2 Bench-Scale Hot-Water Drying

The bench-scale hot-water drying tests with pulverized coal were performed in the EERC's 7.6-liter batch autoclave shown in Figure 1. The bolted-closure autoclave is externally heated and equipped with automatic temperature controllers and a variable-speed magnetically driven stirrer. The autoclave is instrumented to continuously measure and trend pressure plus slurry and vapor temperatures.

Figure 1. Schematic diagram of autoclave hot-water drying system.

Approximately 3000 grams of a 50 wt% coal/50 wt% deionized water feed slurry was used in each hot-water drying test. After feed slurry was charged to the autoclave, residual air was evacuated and the external heaters and stirrer turned on. Heatup to the desired temperature ranged from approximately 2 to 2½ hours, after which the slurry and vapor temperatures were allowed to stabilize. After a 15-minute hold time at temperature, the heaters were shut off, and the autoclave and contents were allowed to cool overnight.

Fractions recovered from the autoclave after cooldown included process gas, product slurry, and condensate. The total volume of process gas (noncondensable decomposition products) was measured with a diaphragm meter. Process gas was sampled for off-line analysis. The product slurry was recovered, weighed, and then dewatered via Büchner filtration.

Two autoclave tests were performed at two different treatment temperatures. The HWD solids were then reslurried in water and evaluated for rheological performance. The rheological behavior for the coal-liquid mixture, specifically the apparent viscosity, is determined as a function of shear rate and CWF solids concentrations. Since any change in solids loading of a CWF has a direct effect on the resulting flow behavior, several rheograms throughout the possible solids-loading range were gathered. The analytical equipment and methods are presented in Table A-1 (Appendix A).

Results from the autoclave experiments indicate that the solids recoveries for the 300° and 325°C tests were 96% and 94%, respectively. The solids losses were mainly due to evolved gases. Table 5 gives the composition of the gas based on the 325° tests performed using a Hewlett-Packard 5880a gas chromatograph. The results indicate that about 82 wt% of the gas evolved as CO₂ and 10 wt% as hydrogen sulfide. This is a high level of hydrogen sulfide and may have to be treated with a sulfur recovery or treatment system such as the Holmes-Stretford process or a scrubber system (2). Process water was weighed and suspended solids determined. Process water

TABLE 5

Gas Chromatography Analysis	
Description	325°C
Gas Concentration, wt%	
Helium	0.07
Hydrogen	0.46
Carbon Dioxide	82.16
Propylene	0.02
Isobutane	0.01
Carbonyl Sulfide	0.01
<i>n</i> -Butane	0.02
Hydrogen Sulfide	11.20
1-Butene	0.06
Ethylene	0.02
Ethane	0.29
Oxygen/Argon	0.11
Nitrogen	3.80
Methane	1.78
Calculated Btu/scf	
Saturated	98.3
Dry	100.0
Calculated Specific Gravity	1.439
Calculated Average Mole Weight	41.53

did have a distinct odor, indicating the presence of sulfur compounds that were extracted from the coal during the hot-water drying process. A more complete water analysis will be performed on the pilot-scale samples. Details of the instrumentation and techniques performed on the water and gas are in Appendix A.

Table 6 summarizes the proximate, ultimate, and heating value analyses for the raw and HWD samples. The results indicate that hot-water drying made several improvements in the coal, most notably a large reduction in oxygen, which translated into a concentration of fixed carbon and other components. The coal's oxygen content was reduced by over 40% at 300°C and over 60% at 325°C, primarily as a result of the decarboxylation and mild pyrolysis experienced during hot-water drying. The moisture-free heating value increased by nearly 15% as a result of hot-water drying. The moisture-free sulfur content indicates an increase; however, sulfur compounds were released by hot-water drying, as indicated in the gas analysis and by the distinct process water odor.

The rheological profiles in Figure 2 show the effect of hot-water drying temperature on CWF solids concentration and viscosity. The results indicate that hot-water drying definitely improves the solids concentration of the fuel, increasing the attainable solids content by over 10 wt%, which translates to an energy density increase of over 30%. For the HWD fuels, the solids loading at 500 cP is approximately 60 wt%, or 6400 Btu/lb, as a CWF. Only a 1 to 2 wt% difference in

TABLE 6

Raw and HWD Coal Analysis (moisture-free)			
	Raw Coal	300°C	325°C
Proximate Analysis, mf, wt%			
Volatile Matter	53.18	46.40	44.33
Fixed Carbon	35.55	41.61	43.08
Ash	11.27	11.99	12.59
Ultimate Analysis, mf, wt%			
Carbon	58.14	62.86	65.82
Hydrogen	4.36	4.39	4.43
Nitrogen	1.04	1.25	1.20
Sulfur	9.32	10.09	9.93
Oxygen	15.87	9.42	6.03
Ash	11.27	11.99	12.59
Heating Value, Btu/lb	9602	10,727	11,025

Determined at 100 Hz decreasing shear rate.

Figure 2. Rheological analysis for raw and HWD coal samples (temperature effect).

attainable solids concentration was observed between 300° and 325°C. Any difference is attributed to decarboxylation, a greater amount occurring at the higher temperature. A reduced hot-water drying temperature translates to lower system pressure, which is critical to the economic viability of a commercial process.

Because of the high sulfur content, which is mainly organic sulfur, EERC personnel processed the coal with an advanced hydrothermal technology being developed at the EERC at temperatures between 250° and 450°C. The multigram unit, a 40-cm³ reactor, is capable of hydrothermally treating 10–20 g at the elevated temperatures and pressures. Figure 3 illustrates the bench-scale extraction system. A pneumatically operated pump capable of continuously pumping water at 10 to 300 cm³/min through the fixed bed of coal was used.

For the Sin Pun coal, extractions were conducted with 6.35- × 0.5-mm coal and at a particle size similar to autoclave testing (average 40 μm). A 10- to 20-g weighed sample of coal was placed in the 40-cm³ reactor. The frits were put in place, the end caps of the reactor were tightened, and the reactor was then placed in the tube furnace. Fluid inlet and outlet tubing was attached, and all couplings were checked to be certain they were secure. The preheater and reactor heater were heated at maximum output for 5 min without fluid flow. When the target temperature was reached, the pump was turned on and the system pressure was brought to target pressure and set to flow at approximately 30 mL/min.

The temperature of the flowing water was monitored at the reactor inlet and outlet and was held at the desired temperature by adjusting water flow through the system. After a selected residence time at extraction temperature and pressure, the system was cooled and depressurized and the extracted coal was taken from the reactor. Extraction temperatures were 400°C for the coarse coal fraction and 380°C for the fine coal. The results from this testing indicated an approximately 50% reduction in total sulfur and solid recoveries of 40%–50%.

Figure 3. Multigram coal extraction system.

A series of four heat exchangers is used to preheat the slurry to the desired processing temperature. A double-pipe steam heat exchanger first heats the slurry up to 80°C, whereafter the slurry is heated in a series of three condensing Dowtherm vapor-liquid heat exchangers. The nominal ratings of the electric immersion heaters are 22, 22, and 30 kW, respectively.

The slurry, after exiting the fourth preheater at the desired processing temperature, is then directed to a series of two downflow reactors. The process piping is configured to allow using a single reactor to attain a residence time of 7 minutes or both reactors to attain a residence time of 15 minutes. Each reactor is equipped with four 2-kW externally mounted heaters to achieve isothermal temperature control.

After processing at the desired temperature and residence time, the coal slurry is throttled through pressure-reducing valves with a resultant flashing of steam and process gas. The gas-water vapor stream is cyclonically separated from the concentrated hot-water-dried coal slurry. The gas-water vapor stream is drawn through a multipass water-cooled condenser, whereafter the noncondensable process gas phase is sent to a natural gas-fired incinerator fired at 800°C. Condensate is collected for possible recycle. The product slurry is dewatered using a recessed filter press, producing damp filter cake and filtrate.

Production Testing and CWF Preparation

Pilot-scale test parameters were based upon the results from bench-scale evaluations, discussed earlier in this report under Task 1. Tests were completed at two temperatures (300° and 325°C). The Sin Pun lignite, pulverized to 250- μ m (60-mesh) top size and an average size of 30 μ m, was processed at a 45%/55% coal-to-water ratio.

The weights of feed slurry, product slurry, condensate, filter cake, and filtrate were collected at each test condition to facilitate calculation of overall material and solids recoveries.

A representative filter cake sample was obtained at each test condition for analysis. Gas chromatographic analyses were performed on select samples of process gas.

Rheological evaluations were performed by admixing the damp cake from hot-water drying with water to produce several different fuel concentrations. The rheological behavior of the slurry fuel, including variation of apparent viscosity as a function of shear rate, was determined for three or four solids concentrations using a Haake RV 100 viscometer.

Slurry feed rate for the pilot-scale testing was 500 lb/hr, which equates to approximately 20 minutes at temperature and pressure. The overall solids recoveries for the two tests were approximately 93 wt%. These values compare favorably with bench-scale hot-water drying recovery values.

Table 7 summarizes the analysis results for the pilot-scale HWD samples; the raw coal is included for comparison. The results indicate that hot-water drying made several improvements to the Sin Pun coal, including an equilibrium moisture reduction of 40%, sulfur reduction of 10%, and a modest increase in heating value. The increases in heating value appeared to be consistent with the effect of increasing the processing temperature.

Process gas samples obtained during processing were nearly equivalent in composition. Carbon dioxide was the primary component at >86 vol%, with hydrogen sulfide at >11 vol% and

smaller concentrations of methane (~0.8 vol%) and hydrogen (~0.1 vol%). The quantity of process gas was not measured. Process water analyses are presented in Table 8 for the pilot-scale tests. For more information on process water and process gas, consult Appendix A.

TABLE 7

Pilot-Scale HWD Sin Pun Lignite Analysis			
	Raw	300°C	325°C
Equilibrium Moisture, wt%	25.17	17.86	14.21
Proximate Analysis, wt% (moisture-free)			
Volatile Matter	52.78	47.32	46.16
Fixed Carbon	35.97	42.15	41.87
Ash	11.25	10.53	11.97
Ultimate Analysis, wt% (moisture-free)			
Hydrogen	4.88	4.39	4.32
Carbon	57.23	62.28	62.53
Nitrogen	1.00	1.10	1.17
Sulfur	9.79	8.92	8.61
Oxygen	15.85	12.78	11.40
Ash	11.25	10.53	11.97
Heating Value, Btu/lb	9470	10,650	10,680

TABLE 8

Process Water Analysis, mg/L				
Analysis	300°C		325°C	
	Filtrate	Condensate	Filtrate	Condensate
BOD ¹	4000	2400	4600	3280
COD ²	6300	3860	7500	6200
Total Suspended Solids	277	51	255	130
Total Dissolved Solids	8820	92	9250	112
Total Organic Carbon	2500	1500	2950	2050
Total Carbon	2530	1500	3300	2140
Sulfate	3890	8	3090	13

¹ Biological oxygen demand.

² Chemical oxygen demand.

The rheological profiles in Figure 5 indicate the effect of temperature (300° and 325°C, respectively) on CWF solids concentration and viscosity. In comparison to the bench-scale rheology there was not a 1-2 wt% increase in solids concentration when the processing temperature was increased from 300° to 325°C. Similar to bench-scale results, pilot-scale processing did significantly improve the solids content (and energy density) of the Sin Pun lignite. Comparison of energy density (slurry basis), for fuels with a viscosity of 500 cP, showed an increase from 4500 to 6070 Btu/lb at 300°C and 6090 Btu/lb at 325°C.

HWD coal produced in the pilot-scale production run was formulated into CWF for subsequent combustion testing. The two fuels were combined in order to produce enough fuel for combustion testing. Approximately 360 kg (800 lb) of CWF was prepared with a target viscosity of nominally 500 cP. The CWF had a solids concentration of 57.2 wt% and an estimated heating value of 6100 Btu/lb. The combined material viscosity curve is included in Figure 5, and it indicates a slight increase in comparison to the two processing conditions. The single point on the combined fuel curve is for the actual fuel that was burned in the combustion test.

