THE UNIVERSITY OF TENNESSEE
SPACE INSTITUTE

DOE/PC/95231-2
DIST. CATEGORY UC-112
UTSI 96-01/02-96



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## TOPICAL REPORT

Report Prepared by:

Marvin E. Sanders

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The University of Tennessee Space Institute
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For

THE UNITED STATES DEPARTMENT OF ENERGY
Under Contract No. DE-AC22-95PC95231



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COAL FIRED FLOW FACILITY



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## ABSTRACT

The original eastern coal processing system at the Department of Energy's Coal Fired Flow Facility (CFFF), located at the University of Tennessee Space Institute in Tullahoma, Tennessee, was modified to pulverize and dry Montana Rosebud, a western coal. Significant modifications to the CFFF coal processing system were required and the equipment selection criteria are reviewed. Coal processing system performance parameters are discussed. A summary of tests conducted and significant events are included.

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# HIGH MOISTURE WESTERN COAL PROCESSING SYSTEM

## 1.0 INTRODUCTION

The Department of Energy's (DOE) Coal Fired Flow Facility (CFFF), located at the University of Tennessee Space Institute (UTSI) in Tullahoma, Tennessee, has served as the government's magnetohydrodynamic (MHD) facility to conduct proof-of-concept (POC) testing for steam cycle components. The coal system at the CFFF processes raw coal and delivers a dry, finely pulverized coal in dense phase to an MHD combustor. The coal is burned in the combustor to provide the simulated MHD flue gas to an integrated bottoming cycle heat recovery/seed recovery (HRSR) subsystem. The original coal processing system was designed by Babcock and Wilcox Company (B&W) for use with low moisture Illinois #6, an eastern type coal. Over 2000 hours of POC testing using Illinois #6 was completed in May, 1991. However, DOE required the use of Montana Rosebud western coal as a fuel source for the latest series of CFFF POC tests. Switching from Illinois #6 to Montana Rosebud coal necessitated modification of the coal pulverizing and drying systems due to higher moisture content and volatility of the coal. A closed-loop inerted gas system, with a condenser to control moisture build-up, was selected to process the Rosebud coal. Nitrogen ($N_2$) is used to limit the oxygen ($O_2$) content of the recycled gas to below 5%. The major system modifications and data relating to the operation and performance of the system while burning Montana Rosebud are described below. A chronological summary of western coal tests conducted at the CFFF, duration of each test, and significant events appears in Appendix A.

## 2.0 BACKGROUND

The CFFF is an open cycle magnetohydrodynamic (MHD) test facility dedicated to the evaluation of heat transfer characteristics and pollution control technology required for the design of a full-scale MHD system. The CFFF has completed the operational goal of 2000 proof-of-concept hours of testing using Illinois #6 coal and over 1000 hours of POC testing using Montana Rosebud coal.

With the Illinois #6 coal, ambient air was pressurized by the system blower and then passed through an indirect, oil-fired heat exchanger. Heated air was mixed with coal in the pulverizer where the hot air evaporated moisture from the coal. Air also functioned as the carrier gas to pneumatically convey the pulverized coal to the baghouse. The baghouse separated the coal and moist air. The moist air was vented to the atmosphere and the coal was collected in the baghouse and sent through a rotary valve into storage tanks. In the tanks, coal was inerted with nitrogen to reduce the possibility of spontaneous combustion. Pulverized coal was transported to the combustor from the storage tanks by dense phase pneumatic conveying. This system was successfully employed to process coal for 2358 hours of eastern coal testing. At no time were test operations interrupted due to failure to pulverize, dry, or deliver coal to the storage tanks.

Prior to the start of testing with western coal in July, 1991, the coal processing system was modified due to the differences between Montana Rosebud and Illinois #6 coal (see Table 1).

Table 1. Comparison of Coal Analysis (Wt. %)

| | Illinois #6 | Montana Rosebud |
|---|---|---|
| Moisture | 8 - 10 | 23 - 30 |
| (on dry basis) | | |
| Ash | 10.78 | 12.78 |
| Carbon | 66.06 | 66.54 |
| Hydrogen | 4.50 | 4.61 |
| Nitrogen | 1.29 | 0.95 |
| Oxygen (by difference) | 11.99 | 16.37 |
| Sulfur | 3.41 | 0.70 |

Several options for drying and pulverizing Montana Rosebud coal were evaluated for implementation at the CFFF. Three options were considered: 1) predrying, 2) once-through combustion gas drying, and 3) closed-loop inerted gas drying.

The predrying of the coal was considered based on recommendations from Babcock & Wilcox Company,[1] (B & W), using a system supplied by the Wyssmont Company. This system centered around a countercurrent rotating tray dryer. The recirculated drying gas was generated by a direct-fired oil or gas burner. The moisture in the gas stream was controlled by exhausting a fraction of the recirculated gas. The coal exiting this process would be sufficiently dry so that further drying in the pulverizer would not be required. Ambient air would be used to transport the pulverized coal from the pulverizer to the baghouse and into the storage tanks. This approach was not chosen primarily due to high capital costs and conflicts with the CFFF testing schedules because of long equipment delivery lead time.

A second option was using combustion gas from an oil- or gas-fired heater to dry and transport coal from the pulverizer to the coal system baghouse. A combination of air and $N_2$ would be mixed with the combustion gas to control the moisture and oxygen content of the combustion gas. This system would have low capital requirements and would be relatively simple to operate; however, the cost of $N_2$ made this process less attractive than a closed-loop gas recirculated system. This system may be capable of drying coal with a higher dewpoint primary gas entering the pulverizer than was allowed in this study. Gas with a higher dewpoint entering the pulverizer would also require a higher pulverizer inlet and outlet temperature. By increasing the allowable dewpoint, the quantity of required $N_2$ can be reduced. This may be the most economical option in a commercial application, but the necessary data to confirm this were not available. This lack of data resulted in uncertainty of this system's capability to dry the coal with a high dew point gas and thus made this option less attractive.

The selected option was a closed-loop recirculated gas system (see Figure 1). The $O_2$ content of the gas stream could be controlled at the desired level by diluting and venting initially with $N_2$. By using a small quantity of $N_2$ makeup, the inerted condition of the gas stream could be maintained. An indirect-contact oil or natural gas-fired air heater preheats the gas prior to entering the pulverizer. The dried, pulverized coal is then pneumatically conveyed to the coal system baghouse where the moisture-laden gas is separated from the coal particles. Moisture is then removed from the gas in a direct-contact, water-cooled condenser (packed column) and recirculated to the system blower.

## 3.0 MAJOR COAL PROCESSING SYSTEM MODIFICATIONS

### 3.1 System Requirements

A description of the original coal system design and the modifications made during Illinois #6 testing is presented in Reference 1. Significant modifications to the CFFF's coal processing system were required to process Montana Rosebud coal. Because the system would be unique and the operating conditions were not certain at the time of equipment selection, the modified system was designed to be flexible and the processing capacity of the system was increased. Preliminary flow tests of Rosebud coal had indicated that the moisture content of coal exiting the feedtank should be below 8% to provide stable coal flow to the combustor, whereas Illinois #6 coal had been dried to less than 4% moisture. Furthermore, a typical utility grind coal was desired (i.e. 70% through 200 mesh).

The $O_2$ content of subbituminous coal (see Table 1) is considerably higher than in bituminous coal. Because of the higher $O_2$ content and the increased volatility of this coal, an inert atmosphere must be maintained from the initial processing until entering the combustor. Since the eastern coal system provided