Relative to bench-scale hot-water drying, pilot-scale testing produced fuels 1 to 2 wt% lower in solids loading. This can be explained by the differences in residence time achieved during batch- and continuous-scale processing. During pilot-scale testing, operating temperature is reached after approximately 2 min., while bench-scale heatup takes approximately 2 hr. Bench-scale fuel performance results are usually better than pilot-scale results because of the extended time in which the coal is exposed to temperatures above 200°C.

Determined at 100 Hz decreasing shear rate

Figure 5. Rheological analysis for pilot-scale HWD coal samples.

2.4 CWF Combustion and Emission Testing

A single test was conducted to evaluate combustion property enhancements resulting from the upgrading of a selected lignite from the Sin Pun coal deposit in southern Thailand using the HWD technique. The CWF product from the process was fired in the EERC's combustion pilot plant, utilizing the combustion test facility (CTF). The CTF is a refractory-lined, bottom-fired furnace sized to achieve firing rates between 550,000 and 750,000 Btu/hr. The CTF, originally built to test pulverized coals, has been enhanced to expand its capabilities to test other fuels such as CWFs and refuse-derived fuels. The balanced-draft unit is fully instrumented to characterize combustion conditions and utilizes a PC-based data acquisition system for data collection and storage. A more complete description of the CTF configuration for utilizing CWFs is included in Appendix B.

This section details the results of the combustion test that was performed to generate data on the combustion and ash fouling characteristics of the Thailand CWF. The CWF was fired in the CTF at a rate sufficient to maintain the furnace exit gas temperature (FEGT) at 2000°F (1093°C), with excess air controlled to about 23%. A water-cooled horizontal slag probe was inserted into the radiant zone of the furnace to evaluate slagging potential of the ash under conditions similar to the furnace walls in an utility boiler. A set of three steam-cooled Type 304 stainless steel deposition probes was inserted into the combustion chamber exit duct to collect ash fouling deposits under conditions similar to those occurring on high-temperature steam tubes located at the furnace exit in a utility boiler. The characteristics of gaseous and particulate emissions were also evaluated during the test burn as well as the relative collectibility of the fly ash from a pilot-scale electrostatic precipitator (ESP).

A video of the main components of the CTF was recorded during the test. This video was narrated to help identify combustion equipment and testing procedures. Photographs were taken during the test of the CWF flame, flue gas sampling, and various CTF components including the control panel, combustor, ductwork, ESP, and feed system. Photographs were also taken of the deposits after the test was completed. Copies of all operator's logs, run data sheets, and recorder printouts from the tests can be found in Appendix C.

CWF Properties

A sample of the as-fired Sin Pun CWF was taken from the feed hopper for analysis. This sample was submitted for proximate, ultimate, higher heating value (HHV), coal ash composition and ash fusibility. Proximate and ultimate analyses show that the fuel had a high sulfur concentration of 5.34 wt% at a solids loading of 56.9%. Over half of the combustibles consist of volatile matter, and the fuel had an ash content of 6.47 wt%. Table 9 shows the results of these analyses.

The results of chemical analyses, determined by x-ray fluorescence (XRF) of the CWF ash, show that the major oxides on a wt% basis were SiO₂ (31%); Al₂O₃ (10.7%); Fe₂O₃ (14.4%); CaO (16.9%); and SO₃ (23.7%). The high silica/alumina ratio (~3:1) indicates that the majority of the ash-forming species are most likely present as quartz grains, with few clay mineral inclusions. While this tends to indicate a higher fouling potential, the lack of sodium and low calcium content may be expected to create weak deposits in the high-temperature regions of the convective pass.

Ash fusion temperatures were determined under oxidizing and reducing conditions. The results of these analyses indicate a relatively low fluid temperature of 2278°F (1248°C) under

TABLE 9

Properties of Southern Thailand CWF					
Test Number:	AF-CTS-719				
Date:	3/11/97				
Fuel:	Southern Thailand CWF				
Proximate Analysis, %		As-Fired		H ₂ O-Free	
Moisture		43.1		—	
Volatile Matter		26.19		46.02	
Fixed Carbon		24.24		42.61	
Ash		6.47		11.37	
Ultimate Analysis, %					
Hydrogen		2.43		4.27	
Carbon		34.91		61.34	
Nitrogen		0.63		1.1	
Sulfur		5.34		9.39	
Oxygen		7.13		12.53	
Ash		6.47		11.37	
Moisture		43.1		—	
	Btu/lb	kJ/kg	Btu/lb	kJ/kg	
HHV	6014	13988	10568	24581	
Ash Input	lb/MMBtu	kg/kg-cal			
	10.76	19.37			
Ash Fusibility		Oxidizing		Reducing	
	°F	°C	°F	°C	
Initial Deformation	2336	1280	2203	1206	
Softening	2341	1283	2237	1225	
Hemisphere	2358	1292	2240	1227	
Fluid	2476	1358	2278	1248	
Oxides, wt%			SO ₃ -Free		
SiO ₂		31.0		40.7	
Al ₂ O ₃		10.7		14.0	
Fe ₂ O ₃		14.4		18.9	
TiO ₂		0.5		0.6	
P ₂ O ₅		0.2		0.3	
CaO		16.9		22.1	
MgO		2.2		2.9	
Na ₂ O		0.0		0.0	
K ₂ O		0.3		0.4	
SO ₃		23.7		—	
Total		99.9		99.9	

reducing conditions. This indicates that excess air levels should be maintained above some minimum level, perhaps 20% (3.5% O₂), dry basis.

Calculations to estimate solid and liquid mineral phases and ash viscosity of the CWF as a function of temperature were performed by using PHOEBE, an equilibrium thermodynamic model developed at the EERC based on the minimization of Gibbs' free energy. The results of the PHOEBE calculations of ash viscosity and percentage of liquid mineral phases versus temperature are shown in Figures 6 and 7, respectively. Note that viscosity is calculated only for the liquid-phase material present. Ash will flow readily at 250 poise. The temperature at which the ash attains a viscosity of 250 poise is called T_{250} and is used by cyclone and wet-bottom boiler operators to assess the potential for maintaining a consistent slag flow from a given fuel. Operators of pulverized coal-fired units would be inclined to either fire a fuel with a T_{250} greater than the operating FEGT or control the FEGT well below this value. The relatively narrow temperature range over which these phenomena can occur can be observed in some pulverized coal units, particularly those with an upper furnace suspended surface preceding secondary superheat surfaces, where tacky or liquid ash may occur at the bottom of the secondary superheat surface while dry powder exists at the top. The liquid mineral phase, which is less than 20% of the ash, consists almost entirely of $\text{CaMgSi}_2\text{O}_6$ and is the line shown on Figure 7. This phase does not become liquid until 2050°F (1121°C), indicating that minimal fouling would take place at temperatures near 2000°F (1093°C). Although the model predicts low viscosity for this liquid phase, there is very little available liquid material to sinter ash deposits at the temperatures discussed here. The model predicts that some increased fouling will occur at a FEGT above 2100°F (1150°C).

Figure 6. Coal analysis - viscosity PHOEBE results.

Figure 7. Coal analysis - liquid-phase PHOEBE results.

Combustor Operating Parameters

A standard 5.25-hr CWF combustion test, AF-CTS-719, was performed on March 11, 1997, to generate data on the combustion and ash fouling characteristics of the Thailand CWF. The CWF was fired in the CTF at an average rate of 123 lb/hr (55.8 kg), with an average FEGT of 2005°F (1096°C).

Feed rates were measured with a mass flowmeter and displayed on a digital readout. A calibration of the flowmeter was performed at the end of the run because of a 36% discrepancy between the amount of fuel fed indicated by the totalizer compared to the fuel fed based on a weighback method. The final totalizer reading indicated that 473 lb (214.6 kg) had been fired, while weighbacks indicated that 649 lb (294.4 kg) had been fed. This calibration verified that the totalizer was indicating a 36% lower flow rate than actual. Using this difference, the totalizer and weighback methods of determining feed rates correlate very closely (645.5 lb or 292.8 kg for the totalizer and 649 lb or 294.4 kg for weighback). The corrected totalizer feed rates are probably more accurate than those from the weighback, as the weighback does not account for the fuel that was not recovered at the beginning of the test, when pluggage occurred because of foreign material that was found in the slurry or possibly slight evaporation in the feed tank.

Combustion air settings were adjusted to achieve an average excess air level of 23%. The atomizing air flow (9% of total combustion air) was set to obtain good atomization of the CWF. Unheated primary air averaged 6% of the total flow, and 85% of the total flow was introduced as secondary air preheated to 500°F (260°C). The secondary air register was set to achieve a swirl number of 0.9. No tertiary air was used for this run. These settings provided for a stable flame and

instantaneous ignition of the fuel, which was verified by low carbon values in the ash. Figure 8 is a photograph of the CWF flame.

The horizontal slag probe inserted in the furnace was cooled to an average skin temperature of 739°F (393°C). Three steam-cooled deposition probes inserted in the duct at the furnace exit were used to determine convective pass fouling tendencies. These probes collected deposits over a 5.25-hr test period, with the surface metal temperature maintained at 1000°F (538°C).

The concentrations of O₂, CO₂, SO₂, and NO_x were continuously monitored at a port located just after the probe bank. Excess air was controlled to approximately 23% (3.83% O₂) during the combustion test. The ESP used to collect the ash in the flue gas had an average inlet temperature of 331°F (166°C) and outlet temperature of 286°F (141°C). A summary of the main combustor operating parameters is provided in Table 10.

Figure 8. Southern Thailand CWF flame.

TABLE 10

Summary of Combustor Operating Parameters - Test Averages

Test Number: AF-CTS-719		
Date of Test: 3/11/97		
Fuel: Southern Thailand CWF		
		SI Units
Total CWF Burned, lb	645.5	292.8 kg
Burn Time on Fuel, hr	5.25	
CWF Feed Rate, lb/hr	123	55.8 kg/hr
Heat Input, Btu/hr	739421	780530 kJ/hr
Furnace Exit Gas Temperature, °F	2005	1096°C
Ash Fouling Probe Metal Temperature, °F	1008	542°C
Horizontal Slag Probe Metal Temperature, °F	739	393°C
Flue Gas Analysis, dry, v/v		
O ₂ , %	3.83	
CO ₂ , %	15.05	
CO, %	na	
SO ₂ , ppm	6252	
NO _x , ppm	679	
Flue Gas Moisture, % v/v	17.4	
Excess Air, %	22.75	
Combustion Air, scfh		
Atomizing Air	742	21.01 m ³ /hr
Primary Air	582	16.48 m ³ /hr
Secondary Air	7368	208.66 m ³ /hr
Swirl Number	0.9	
ESP Specific Collection Area	75.18	
System Temperatures, °F		
Coal-Water Fuel	72	22°C
Atomizing Air	72	22°C
Primary Air	93	34°C
Secondary Air	500	260°C
Probe Bank Exit	1651	899°C
ESP Inlet	331	166°C
ESP Outlet	286	141°C
Induced-Draft Fan Inlet	227	108°C
Stack	179	82°C
System Pressures		
Forced-Draft Fan Exit Static, in. H ₂ O	65.7	1.63 kPa
CWF Feed Pressure, psig	100.0	7.03 kg/cm ²
Atomizing Air, psig	36.4	2.56 kg/cm ²
Combustor Static, in. H ₂ O	-0.3	-0.01 kPa
ESP Inlet Static, in. H ₂ O	-8.5	-0.21 kPa
ESP Outlet Static, in. H ₂ O	-11.0	-0.27 kPa
Induced-Draft Fan Inlet Static, in. H ₂ O	-19.2	-0.48 kPa

Summary of Ash Results

Ash Probe Deposit Characterization

Photographs of the deposits formed on the steam-cooled convective pass probes were taken at the completion of the test burn. The ash was then collected and analyzed.

The sintered ash deposits that formed on the north and middle steam-cooled probes in the probe duct arose from deposit growth initiated on the refractory wall in the duct. The ash was reddish brown in color and medium in hardness. Figures 9 and 10 are photographs of the ash formed in the probe bank area. Figure 9 shows the probe bank removed from the duct and the ash remaining in the duct. As seen in the photograph, most of the sintered ash deposit that had initiated from the refractory walls of the duct and probe bank remained in the duct when the probes were removed. The photos also show a portion of this sintered ash that remained on the probe bank. X-ray fluorescence analyses (XRFA) and scanning electron microscope point count (SEMP) results of this ash (Table 11) indicate high amounts of quartz- and silicon-rich particles. X-ray diffraction (XRD) results for this ash (Table 12) also shows the major mineral component of the probe bank duct ash is quartz. The major/minor components of quartz, hematite, calcium silicates, and calcium sulfate are typical of fuel having high Si/Al ratios with moderate alkali and alkaline-earth elements and lower FEGT temperatures.

Figure 9. Probe bank duct ash deposits.

Figure 10. Probe bank deposits.

TABLE 11

SEMPC and XRF Analyses of Probe Bank Duct Deposits

Test Number:	AF-CTS-719
Date:	3/11/97
Fuel:	Southern Thailand CWF
Particle Types, % of Total Count	
Pyrite	3.2
Calcium Sulfate	1.6
Mixed Sulfur-Rich	4.0
Mixed Carbon-Rich	1.2
Quartz	30.4
Anorthite	3.2
Montmorillonite	3.2
Pyroxene	0.4
Wollastonite	5.2
Mixed Silicon-Rich	43.2
Other	4.4
Total	100

Table 11 (continued)

Average Composition, wt%	SEMPC	SEMPC	XRF
	Bulk	Si-Rich	Results
SiO ₂	49.3	31.8	49.9
Al ₂ O ₃	9.9	14.5	7.7
Fe ₂ O ₃	15.0	22.9	18.5
TiO ₂	0.3	0.4	0.5
P ₂ O ₅	0.1	0.2	0.0
CaO	19.2	25.8	16.8
MgO	1.2	1.7	0.8
Na ₂ O	0.2	0.2	0.1
K ₂ O	0.2	0.2	0.3
SO ₃	4.5	2.3	5.4
Total	100	100	100
Total Count, Points	250	108	

TABLE 12

Results of XRD Analysis -

Probe Bank Duct Sintered, Probe Bank, Horizontal Slag Probe, and ESP No. 1 Ash

Mineral Component	Probe Bank	Probe	Horizontal	ESP No. 1
Quartz (SiO ₂)	Major	Minor	Major	Major
Anhydrite (CaSO ₄)	Minor	Minor	Minor	Minor
Hematite (Fe ₂ O ₃)	Minor	Minor	Minor	Minor
Clinopyroxene (Ca (Fe, Mg, Al) Si ₂ O ₆)	Minor	Minor	—	—
Augite (Ca (Mg, Fe) Si ₂ O ₆)	Minor	—	Minor	Minor
Cristobalite (SiO ₂)	Minor	—	—	—
Ferrite Spinel ((Mg, Fe, Fe, Al ₂ O ₃))	—	Minor	—	—

The computer program VISCALC developed at the EERC calculates viscosities for silicate phases from the point-by-point SEMPC analysis using a modified form of the Urbain equation. Viscosities were calculated by VISCALC for the probe bank duct ash, with the percentage of the deposit with viscosities less than 250 poise (T_{250}) plotted as a function of temperature. The median viscosity of the duct ash crosses T_{250} at $\sim 2425^{\circ}\text{F}$ (1329°C). Figure 11 plots the cumulative percent versus viscosities ($\log_{10}$ poise) for three temperatures. At 1832°F (1000°C), less than 1% of the ash is lower than T_{250} . At 2012°F (1100°C), 5% is less than T_{250} , and at 2192°F (1200°C), 29% of the ash is less than T_{250} . This indicates that at low temperatures, the ash has low fouling potential and should be easily sootblown from convective pass boiler tubes. This supports the results of the CTF combustion test, which showed very little or no fouling deposit formation at 2000°F . Firing of the Sin Pun CWF at an FEGT above 2000°F should be approached with caution. Modeling and analytical results indicate a significant change in deposit character may occur at temperatures above 2050°F . No deposits were formed at higher temperatures to establish deposit properties. Careful

Figure 11. Probe bank duct ash viscosity results.

examination of boiler tube fouling as a function of temperature above this threshold should be performed at full-scale or pilot-scale prior to establishing a higher FEGT as a normal boiler operating parameter.

The soft ash that was next to the probes was reddish brown in color. This ash (identified as probe bank) was brushed off and submitted for XRFA, XRD, and carbon-hydrogen-nitrogen (CHN) analyses. There was a rough enamel layer of ash that had formed on the probe surface that did not brush off, but was removed with sanding. XRFA results are reported as oxides on a weight percent basis and on a SO_3 -free basis in Table 13. These results indicate that a majority of the ash consists of quartz, iron, and calcium. There is also 13.7% SO_3 , which could be combined with the iron or calcium as sulfated mineral components. This could be attributed to the cooler probe surfaces, which favor sulfate deposits to form. The adhesion of these sulfated deposits to the probes was strong enough to prevent the erosion from impacting ash particles. XRD results (Table 12) do not list any major phases for the probe bank ash. CHN analysis of the ash showed there was good burnout of the fuel at this point, with only 0.16 wt% carbon in the ash.

Slag Probe Deposit Characterization

The ash that was deposited on the horizontal slag probe was a dark, reddish brown color. Figure 12 is a photograph of those deposits. It was deposited to a thickness of about 1/8 in. (3 mm) thick on the top surface. The ash was soft and easily brushed off. XRD results show quartz (SiO_2) to be the major crystalline phase. XRFA results (Table 13) also agree, with over 50% of the ash consisting of SiO_2 . There was less than 1% carbon in the ash collected from this probe. High quartz or silica content with minor oxides and silicate minerals are often associated with high- viscosity, nonsticky or more dry types of deposits and not usually prone to troublesome slag formation.

Figure 12. Horizontal slag probe ash deposits.

System Ash Characterization

The results of a mass balance performed after the completion the test burn are presented in Table 14. These samples accounted for only 43 % of the total ash input from the fuel. A significant portion of the unaccounted for ash was likely emitted from the stack, either as a fine gas or solid particulate. Collection efficiency of the ESP was less than 90% for this run. (ESP performance is discussed below.) Figure 13 shows the combustor bottom and ash deposits that were formed. This sintered ash was easily removed, with no evidence of any heavy slagging deposition. Selected ash samples were collected and submitted for analyses (Table 13). All of the samples submitted for carbon determination indicate that the CWF burned well in the CTF. XRFA results show that SiO_2 is the dominant component of the ash samples taken.

Stack Emissions and ESP Performance

Particulate concentrations at the inlet and exit of the ESP were determined using the U.S. Environmental Protection Agency (EPA) Method 5 protocol. Two sets of isokinetic sampling were performed to provide data on the collection efficiency of the ESP and the particle-size distribution of the ash entering the ESP. The first set consisted of an inlet and outlet dustloading, which were performed simultaneously. The ash for these dustloadings was collected on bulk filters. This set indicated a collection efficiency of 89%. For the second set of sampling, a five-stage multicyclone with a backup filter was used to get an aerodynamic size distribution of the ash entering the ESP while the outlet dust loading was collected with a bulk filter. These dust loadings were also performed simultaneously. The ESP had a collection efficiency of 87 % during this sampling period. The results of these dust loadings are presented in Table 15. The multicyclone data are

TABLE 13

Analyses of Selected Ash Deposits

Test Number:	AF-CTS-719									
Date:	3/11/97									
Fuel:	Southern Thailand CWF									
	Horizontal Probe	Horizontal Probe	Probe Bank	Probe Bank	Probe Bank Duct	Probe Bank Duct	ESP No. 1	ESP No. 1	ESP Final	Sampling Cyclone
Carbon, wt%	0.93	—	0.16	—	—	—	0.66	—	0.84	0.5
Oxides, wt%	N	R	N	R	N	R	N	R		
SiO ₂	51.0	56.8	28.9	33.5	49.9	52.7	46.1	49.8	—	—
Al ₂ O ₃	7.2	8.0	10.6	12.3	7.7	8.1	8.2	8.9	—	—
Fe ₂ O ₃	16.0	17.9	23.4	27.1	18.5	19.5	19.0	20.5	—	—
TiO ₂	0.4	0.5	0.2	0.3	0.5	0.5	0.5	0.6	—	—
P ₂ O ₅	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	—	—
CaO	13.5	15.0	19.9	23.0	16.8	17.8	17.1	18.5	—	—
MgO	1.0	1.1	2.1	2.4	0.8	0.9	1.0	1.1	—	—
Na ₂ O	0.2	0.2	0.3	0.4	0.1	0.1	0.1	0.1	—	—
K ₂ O	0.4	0.5	0.9	1.1	0.3	0.4	0.4	0.5	—	—
SO ₃	10.3	—	13.7	—	5.4	—	7.5	—	—	—

N = normalized to 100% closure.

R = renormalized to a SO₃-free basis.

TABLE 14

System Ash Mass Balances	
Test Number:	AF-CTS-719
Date:	3/11/97
Fuel:	Southern Thailand CWF
Test Duration, hr	5.25
Total Fuel Burned, lb	646
Total Fuel Burned, kg	292.80
Ash Input Rate, lb/MMBtu	10.76
Ash Input Rate, kg/kg-cal	19.37
Total Ash Input, lb	41.76
Total Ash Input, g	18942
Ash Balance	
Furnace, g	1828.2
Horizontal Slag Probe	77.0
Total	1905.2
% of Input	10.06
Probe Area, g	
Probe Bank	28.0
Probe Bank Duct	2503.6
Total	2531.6
% of Input	13.36
Heat Exchangers, g	
Horizontal	81.8
Air-Cooled	80.3
Total	162.1
% of Input	0.86
Electrostatic Precipitator	
Hopper Catch	3114.2
Sampling Cyclone	59.6
Flue Gas Piping	160.0
Bypass Cyclone	279.1
Total	3612.9
% of Input	19.07
Unaccounted for, g	10730.5
% of Input	56.65

Figure 13. Combustor bottom ash deposits.

presented in Table 16. The D_{50} particle size is reported for each cyclone in μm . Figure 14 plots the cumulative mass percent of these particles on a log scale.

The ESP collection hopper was emptied during the run to get a sample. This sample is referred to ESP No. 1. This ash was submitted for XRD (Table 12), XRFA and carbon determination (Table 13), and for particle-size determination (Figure 15). The ESP collection hopper was emptied again at the end of the run and submitted for carbon determination. This sample is identified as ESP Final.

The ESP obtained a collection efficiency of less than 90% for this run. This may not be entirely due to the ash characteristics, but rather to a low specific collection area (SCA). The SCA is defined as the effective collecting-electrode surface area per thousand acfm of gas treated. Depending upon the physical, chemical, and electrical characteristics of the coal ash, precipitator SCAs range from 300 to 1000 for collection efficiencies above 99.5%. (4) Higher flow rates through the ESP for the test burn of the CWF resulted in a SCA of 75.18 $\text{ft}^2/1000 \text{ scfm}$.

Figure 16 is a graph of the calculated resistivity (R) of the CWF ash in ohm-cm, predicted by the Bickelhaupt Model (5). The CWF resistivity of 1×10^{14} at 300°F (150°C) is high. Resistivities between 1×10^8 and 2×10^{10} ohm-cm usually are normal for satisfactory and predictable precipitator design. Ashes with resistivities greater than 5×10^{10} ohm-cm generally are difficult to collect. The high resistivity calculated from the Bickelhaupt Model is caused in part by the high concentrations of silica, alumina, and calcium. Combustion Engineering, Inc. (4) states that ash resistivity is inversely proportional to the concentration of sulfur trioxide and moisture in the flue gas and is directly proportional to the ash constituents of calcium, magnesium, alumina, and silica.

TABLE 15

ESP Dust-Loading Results

Test Number:	AF-CTS-719			
Date:	3/11/97			
Fuel:	Southern Thailand CWF			
	ESP Inlet No. 1	ESP Outlet No. 1	ESP Inlet No. 2	ESP Outlet No. 2
	Dust Loading	Dust Loading	Dust Loading	Dust Loading
Time	13:54:00	13:54:00	15:23:00	15:23:00
Duration, min	60	60	60	62
Dust Collected, g	6.34449	0.51408	5.9906	0.77178
Grains/scf	2.6479	0.2923	2.7011	0.3561
% Efficiency	—	88.962	—	86.818
% Isokinetic	101.5	104.1	100.3	103.2

TABLE 16

Inlet ESP Multicyclone Results

Test Number:	AF-CTS-719			
Date:	3/11/97			
Fuel:	Southern Thailand CWF			
	Mass, g	Percent Total	D ₅₀ , μm	Cumulative Percent
Stage 1	5.4292	90.63	7.66	9.37
Stage 2	0.3548	5.92	4.45	3.45
Stage 3	0.1373	2.29	2.34	1.16
Stage 4	0.0333	0.56	1.64	0.60
Stage 5	0.0210	0.35	0.69	0.25
Filter	0.0150	0.25

Figure 14. Inlet ESP multicyclone particle-size distribution.

Figure 15. ESP collection hopper ash Sample No. 1 particle-size distribution.

The concentrations of O_2 , CO_2 , SO_2 , and NO_x were continuously monitored at a port located just after the probe bank (Sample Port No. 1). The concentrations of O_2 , CO_2 , and SO_2 were also taken upstream of the induced-draft (ID) fan (Sample Port No. 3). A flue gas leak was indicated by a high O_2 percentage on Sample Port No. 3, and the high flue gas flow was traced to a flange after the ESP. The flange was tightened and the leakage was reduced by about 22 scfm. This leak was after the outlet sampling port, so it affected only flue gas flow and gas analyzer readings and not dust-loading results.

As the CWF's sulfur concentration was too high to be measured with the SO_2 analyzers, nitrogen was used to dilute the flue gas sample flow to the SO_2 analyzers. Mass flow controllers were installed in the SO_2 sample lines to regulate the nitrogen flow to one-half of the total flow. Thus actual SO_2 ppm concentrations were twice that indicated on the data sheets. The chart recorder scale was changed to a 0–10,000-ppm range to account for this correction. The SO_2 average of 6252 ppm, reported in Table 10, reflects the corrected concentration. The calculated SO_2 concentration of 8347 ppm on a dry basis was higher than the 6252-ppm average from the test. This difference could be due to a number of factors, including N_2 dilution errors, SO_2 scrubbing in the sample conditioner, and the formation of sulfates.

CHAPTER 3. CONCLUSIONS

- Hot-water drying decreased the equilibrium moisture content of Sin Pun lignite by 40%.
- In comparison to raw coal slurry, hot-water drying increased the solids loading concentration of fuel samples by 10%.

Figure 16. Sin Pun CWF ash resistivity.

- Hot-water drying enhanced the energy density of a pumpable Sin Pun CWF by 35%.
- Approximately 360 kg of HWD CWF was successfully produced using the pilot-scale system.
- The CWF exhibited good atomization properties and burned well in the CTF with good flame stability and reactivity.
- The ash formed from this fuel exhibited weak fouling deposits because of the quartz and iron oxides or spinels that dominated the deposits. The fuel was apparently rich in quartz and possibly iron oxide or iron/aluminum hydroxide.
- High viscosity calculations for liquid phases in the CTF convective pass fouling deposits verified visual examination of low fouling propensity. These deposits should be easily soot-blown if they are formed in temperature regions less than 2050°F (1121°C).
- The CWF had a high as-fired SO₂ weight percent of 5.34, with very little of the sulfur being associated with iron sulfides. Only 4% of this sulfur was bound with the calcium in the probe bank duct ash. If this fuel is used, some type of flue gas conditioning will be necessary.
- The ESP obtained a collection efficiency of only 89%, possibly due to high flows through the ESP and high resistivity (1×10^{14} at 150°C) of the ash.
- Particle-size analysis of the ESP ash shows that 37% of the ash collected was below 10 μm . Only 1.4% of the ash was less than 2.6 μm , which would suggest that the submicron ash was not collected in the ESP, thus accounting for the low collection efficiency.

CHAPTER 4. REFERENCES

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APPENDIX A

**ANALYTICAL EQUIPMENT
AND PROCEDURES**

ANALYTICAL EQUIPMENT AND PROCEDURES

The Energy & Environmental Research Center (EERC) has researched numerous drying and conversion technologies that can be applied to coal and subbituminous coals to upgrade the quality of the coal. Table A-1 summarizes the test procedures used to analyze the coal samples for this project.

TABLE A-1

Analytical Equipment and Procedures		
Analysis	Equipment	Procedure
Hot-Water Drying	2-gallon autoclave and PDU	NA ¹
Fuel Viscosity	Haake® 100 rotoviscometer	NA
Static Stability	Rod penetrometer	
Particle Size	Malvern® 2600c laser Diffraction Analyzer	NA
Gas Analysis	Hewlett-Packard® 5880a gas chromatograph	
Carbon	Leco® CHN 600 analyzer	NA
Hydrogen	Leco® CHN 600 analyzer	NA
Nitrogen	Leco® CHN 600 analyzer	NA
Sulfur	Leco® induction furnace	ASTM D3177
Sulfur Forms	NA	ASTM D2492
Equilibrium Moisture	NA	ASTM D1412
Moisture	Fisher® coal analyzer	ASTM D3175
Volatile Matter	Fisher® coal analyzer	ASTM D3175
Ash	Fisher® coal analyzer	ASTM D3174
Ash Characterization	KeveX® energy-dispersive x-ray spectrometer	NA
Combustion Behavior	Drop-tube furnace (DTF)	NA

¹ Not applicable.

PROXIMATE AND ULTIMATE ANALYSIS

Proximate analysis (moisture, ash, volatile matter, fixed carbon) was performed on the raw and treated coal using a Fisher® coal analyzer. The instrument determines moisture at conditions specified in American Society for Testing and Materials (ASTM) Method D3175. Volatile matter is determined by heating the dried sample to 950°C in a nitrogen atmosphere at conditions specified in ASTM D3175. The sample is covered during this process in order to exclude oxygen and prevent the sample from being ashed. Following the volatile matter determination, the sample is

uncovered and combusted, and the ash is determined at conditions specified by ASTM D3174. Fixed carbon is determined by difference, following the previously described methods.

Ultimate analysis determines carbon, hydrogen, nitrogen, sulfur, oxygen, and ash content in a sample. Carbon, hydrogen, and nitrogen (CHN) content are determined using a Leco® CHN-600 analyzer. Carbon and hydrogen are determined by infrared cells, and elemental nitrogen is measured by a thermal conductivity cell. This method gives the total percentages of CHN in the organic sample as analyzed and includes the carbon in carbonates and the hydrogen in the moisture and in the water of hydration of minerals. Sulfur is determined using a Leco® SC-132 sulfur analyzer in which a sample is combusted in oxygen, forming sulfur dioxide, which is determined by an infrared cell detector. Ash is determined by the ASTM method described under proximate analysis. Oxygen is determined by difference in order to achieve a balance of the ultimate analysis. Forms of sulfur are determined according to ASTM D2492. Ash characterization is determined using x-ray fluorescence techniques using the equipment in Table A-1.

RHEOLOGICAL CHARACTERIZATION

The rheological properties are determined based on the Yield Power Law equation for fluids. The Haake® RV 100 viscometer, shown in Figure A-1, is used to measure the flow properties of various liquid fuels from shear rates of near zero to 1100 sec⁻¹ (Hz) over a temperature range of 4° to 95°C. Results from the Haake® are logged and compiled using a computer network system. The Haake® viscometer shears the slurry in the annular space between the rotating cylinder and a stationary cup. The torque necessary to rotate the cylinder at a given speed is measured by a torsion spring. Various rotor assemblies allow the user a complete profile of the rheological characteristics. The computer indicates the independent flow behavior, viscosity, and yield stress values for the fluid as each correlates to the Yield Power Law. Rheological data are used to assess the effect of

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Figure A-1. HAAKE® rheological measuring equipment.

the hot-water drying (HWD) process variables on the relationship between viscosity and dry solids concentrations.

PARTICLE SIZE

The particle-size distribution of the raw and hot-water-dried coal is determined using a Malvern® 2600c laser diffraction particle-size analyzer, capable of measuring particle sizes from 0.5 to 564 microns. Figure A-2 depicts the Malvern® instrument setup. The basic principle of the Malvern® involves a He-Ne low-power visible wavelength laser that is first expanded and spatially filtered to provide a clean parallel beam. As particles pass through the beam, they scatter or diffract the light at different angles, depending upon their diameter; large particles scatter at small angles and vice versa. The scattered light is collected by a lens and brought to focus on a multielement solid-state detector that simultaneously measures the light at a number of angles. During analysis, the sample particles move rapidly through the laser beam. The results indicate the volume percentage distribution, as well as report the average particle size.

EQUILIBRIUM MOISTURE

The moisture contents of the raw and HWD coals as a function of incubation time are determined using a standard or modified ASTM equilibrium moisture method. The standard equilibrium moisture tests use an incubation time of 3 or 4 days, while the modified test uses incubation times of 2 to 30 days. The extended time period is used because the standard 3 or 4 days is often too short to allow the raw and HWD low-rank coals to attain an equilibrium moisture.

Figure A-2. Malvern® instrument setup.

PROCESS WATER ANALYSIS

Various tests are performed on the process water produced during HWD to evaluate the amount of carbonaceous material, the recyclability of the stream, and treatability. The most widely used parameter of organic pollution applied to both wastewater and surface water is the 5-day biochemical oxygen demand (BOD) test. The BOD test is completed on the water sample to measure the oxygen required for the biochemical degradation of organic material and the oxygen used to oxidize inorganic material. The BOD is computed from the difference between initial and final dissolved oxygen. The chemical oxygen demand (COD) test is used to measure the content of organic matter of both wastewater and natural waters. The COD of a waste is, in general, higher than the BOD because more compounds can be chemically oxidized than can be biologically oxidized. For many types of wastes, it is possible to correlate COD with BOD. This can be very useful because the COD can be determined in 3 hours, compared to 5 days for the BOD. Once the correlation has been established, COD measurements can be used to good advantage for treatment plant control and operation. Total organic carbon (TOC), another means for measuring the organic matter present in water, is especially applicable to small concentrations of organic matter. To determine the quantity of TOC, the organic molecules must be broken down to single carbon units and converted to a single molecular form that can be measured quantitatively. TOC methods utilize heat and oxygen, ultraviolet irradiation, chemical oxidants, or combinations of these oxidants to convert organic carbon to carbon dioxide. Total carbon (TC) is determined by taking a quantity of sample and analyzing directly using an infrared carbon analyzer. In order to determine TOC, the sample must be sparged of the inorganic carbon (IC). Total solids determination is also performed on the sample. This includes total dissolved solids (TDS) and total suspended solids (TSS). TSS includes the portion of total solids retained by a filter, and TDS is the portion of the total solids that passes through the filter.

GAS ANALYSIS

Gas analysis is evaluated using a Hewlett-Packard® Model 5880a gas chromatograph with a refinery gas analyzer package used to detect selected gases in process gas samples. The method of detection is based upon relationships of thermal conductivity of the various gas compounds. The refinery package consists of five different absorbing columns and four heated valves for column switching. The instrument uses two carrier gases, and hydrogen is used for the determination of CO₂, CO, O₂, N₂, H₂S, and carbon chains C₁ through C₅ hydrocarbons. Argon is used for the determination of helium and hydrogen.

APPENDIX B

DESCRIPTION OF THE COMBUSTION TEST FACILITY (CTF) AND EXPERIMENTAL PROCEDURES FOR COAL-WATER FUEL COMBUSTION

COAL-WATER FUEL COMBUSTION DESCRIPTION OF FACILITIES AND PROCEDURES

BACKGROUND

Research programs have been under way at the Energy & Environmental Research Center (EERC) for more than 25 years to study fouling of boiler heat-transfer surfaces in coal-fired utility boilers. A 550,000 Btu/hr pulverized coal pilot plant test furnace was constructed in 1967 to evaluate the influence of variables, including ash composition, excess air, gas temperature, and tube wall temperatures, on ash fouling. Results from this work have shown a strong correlation between ash characteristics and degree of fouling.

The research capabilities of the EERC combustion test facility (CTF) have been enhanced and expanded to provide information on a wide range of combustion-related issues. The many research applications of this pilot-scale combustion equipment over the years have included:

- Determining ash-fouling rates and the strength, composition, and structure of fouling deposits
- Applying sophisticated analytical methods to characterize input coal, ash, and deposits and to correlate coal and ash properties with deposit growth rates and strength development
- Evaluating the effectiveness of ash-fouling additives
- Studying particulate-size distribution and velocity prior to deposition on convective section heat-transfer surfaces
- Evaluating combustion characteristics of coal-water slurries
- Studying high-temperature baghouse operation and performance
- Evaluating sorbent injection for SO_x control
- Assessing integrated particulate and SO_x/NO_x control
- Studying NO_x control using selective catalytic reduction and disposable catalysts
- Evaluating ash slagging potential in a simulated wet-bottom firing mode
- Performing flame stability tests for comparing a particular fuel at full load and under turndown conditions

COMBUSTION TEST FACILITY

An isometric drawing of the EERC combustion test facility (CTF) is shown in Figure A-1. The furnace capacity is approximately 700,000 Btu/hr of slurry fuel firing at a rate between 95 and 115 lb of slurry fuel/hr. The combustion chamber is 30 inches in diameter, 8 feet high, and refractory-lined.

Although designed as a pulverized coal-fired unit with more than 700 combustion tests completed to date, more than 200 combustion tests firing slurry fuels have been performed on coals of varying rank.

When slurry fuels are fired, the bottom of the combustion chamber is replaced to accommodate a burner with adjustable, secondary air swirl vanes. The slurry is pumped from a continuously stirred storage tank through the burner gun to the atomizer, where it mixes with atomizing air prior to entering the burner throat (see Figure A-2). A schematic of the atomizer used during combustion of slurry fuel is presented in Figure A-3. Heated primary air carries the atomized slurry out of the burner gun, while heated secondary air is introduced in an annular section surrounding the burner gun. Heated tertiary air is added through two tangential ports located in the furnace wall about 1 foot above the burner cone. The percentages of the total air used as primary, secondary, and tertiary air are usually 10, 65, and 25, respectively. Flue gas passes out of the furnace into a 10-inch-square duct that is also refractory-lined. Located in the duct is a vertical probe bank designed to simulate superheater surfaces in the convective pass of a utility boiler. Located in the duct is a vertical probe bank designed to simulate superheater surfaces in the convective pass of a utility boiler.

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Figure A-1. Slurry-fired test combustor and auxiliary systems.

Figure A-2. Schematic of combustion test furnace.

Figure A-3. BII atomizer used during combustion testing of slurry fuel.

The furnace is fired at a rate sufficient to maintain the furnace exit gas temperature at a constant level (usually 2000°F or 2200°F), with excess air maintained at a specified level (usually 20% or 25% excess air). The slurry fuel feed rate and air flow rates are adjusted accordingly to maintain these operating conditions. Upon leaving the probe bank duct, the flue gas passes through a series of water-cooled heat exchangers used to control the temperature entering the particulate control device (either an electrostatic precipitator [ESP] or a pulse-jet baghouse). The ESP is operated at a constant inlet gas temperature (usually specified between 300° and 350°F) with voltage input regulated to the highest voltage attainable without sparkover or back-corona effects (usually about 60 kV). ESP performance is characterized by obtaining a series of U.S. Environmental Protection Agency (EPA) Method 5 particulate samples at both the ESP inlet and outlet. The fly ash collected by the ESP is subjected to a laboratory determination of resistivity in addition to standard American Society for Testing and Materials (ASTM) analyses and advanced scanning electron microscope (SEM) analyses.

In addition to the fouling probe bank at the furnace exit, the test furnace contains numerous ports through which gas and fly ash samples may be collected, and various probes may be inserted for collection of deposits. Standard ASTM techniques and advanced laboratory and SEM techniques are utilized to analyze the various samples collected.

Figure A-4 shows the construction of the ash-fouling test probe bank, which is located in a hinged door to facilitate inspection and cleaning. The three fouling probes are constructed of 1.66-inch-OD, Type 304 stainless steel pipe and are cooled with compressed air. Each probe has two thermocouples embedded in its upstream edge to measure metal temperature. One of the thermocouples on each probe is attached to a temperature recorder/controller that regulates the cooling air to the probe. Normally, the surface temperature of each probe is maintained at 1000°F, while the gas temperature entering the probe bank is maintained at approximately 2000°F. When the furnace is fired in the bituminous mode, the temperature entering the probe bank has been as high as 2400°F. The gas velocity between the tubes is normally about 25 ft/s when low-rank coals are fired.

After leaving the probe bank duct, the flue gas passes through a series of water-cooled heat exchangers before being discharged through either an ESP or a baghouse. An ESP is normally used for collection of fly ash during standard combustion tests.

General Test Method

The relative fouling potential and other tendencies of test coals are determined by burning coal samples under specified conditions. When starting with a cold furnace, the following 13.25-hour test program is normally used:

	Hours
Preheat on gas	8.00
100% slurry fuel firing	<u>5.25</u>
Total	13.25

The slurry fuel feed rate is commonly adjusted to keep the flue gas temperature entering the upper duct to the probe bank at 2000°F with 25% excess air. Slurry samples are taken periodically to form a composite sample. Oxygen, carbon dioxide, nitrous oxides, carbon monoxide, and sulfur dioxide in the flue gas are continuously monitored by recording analyzers.

Figure A-4. Detail of probe bank construction.

The operating conditions and procedures described above are those normally utilized in studying the ash-fouling tendencies of low-rank western coals. They are included for the purposes of reference and description, and for comparison with the conditions actually utilized when burning slurry fuel.

The test furnace has numerous ports that permit observation of the probes and the furnace burner zone during the test run. These ports can also be used for installation of additional test probes, auxiliary measurements, photography of probes, or injection of additives.

At the completion of the test period, the probe door is carefully 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 weighs less than 10 grams, as compared to 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 for its relative fouling potential. To ensure that the pilot-scale test results are meaningful for evaluation of ash-fouling potential in full-scale utility boilers, calibration tests were previously conducted with low-rank coals known to produce low and high fouling in utility boilers. Comparisons of ash fouling have been made based on tests conducted at a number of power stations throughout the western United States: 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 these tests, the ash deposit buildup rate on the probe bank was found

to be a good indicator of fouling potential. The relationship between deposit weight and a fuel's fouling potential is generally categorized as indicated below:

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

Deposit Strength Tests

The weight of the ash deposit from the probe bank has proven to be a good indicator of the fouling potential for most coals tested in the this furnace. Heavy deposits in the 5.25-hour test indicate high deposition rates, which can usually be related to potential ash-fouling problems in utility boilers. However, the deposition rate does not provide an indication of the ease of deposit removal by sootblowing. Methods to measure deposit tenacity and strength have been reviewed at the EERC, and strength test methods have been developed that appear to provide reliable, reproducible results.

Deposit strength is initially assessed by means of the strength rating factor (SRF). This factor is determined based on observations made by a pilot-plant operator during removal of ash deposits from the probe bank. Deposit hardness and breakability is rated from 1 to 10, with 1 indicating soft and crumbly and 10 indicating hard and unfragmented.

The probe deposit is also subjected to a laboratory deposit strength evaluation procedure developed at the EERC, which utilized a drop impactor technique. A known weight is dropped with a measured impact on the sliced face of a 1-inch-long deposit sample. After the drop test, the sample is sieved in a sonic sifter through a series of six screens ranging in size from 5.66 to 0.21 mm. The percentage of each size is determined and, using the procedure from the ASTM Tumbler Test (ASTM Method D441-45), the dust index, friability, and mass mean diameter of the crushed deposit sample are determined. An impact resistance value (IRV) is calculated, which adjusts the results of the impactor tests for the test parameters under which they were obtained. The calculation was developed by analysis of a large body of data obtained by this procedure.

Flame Stability Testing

Background

Flame stability is assessed by observation of the flame and its relation to the burner quarl as a function of secondary air swirl and operating conditions at full load and under turndown conditions. An International Flame Research Foundation (IFRF)-type adjustable secondary air swirl generator (shown in Figure 3) uses primary and secondary air at approximately 15% and 85% of the total air, respectively, to adjust swirl between 0 and a maximum of 1.9. Swirl is defined as the ratio of the radial (tangential) momentum to axial momentum imparted to the secondary air by movable blocks internal to the burner and is used to set up an internal recirculation zone (IRZ) within the flame that allows greater mixing of combustion air and coal. Swirl is imparted by moving these blocks to set up alternate paths of radial flow and tangential flow, creating a spin on the secondary air stream that increases the turbulence in the near-burner zone. At the fully open position of the swirl block, the secondary air passes through the swirl

burner unaffected and the momentum of this stream has only an axial component (the air enters the combustion chamber as a jet). As the angle of the blocks changes, the air begins to spin or "swirl" and the radial component to the momentum is established, creating the IRZ in the near burner region. It is the ratio of this radial component of the momentum to the axial component that establishes the quantity defined as "swirl".

The adjustable swirl burner used by the EERC during flame stability testing consists of two annular plates and two series of interlocking wedge-shaped blocks, each attached to one of the plates. The two sets of blocks can form alternate radial and tangential flow channels, such that the air flow splits into an equal number of radial and tangential streams which combine further downstream into one swirling flow as shown in Figure 4. By simply rotating the movable plate, radial channels are progressively closed and tangential channels opened so that the resulting flux of angular momentum increases continuously, between zero and a maximum value. This maximum swirl depends on the total air flow rate and the geometry of the swirl generator. Swirl can be calculated based on dimensions of the movable blocks (the ratio of the tangential and radial openings of the blocks) or based on the measurement of the velocity of the air stream (obtaining both radial and axial components). The following description of that calculation is provided by Beer and Chigier (3).

When rotating motion is imparted to a fluid upstream of an orifice, the fluid flow emerging from the orifice has a tangential velocity component in addition to the axial and radial components of velocity encountered in non-swirling jets. The presence of the swirl results in the setting up of radial and axial pressure gradients which, in turn, influence the flow field. In the case of strong swirl, the adverse axial pressure gradient is sufficiently large to result in reverse flow along the axis, setting up the internal recirculation zone.

Figure A-5. IFRF adjustable swirl burner.

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Figure A-6. Cross-section of movable block assembly.

In swirling free jets or flames, both axial flux of the angular momentum (G_θ) and the axial thrust (G_x) are conserved. These can be written as

$$G_\theta = \int_0^R [(Wr) \rho U 2\pi r] dr = \text{const}$$

$$G_x = \int_0^R [U \rho U 2\pi r] dr + \int_0^R [p 2\pi r] dr = \text{const}$$

where, U , W and p are the axial and tangential components of the velocity and static pressure, respectively, in any cross section of the jet. Since both these momentum fluxes can be considered to be characteristic of the aerodynamic behaviour of the flame, a non-dimensional criterion based on these quantities can describe the swirl intensity as

$$S = G_\theta / G_x R \quad (R = \text{exit radius of the burner nozzle}).$$

Experiments have shown that the swirl number S was the significant similarity criterion of swirling jets produced by geometrically similar swirl generators. Other similarity criteria which take account of non-isothermal conditions and of confinement of jet flow by walls can also be applied in conjunction with the swirl number. The calculation of swirl in other types of swirl generators such as the air registers on a utility boiler are also described by Beer and Chigier (3), though not mentioned here.

Secondary air swirl is used to stabilize the flame. In the absence of swirl, loss of flame may result, increasing the risk of dust explosion. As swirl is applied to the combustion air, coal particles are entrained in the IRZ, increasing the heating rate of the particles, leading to increased release of volatiles and char combustion. The flame becomes more compact and intense as swirl is increased to an "optimum" level, which is characterized in EERC's test facility as the point at which the flame makes contact with the burner quarl. Increasing swirl beyond this level can pull the flame into the burner region, unnecessarily exposing metal burner components to the intense heat of the flame and possible combustion in the coal pipe.

Increasing swirl to provide flame stability and increased carbon conversion can also affect the formation of NO_x . The high flame temperatures and increased coal/air mixing associated with increased swirl create an ideal situation under which NO_x may form. In full-scale burners with adjustable vanes, swirl is often increased to reach the "optimum" condition and then decreased slightly to reduce the production of NO_x .

General Test Method

The general test method sets the burner at its maximum level of swirl and monitors system parameters such as fuel feed rate, excess air, gaseous emissions (CO_2 , CO , SO_x , and NO_x), combustor static, and air flow rates. Photographs of the flame and burner zone are then taken through a sight port in the furnace proper just above the burner cone using standard 35-mm film. Flame temperature is also measured using a high-velocity thermocouple (HVT) at a set location in the furnace, and heat flux is monitored using a baseline heat flux probe at the same location. An ash sample is also collected at each swirl setting to establish carbon burnout. The swirl setting is then reduced until the flame is visually observed to lift off the burner quarl. At this point, the flame is characterized as unstable under full load conditions (between 600,000 and 650,000 Btu/hr firing rate). Photographs are again taken to record the flame at this setting, temperature and heat flux measurements are taken, and an ash sample is taken once again. Having established flame liftoff, the optimum swirl setting is then located by visual observation of the flame, and measurements are recorded once again.

Flame stability under turndown conditions is characterized by firing the test fuel at reduced load (typically one-half to three-quarter the full load rate), maintaining the same primary air flow and adjusting the secondary air flow to meet excess air requirements. The procedure described above is then used to establish flame stability at reduced load.

Furnace Wall Slag Probes

The combustion test facility (CTF) at EERC was originally designed for tests of fouling potential of low-rank coals. As a result, the nominal design values of heat input (550,000 Btu/hr), furnace exit gas temperature ($\text{FEGT} = 2000^\circ\text{F}$), and excess air levels (25%) reflect utility industry experience on such fuels. More recently, efforts were made to evaluate slagging potential in the CTF. Utilizing information provided by Foster Wheeler Development Corporation, two slagging probes were designed, constructed, and positioned close to the flame region of the furnace. A simulated waterwall probe and a horizontal probe were installed just above the flame. Both slagging test probes are water-cooled to enable monitoring and maintaining surface metal temperatures between 500° and 800°F .

FLY ASH PARTICULATE CHARACTERIZATION

Fly ash samples are obtained by various means at the inlet and outlet of the pilot-plant ESP or baghouse, as shown in Figure A-1. EPA Method 5 is used to establish particulate concentrations in flue gas. High-volume sample extraction and the pilot plant control device collection hoppers can provide larger samples for study. Particulate sizing and laboratory ash resistivity techniques used to characterize the fly ash from each test are described below.

Five-Stage Cyclone System

A five-stage cyclone system, shown in Figure A-5, is used to determine the size distribution of particulate entering the ESP. The system consists of five cyclones and a backup filter connected in series to provide five equally-spaced particle-size cuts on a logarithmic scale from 0.1 to 10 μm . The nominal flow rate for the system is 1.0 acfm. The five-stage cyclone system was designed to operate in-stack, but is operated out-of-stack (particulate-laden flue gas is isokinetically extracted from the stack using a sampling probe) at the EERC because of the small pipe diameters associated with the pilot-scale combustion equipment.

Laboratory Resistivity Unit

Bulk electrical resistivity measurements are made with an apparatus designed and built according to the ASME Power Test Code 28 that provides control of temperature and flue gas environment for the ash samples being tested. Temperature control is maintained by an oven consisting of two concentric cylinders separated by 3 inches of ceramic fiber insulation (Figure A-6). The outer cylinder is made of

Figure A-7. Five-stage cyclone sampling system.

mild steel and is 34 inches high and 16 inches in diameter. The inner cylinder is constructed of stainless steel and is 28 inches high and 10 inches in diameter. Heating is achieved with 3000-watt strip heaters placed around the outside of the inner cylinder. The oven can be heated to a maximum of 800°F in approximately 1/2 hour and can maintain any temperature between room temperature and 800°F. Oven temperature is measured with a thermocouple, and temperature control is achieved with an automatic controller. A second thermocouple with digital readout is mounted near the ash layer for a precise determination of the oven temperature. Flue gas components (O_2 , CO_2 , SO_2 , and N_2 from compressed gas cylinders) are metered with rotameters to match the flue gas concentrations in which the fly ash was collected. Humidity is controlled by bubbling the simulated flue gas through a constant temperature humidification bath. Sulfur dioxide and CO_2 do not go through the humidity bath, but enter the simulated flue gas stream just prior to the oven.

Fly ash resistivity measurements are made using a movable disk electrode, as shown in Figure 7. This electrode was designed to put a pressure of 10 g/cm² on a layer of ash 5 mm thick. The ash sample container and the electrode are made of sintered stainless steel of 25-micron porosity to allow contact between the ash and the flue gas. The electrode can be raised or lowered by a crank on the outside of the oven.

Figure A-8. Schematic of laboratory resistivity apparatus.

A high-voltage supply with a range of 0 to 1200 volts is wired to the sample pan electrode. Current passing through the sample layer from the sample pan to the measuring electrode is measured by an electrometer capable of reading currents from 10^{-14} to 10^{-1} amperes. Coaxial cable is used on the voltage source and electrometer to shield against external noise.

A uniform ash layer is introduced to the conductivity cell and the electrode is carefully lowered onto the ash layer. The oven door is then closed and the temperature is set to 200°F. After the oven has maintained the designated temperature for at least 40 minutes, 750 volts are applied to the 0.5-cm ash layer. This produces a field strength of 1.5 kV/cm. The current through the ash layer is measured with a high-sensitivity electrometer. The temperature of the oven is increased to the next higher temperature, after which there is a 40-minute waiting period to ensure that the ash layer has a uniform temperature. The test voltage is then applied, the current reading is recorded, and the temperature is increased to the next setting. One set of readings from 200° to 750°F normally requires 8 to 10 hours to complete.

The fly ash resistivity (in ohm-cm) is calculated using the equation

$$\rho = \frac{VA}{IL}$$

Figure A-9. Resistivity-measuring electrode.

where V is the applied voltage (held constant at 750 volts), A is the area of the inner electrode (5.07 cm^2), L is the thickness of the ash layer (0.5 cm), and I is the measured current in amperes. For a given test, the data are presented as a plot of fly ash resistivity in ohm-cm versus temperature.

ANALYTICAL PROCEDURES

Slurry Fuel Analysis

The slurry fuel sample is analyzed to determine its proximate and ultimate analysis, heating value, and particle-size distribution.

Proximate analysis (moisture, ash, volatile matter, fixed carbon) is performed on the raw and treated fuel using a Fisher® coal analyzer. The instrument determines moisture according to the ASTM D3302-74 standard method. Volatile matter is determined by heating the dried sample to 950°C . The sample is covered during this process in order to exclude oxygen and prevent the sample from being ashed. Following the volatile matter determination, the sample is uncovered and combusted, and the ash is determined by ASTM D3174-73. Fixed carbon is determined by difference following the previously described methods.

Ultimate analysis determines carbon, hydrogen, nitrogen, sulfur, oxygen, and ash content in a sample. Carbon, hydrogen, and nitrogen (CHN) content are determined using a Leco® CHN-600 analyzer. Carbon and hydrogen are determined by infrared cells, and elemental nitrogen is measured by a thermal conductivity cell. This method gives the total percentages of CHN in the organic sample as analyzed and includes the carbon in carbonates and the hydrogen in the moisture and in the water of hydration of silicates. Sulfur is determined using a Leco® SC-132 sulfur analyzer. It operates on the principle of determining sulfur by combusting the sample in oxygen, forming sulfur dioxide, which is determined by an infrared cell detector. The level of chlorine in the CWF is determined by ASTM method D2361. Ash is determined by the ASTM Method described above under proximate analysis. Oxygen is determined by difference in order to achieve a balance for the ultimate analysis. Forms of sulfur are determined according to ASTM-D2492-80.

Gross caloric value is measured by ASTM Method D2015 using a Paar adiabatic calorimeter and master controller.

The particle-size distribution of the fuel is determined by wet-sieve analysis according to ASTM Method D410.

Inorganic and Mineral Component Analysis

Slurry Fuel Ash Analysis

Concentrations of major mineral oxides (Al, Si, Na, Mg, Ca, P, K, Fe, Ti, and S) in the fuel ash are determined by x-ray fluorescence. The RDF slurry ash samples are prepared using the ASTM D3174 procedure. Analysis is performed using a Kevex x-ray spectrometer. The elemental percentage is expressed as a weight percent of the total equivalent oxides.

Fusion temperatures of the RDF slurry ash are determined under oxidizing and reducing conditions in accordance with ASTM Method D1857 using a Preier/Mineco electric tube furnace.

Ash Deposit Characterization

Chemical compositions of probe deposit and fly ash samples are determined by means of x-ray fluorescence (XRF). X-ray diffraction (XRD), which allows the identification of major crystalline forms, is used to support more quantitative SEM techniques in evaluating ash deposition phenomena. Identification, selection, and analysis of critical regions of the deposits are accomplished using SEM techniques.

A scanning electron microscopy point-count technique (SEMPC) is used to quantify the phases present in the deposit. The SEM microprobe system is a powerful tool that can be used to examine the microscopic features of deposits and fly ash and provide chemical analysis of points as small as 1 μm in size. The system is automated and computer-controlled, which increases data manipulation and data storage capabilities. The SEMPC technique was developed at the EERC to systematically and quantitatively determine the distribution of phases in ash deposits and fly ash. The SEMPC technique provides information on the degree of interaction and melting of the deposited ash components and the abundance of crystalline, amorphous, and unreacted ash particles. The data obtained from the technique are critical in identifying the components in ash deposits that are responsible for deposit growth and strength development. In addition, viscosity distribution profiles can be calculated for the amorphous or liquid phases using SEMPC data. This information provides insight into the propensity of a particular ash to form a strong deposit.

The procedure for SEMPC analysis involves preparing a cross section of the sample by mounting the ash deposit sections in epoxy. The epoxy block is sectioned to expose the ash deposit material. The exposed section is then polished to provide a very smooth surface for examination with the SEMPC technique.

The polished sample is placed in the SEM, and a compositional analysis is obtained from a series of 250 grid points across approximately 35 mm² of the sample. The Tracor Northern 5500 computer system differentiates between epoxy and deposit material and stores the chemical information. The stored chemical information is transferred to a microcomputer that identifies and quantifies the amorphous and crystalline components in the deposit. The crystalline components are readily identified as minerals based on chemical composition and molar ratios. The amorphous component is classified as either derived phases or unclassified material. Derived phases resemble their coal mineral precursor. Unclassified material has no crystalline structure and shows no molar ratios that conform to mineral formulas stored in the SEMPC program.

Fly Ash Analysis

The elemental oxide concentration of each sample is determined by XRF. As mentioned above, this analysis includes the major mineral oxides normally associated with fossil fuels.

The particle-size distribution of the fly ash can be determined by a number of methods. One method uses a Malvern® 2600c laser diffraction particle-size analyzer capable of measuring particle sizes from 0.5 to 564 microns (see Figure A-8). The Malvern® uses a He-Ne low-power visible wavelength laser that is first expanded and spatially filtered to provide a clean parallel beam. As particles pass through the beam, they scatter or diffract the light at different angles, depending upon their diameter: large particles scatter at small angles and vice versa. The scattered light is collected by a lens and brought to focus on a multielement solid-state detector that simultaneously measures the light at a number

of angles. During analysis, the sample particles move rapidly through the laser beam. The results indicate the volume percentage distribution, as well as report the average particle size.

Trace element analysis of the flue gas is conducted by extractive sampling of the gas stream at the inlet and exit of a particulate control device using the tentative EPA Method 29 sampling train and subsequent analysis.

Tentative EPA Method 29 (currently being established for EPA by the EERC) multimetals train is the primary sampling procedure for determining trace element concentrations in the flue gas. The impinger train consists of a series of glass impingers filled with trapping solutions ending with a final moisture trap, vacuum pump, and dry gas meter. The filter assembly and impinger train are prepared by cleaning with brushes and hot, soapy tap water. Next, the train is rinsed three times in tap water and then three times in deionized (DI) water. All glassware, including quartz and teflon parts, are soaked a minimum of 4 hours in a 10% nitric acid (HNO_3) bath. After 4 hours, the glassware and Teflon parts are removed from the acid bath and are again rinsed in DI water three times. The sampling train is dried in as contaminant-free an environment as possible. The DI water is checked periodically for trace metal contamination.

A total of six impingers are included in the train. Impingers 1 and 2 are filled with 200 mL of 10% hydrogen peroxide (H_2O_2) in a 5% HNO_3 solution. All trace metals, with the exception of elemental Hg, will be captured in these impingers. Impinger 3 is empty to prevent any mixing of the two types of trapping solutions. Impingers 4 and 5 are filled with a 4 wt% potassium permanganate (KMnO_4) solution in 10% sulfuric acid solution. Impinger 6 contains silica gel to ensure that the flue gas is thoroughly dried before leaving the impinger train. The actual sampling procedure is similar to EPA Method 5 in that particulate matter is collected on a quartz fiber filter; however, in Method 29, vapor-phase metals that penetrate the filter are collected in the impinger solutions downstream from the filter. Analysis of trace metals in the collected samples will be performed as indicated in Table A-1. Since mercury can exist as either elemental mercury or as an oxide, special care is required in sample preparation and analysis to distinguish and quantify these forms.

To prepare a coal sample for mercury analyses, approximately 0.5 g of coal, 2 mL of H_2SO_4 , and 2 mL of HNO_3 are added to a microwave digestion vessel. The vessel is sealed, placed in the microwave, and heated to attain a pressure of 40 psi for 140 minutes. After the vessel is cooled to room temperature in an ice bath, an additional 2 mL of HNO_3 is added. The vessel is then heated to attain a pressure of 80 psi for 70 minutes. The sample is again cooled, followed by reheating to 80 psi for 70 minutes. An additional three cycles of heating to a pressure of 100 psi for 40 minutes and subsequent cooling are performed. The final step in the procedure is heating to attain a pressure of 120 psi for 40 minutes. After the sample has been cooled, it is quantitatively transferred to a 50-mL volumetric flask, brought to volume, and filtered.

Similarly to the coal samples, ash samples are also digested using a microwave digestion system. Approximately 0.5 g of ash, 3 mL of HNO_3 , 3 mL of hydrochloric acid (HCl), and 3 mL of hydrofluoric acid (HF) are added to a microwave digestion vessel. The vessel is placed in the microwave, heated to a pressure of 100 psi for 40 minutes, and then cooled to room temperature in an ice bath. Four percent boric acid (H_3BO_3) (15 mL) is then added to the vessel, which is heated to attain a pressure of 50 psi for 20 minutes cooled and reheated. The sample is quantitatively transferred to a 50-mL volumetric flask, brought to volume, and filtered.

To analyze the Method 29 H_2O_2 solutions, 5 mL of sample is transferred to a 50-mL test tube. A sufficiently sized tube is necessary to prevent the sample from overflowing during the effervescent neutralization step. The samples are placed in an ice bath and allowed to cool for 15 minutes. To decompose the H_2O_2 , 0.25 mL of KMnO_4 solution is added. After cooling for 15 minutes, the procedure is repeated four times. As a final step, an additional 2 mL of KMnO_4 solution is added in 0.5-mL additions to provide an excess of reagent. After each addition, the samples are cooled and agitated. As a final step, 2 mL of hydroxylamine sulfate solution is then added in 1-mL additions, (cooled and agitated after each addition) to reduce the KMnO_4 .

For the KMnO_4 solutions, solid hydroxylamine sulfate is added to the sample to reduce the KMnO_4 until no color persists and the KMnO_4 residue is dissolved. The sample, which is usually in a 250- or a 500-mL volumetric flask, is brought to volume.

Mercury analyses at the EERC are done using a commercial cold-vapor atomic adsorption (CVAA) analyzer (Leeman PS200). In this instrument, a prepared sample enters the system and is mixed with a reducing agent (10% stannous chloride) to form elemental mercury vapor. The mixture flows into a liquid-gas separator where nitrogen is introduced to carry the mercury vapor through a drying tube for water vapor removal. The dry vapor then enters one path of a double optical cell that has been optimized for fast response time and sensitivity. A mercury source, powered by a constant current power supply, delivers a stable source of emissions at 254 nm. Absorbance by the mercury cold vapor is measured using a solid-state detector with a wide dynamic range. The resulting signal is referenced to the simultaneous absorbance of the pure carrier gas flowing through the second optical path under identical conditions. These signals are then sent to a computer system where the mercury concentration of the solution is calculated and reported. Although 0.1 ppb is reported as the detection limit of the instrument, EERC personnel have determined that the instrument has a credible detection limit below 0.1 ppb.

To ensure the precision and accuracy of the instrument, it is calibrated on a regular basis using quality control standards. The calibration check standards are analyzed every five samples to check for instrument drift, and every ten samples a reslope is performed. All samples are run in duplicate, and one in every ten samples is spiked to verify analyte recovery.

TABLE A-1

Trace Element Analysis of Raw and Chemically Cleaned Coal

Parameter	Instrument
Mercury	CVAAS ^a
Selenium	HGAAS ^b
Antimony, Arsenic, Cadmium, Lead	GFAAS ^c
Chromium, Cobalt, Manganese, Nickel, Lead and Beryllium	ICAP-AES ^d
Chloride	IC ^e

^a Cold-vapor atomic absorption spectroscopy.

^b Hydride generation atomic absorption spectroscopy.

^c Graphite furnace atomic absorption spectroscopy.

^d Inductively coupled argon plasma-atomic emission spectroscopy.

^e Ion chromatography.

Analytical Equipment for Trace Element Concentration

A description of the analytical equipment used to determine trace element concentrations follows:

- Leeman Labs PS1000 sequential ICAP atomic emission spectrophotometer with integrated computer, autosampler, and Hildebrand grid nebulizer for quantitative multielement analysis. Purged optics allows for increased analytical capabilities by expanding the wavelength coverage to a range of 178–800 nm.
- Perkin Elmer 5100 atomic absorption spectrophotometer with heated graphite furnace atomization and Zeeman background correction. This allows for quantitative trace element analysis at the parts-per-billion level for highly complex sample matrices such as coal and coal fly ash mixed acid digestions.
- Dionex 2120i dual-channel ion chromatograph with auto sampler and conductivity, UV/Vis, and electrochemical detectors for the quantitative analyses of anions and cations at the parts-per-billion level.
- Leeman Labs PS200 automated mercury analyzer based on CVAA for the determination of mercury with parts-per-trillion sensitivity.
- Varian AA1475 atomic absorption spectrophotometer equipped with a VGA-76 vapor generation accessory and electrically heated quartz cell for the determination of hydride-forming elements such as selenium, arsenic, and antimony.

Leaching Potential of HAPS (SGLP, TCLP, LTL)

To determine the leaching potential of the HAPs captured in the fly ash, a thorough materials chemical characterization will be initiated with a qualitative screening technique. Qualitative identification of elements present is particularly helpful in determining which elements need to be evaluated for leachability. This screening step provides information on elemental constituents present in individual materials. Identifying the chemical constituents in this manner has several advantages over the use of a predetermined list of analytes. These advantages include avoiding analyses of elements not present in large enough amounts to be of concern and avoiding the omission of analyzing other elements whose presence is unexpected. The qualitative screening is followed by quantitative analysis using more sensitive techniques, such as flame and graphite furnace atomic absorption spectroscopy, inductively coupled argon plasma emission spectroscopy, ion chromatography, and other instrumental and classical analytical techniques. These techniques, coupled with appropriate dissolution techniques, will be used to determine the concentrations of the chemical constituents in the bulk materials.

The chemical characterization scheme for utilization–disposal also includes an evaluation of the leaching characteristics of the materials. Leaching characteristics are very important for environmental and health reasons, both in disposal and utilization scenarios. The leaching characterization protocol developed at the EERC includes the use of both short- and long-term leaching procedures and a

mineralogical evaluation of the leached material following long-term leaching. The leaching procedures used can be summarized as follows:

- The toxicity characteristic leaching procedure (TCLP)
 - The EPA regulatory test for hazardousness of materials to be disposed in a sanitary landfill
 - Short-term (< 48 hours) leaching with a predefined leaching solution
- The synthetic groundwater leaching procedure (SGLP)
 - Developed at the EERC
 - Short-term leaching with leaching solution determined by the type of water expected to contact the used or disposed material
- The long-term leaching procedure (LTL)
 - Developed at the EERC
 - Long-term leaching procedure (> 48 hours) with leaching solution identified for the SGLP with leachate analysis at time intervals to evaluate changes in leachate quality

There are two important reasons that the TCLP alone may be inappropriate and provide incomplete or inadequate leachate characterization information. First, the TCLP utilizes an acidic solution containing acetic acid. The use of acetic acid as a leaching solution is, by EPA definition, designed to simulate the leaching a waste will undergo in a sanitary landfill. Under utilization and many disposal scenarios, the water to contact the by-product is extremely unlikely to contain acetic acid. The actual pH and chemistry of the leaching fluid likely to contact the by-product must be considered in order to perform a laboratory evaluation of leaching potential that will provide information pertinent to commercial applications. If it is the case that rainwater or alkaline water will be doing the actual field leaching, the solution used in the lab must exhibit a similar chemistry. Rainwater can often be simulated by a neutral solution (distilled water). The SGLP will be performed in addition to the TCLP to provide a complete and realistic evaluation of the short-term leaching characteristics of the materials selected for the study. Results of these two short-term leaching procedures will be compared and evaluated along with results of long-term leaching procedures. The use of a long-term leaching procedure addresses the second potential shortcoming of leaching evaluation by TCLP only. Combustion by-products, including fluid-bed combustion (FBC) by-products, may change mineralogical composition owing to hydration reactions upon contact with water and interaction between different minerals and constituents of the by-product or other added material in the product. These chemical reactions can have a significant impact on the leachate generated and must be considered to fairly evaluate these materials for use or disposal. Many of the reactions are slow and can take up to 30 days to exert an effect, as demonstrated by previous research projects at the EERC. The effect can be more than an order of magnitude with respect to solution concentration of several potentially hazardous elements. LTL procedures (30 and 60 days) will be used to evaluate long-term phase changes and to establish the direction of concentrations of trace elements as equilibrium is approached, providing more realistic information regarding the potential mobility of elements in a material under disposal conditions. X-ray diffraction will be performed on the original material and the leached material from long-term leaching to aid the evaluation of trace element mobility in this material.

APPENDIX C

**DATA SHEETS, OPERATORS'S LOG,
AND CIRCULAR CHARTS**

From Page No. _____

~~0300~~

STARTED UNIT ON GAS

0415

LOST 25 H.P. COMPRESSOR - TURNED ON 75 HP.

0705

FLOW THROUGH ESP - BRING UP TEMP IN ESP

GROSS WT. BARREL/W.O. LID 402 LBS

810

Zero ~~at 2000~~ ~~ESP~~ ~~temp~~ (CO not working)Changed Rec Span Changed ~~5000~~ range O₂ level block
messy sand + installedHave SO₂ Blended with N₂ 1:1 ratio to deliver
as per range to 5000

1030

analysis on sample

1240

Installed Horizontal Probe

when Tried Stem - couldn't get flow
Cleaned out Strainer on RegulatorFound ? RDF in slurry line (could be reason
for Pluggage - couldn't get flow earlier
Had added some water to slurry - 57% solids
530-540 CP

1246

started Slurry - (still plugged through rotolys)
Bypassed

1249

started distillation

1253

went through ESP - ~~OK~~also got another RDF chunk out of rotolys - rungs now
also have been seeing RDF pellets in slurry - catch in screen
there's ~ 4% leak between SP1 + 5 - ~~OK in sample~~
~~Sample~~

To Page No. _____

Witnessed & Understood by me, _____

Date _____

Invented by _____

Date _____

Recorded by _____

From Page No.

1257 near @ 740 SESH on stinging air

1300 purged SC 1+3

1337 Have been Trying to find leak on Sample B
 - have checked out to pump - changed to pump
 up still shows leak ~ 4%
 - there is higher F.G. Flow than theoretical
 not sure if leak is in system

1340 Increased Secondary air to bring O₂ up

1342 Port open for downloading

H310 North Probe Thermocouple is bad? reading
 859°F

1418 Runged Sample System

There's ~ 1/2 thick deposit bridged between
 North wall + North Probe @ this time on upper 3/4
 of Tube other Tube Tracts look clear

1535 Runged SC

1545 There's ~ 1" of ash on north probe bottom wall
 there's ~ 1/2" of ash TOP + bottom leading edge of middle
 probe - can't see any on South Probe

Temps for Probe bank are not logged correctly

1550 O₂ & CO₂ on zero gas OKO₂ & CO₂ on span gas OK

Put a sample but ± 1 read same (found a loose flange)

Put on Sample B Now 1% O₂ difference

late note
 ~ 1530

stinging air on 760 SC+H

To Page No.

Witnessed & Understood by me,

Date

Invented by

Don

Date

2-11-97

from Page No. _____

1605

using SP #3 on Sample B now (Had been using Rep
2 earlier while checking)

1615

Purged SC
adjusted ESP output to 4.0

1622

SO₂ A on zero gas 60 on analyzer 34 check
SO₂ B on zero gas 135 on analyzer 150 check

1623

check with sampling

1626

SO₂ A on span gas 2945 analyzer 2955 check
SO₂ B on span gas 2897 " 2897 "

adjusting flow to take cyclone sample

1632

SO₂ back on line

1639

O₂ CO₂ A on zero OK
O₂ CO₂ A span O₂ 4.6 CO₂ 93

1645

O₂ CO₂ A back on sample

1650

still adjusting flow for cyclone sample

1651

there is ~ 3" leading deposit on north
Probe tapping down to nothing on both

there is ~ 2 1/4" leading deposit on mid probe
+ ~ 1 1/2" on both

Can't see any deposit on Probe south

1700

dumping ESP 14 kpsi.

Can't get cyclone sample system pressure
limitations

To Page No. _____

Witnessed & Understood by me, _____

Date _____

Invented by _____

Date _____

Recorded by _____

3-11-97

From Page No.---

1730

Took Sample of Slurry - Temp & and O_2 ↑

1740

always air @ 740 changed on captr.

1750

Slurry is falling Side of Cone

large building on N. Peak + top + bottom of middle
do not see any on South - ash appears to
have started from Refractory Surfaces

1800

Shut off Slurry

Totalizer Reading = 473

Turned H₂O on to Slurry pulled Probes/shut far off
Pulled Horizontal Probe

removed Gun Shut off Sample System HT lines
shut off Steam

Turned off NOP pumps + ozone

Shut off 10 fan + PH Breakers

Note on zero SO_2 A is reading 300-800 ppm
fluctuating

Shut ESP off, Shut water off of Steam Condensate
and air Heaters

1820

 SO_2 A. settles down now

Light & no dusting on P-bes

Horizontal fine finger of reddish brown soft ash
growing darker & heavier slightly sintered toward Refractory
on Top side

To Page No.---

om Page No. _____

FEED SLURRY BBL'S

BBL#2 $378^{\#} + 8^{\#} \text{ water} = 386^{\#}$ Slurry added

1 BBL#2 weighback $\frac{- 5^{\#}}{381^{\#}}$ Slurry used

BBL#1 $384^{\#} + 8^{\#} \text{ water} = 392^{\#}$ Slurry added

BBL#1 weighback $\frac{- 4^{\#}}{388^{\#}}$ Slurry used

$$\begin{array}{r} 381 \\ 388 \\ \hline 769 \end{array}$$
 total Slurry added

$$\begin{array}{r} 769 \\ - 120 \\ \hline 649 \end{array}$$
 Slurry weighback
 Slurry used.

Slurry FEED RATES FROM AFTER TEST CALIBRATIONS.

2 calibration tests ~~58~~ WERE DONE

~~MINIMUM~~ #1 Actual Rate $115.8^{\#}/\text{HR}$ Micromotion $85^{\#}-84^{\#}/\text{HR}$
 #2 Actual Rate $117.0^{\#}/\text{HR}$ $85^{\#}-86^{\#}/\text{HR}$

To Page No. _____

Witnessed & Understood by me, _____

Date _____

Invented by _____

Date _____

Recorded by _____

From Page No. _____

77.0 gr Dark ash on Horizontal Probe (soft sintered)
and ~1/8" layer of lighter reddish brown
XRF, YRD, CHN

28.0 gr ash Probe Bank (all three)
light layer reddish brown - there is a
rough enamel layer of stuck to probe
XRF, YRD, CHN

Probe Bank dec ash = 2503.6 g Sample to 1000 g probe bank

Comb + bottom ash = 1828.2 g
ESP #1 ash = 2106.2 g - XRF, YRD, CHN, NH₄VERA, Res.

ESP Final ash = 1008.0 g EOR (CHN)

Horizontal Hx ash = 81.8 g

Sampling cyclone = 59.6 g CHN

Flue gas piping = 160.0 g

air cooled Hx = 80.3 g

Bypass cyclone + barrel = 279.1 g

PO Tube in Shell 70% ash

~~XRF, YRD, CHN, NH₄VERA, Res.~~
~~X on final sample (large unit)~~
~~2/2/77~~

To Page No. _____

Witnessed & Understood by me, _____

Date _____

Invented by _____

Date _____

SYSTEM PRESSURES

AFU/CWS/DSU Data Sheet 1A

Run No. AF-CTS-719 Date 3-11-97 Acct. No. 4874

	Time	*	1351	1452	1541				
156 Sec. Air Static (WC)	C		20.0	19.5	20.0				
157 Sec. Air dP (WC)	C		22.	22.	22				
154 Primary Air Static (WC)	C		3.0	3.0	3.0				
155 Primary Air dP (WC)	C		3.0	3.0	3.0				
158 Tert. 1 Static (WC)	C		NA						
159 Tert. 1 dP (WC)	C		NA						
160 Tert. 2 Static (WC)	C		NA						
161 Tert. 2 dP (WC)	C		NA						
150 Total Air Static (WC)	M		61	61	61				
151 Total Air dP (WC)	M		2.7	2.7	2.7				
250 Combustor Static (WC)	C		-0.8	-0.5	-0.3				
251 PB 1 Exit Static (WC)	M		-1.0	-1.1	-1.0				
252 ^{EXIT 1ST HX} Post Dropout Static (WC)	M		-1.0	-1.0	-1.0				
253 ^{EXIT 4TH HX} PB 2 Inlet Static (WC)	M			-1.2	-1.1				
254 ^{EXIT 1ST AIR COOL CO} PB 2 Exit Static (WC)	M		-3.7	-3.8	-3.7				
255 ^{EXIT SEC AIR HX} HX 2 Exit Static (WC)	M		-8.2	-8.2	-8.2				
256 HX 5 Exit Static (WC)	M		-9.1	-9.1	-9.1				
257 HX 8 Exit Static (WC)	M		-11.7	-11.5	-11.5				
258 Bypass Cyclone Inlet Static (WC)	M		-10.5	-11.0	-11.0				
259 Bypass Cyclone dP (WC)	M		.6	.6	.6				
Operators Initials			BR	BR	BR				

* C = Computer reading; M = Manual reading; K = Kaye reading

SYSTEM PRESSURES cont.

AFU/CWS/DSU Data Sheet 1B

 No. AP-CTS-719 Date 3-11-97 Acct. No. 4874

	Time		1400	1454	1544					
260 Annubar Static (WC)	C		-18.0	-18.0	-18.0					
261 Annubar dP (WC)	C		2.6	2.7	2.7					
262 Stack Static (WC)	M		4.5	4.5	4.5					
555 Sampling Cyclone dP (WC)	M		1.4	1.0	1.3					
554 Sampling Cyclone Inlet Static (WC)	M		-11.0	-11.0	-11.0					
553 ESP/BH Orifice dP (WC)	M		4.4	4.2	4.3					
552 ESP/BH Orifice Static (WC)	C		-17.0	-17.2	-17.0					
551 ESP/BH Outlet Static (WC)	C		11.0	-11.0	-11.0					
550 ESP/BH Inlet Static (WC)	M		8.5	8.5	8.5					
350 PB1 Steam Trap Exit Static (psi)	M									
351 PB1 Middle Probe Exit Steam Static (psi)	M		20							
450 PB2 Steam Trap Exit Static (psi) South	M		20							
451 PB2 North Probe Exit Steam Static (psi)	M		20							
152 Natural Gas Static (psi)	M		NA							
153 Natural Gas dP (psi)	M		NA							
162 Coal Feed Venturi Static (WC)	M		NA							
F171 Coal Feed Rate	C									
F172 Coal Feeder Screw Speed	C									
Operators Initials			BR	BR	BR					

* C = Computer reading; M = Manual reading; K = Kaye reading

Page 1 of

CTF Data Sheet 2A

[illegible]

Names are wrong

FLUE GAS ANALYSIS

CTF/CWS Data Sheet 4

Run No. AF-CTS-719 Date 3-11-97 Acct. No.

4874

Time		1348	1427	1457	1542				
O ₂ - A %	Port 1	3.8	4.1	3.9	3.8				
	Port 2		-	-					
	Port 3		-	-					
O ₂ - B %	Port 1		-	-					
	Port 2			-					
	Port 3	7.5	7.5	7.7	7.2				
CO ₂ - A %	Port 1	88.7	87.6	87.3	89.3				
	Port 2								
	Port 3								
CO ₂ - B %	Port 1								
	Port 2								
	Port 3	73.9	74.1	73.8	74.5				
SO ₂ - A %	Port 1	3200	3213	3122	3155				
	Port 2		-	-					
	Port 3		-	-					
SO ₂ - B %	Port 1		-	-					
	Port 2		-	-					
	Port 3	3091	2835	2792	3010				
CO %	Port 1		-	-					
	Port 2	NA	-	-					
	Port 3		-	-					
NO _x %	Port 1	777	745	652	696				
	Port 2		-	-					
	Port 3		-	-					
Operators Initials		BL	BL	BL	BL				

use a dash (-) for readings not required

Page 1 of

SO₂ readings = 1/2 actual

COAL SLURRY
CWS Data Sheet 10

Run No. AF-CTS-719 Date 3-11-97 Acct. No. 4874

Slurry Trade Name _____ Manufacturer _____

% Solids _____ Slurry Nozzle _____ Throat _____

Slurry Start Time _____ Slurry Stop Time _____

Total Slurry Burned _____

Time	1405	1451	1540	1725	1800		
Pump Setting (Dial)	4.2	4.3	4.4	4.2	4.2		
Pump Discharge Press. (psi)	100	100	100	100	100		
Slurry Feed Press., (psi)	100	100	100	100	100		
Slurry Feed Rate (lbs/hr)	105	93	88	86	86		
Total Slurry Feed (lbs)	127	198	269	424	470		
Coal Slurry Temperature (ambient) (°F)	72°	72°		72°	72		
Inlet Air Press., (regulator) (psi)	35	35	40	41	41		
Atomizing Air Press., (psi)	31	33	39	39	40		
Atomizing Air Flow (%)	700	740	760	730	740		
Atomizing Air Temp., (°F)							
Air register Setting (Dial)							
Operators Initial	BA	BR	BA	A	A

Run No. AF-675-712 Acct. No. 4874
Date 3-11-92 Chart No. 1 Op.
Ink: CO2A Pen Color RED Scale 0-20%
02A GREEN 0-10%

THE PARLOW CORPORATION
NEW YORK, N.Y. 10017
FAX 212 691 1111
TEL 212 691 1111

Run No.	AF-175-712		Acct. No.	4224
Date	3-11-97	Chart No.	1	Op.
Inst.	Co2B	Pen Color	RED	Scale
	O2B	GREEN	0-20%	0-10%

Run No. AF-CT5-712 Acct. No. 4874
Date 3-11-97 Chart No. 1 Op. 1
Inst. CO Pen Color RED Scale 0-1000PM
SO2A GREEN 0-10000PM

Form No. AF 475-7/8	Acct. No. 4874
Date 3/15/97	Chart No. 1
Probe Color 0-2000	Scale 100
North Probe Metal Part	Ref. 181
North Probe Probe	Green Probe

Run No. AF-ETS-718 Acct. No. 4874
 Date 3-11-57 Chart No. 1 Op.
 Instr. Pen Color 0-2000°F
Middle Probe Metal Front Red
Nalwa Jacket Green (B2)

Run No. AE-CTS-28 Acc. No. 4874
Date 3-11-97 Chart No. 1 Op. 80
Inst. 0-2000°F Pen Color: Scale
Soil Probe Metal Front Red PB1
NAS (Soil Probe Gregg PB2)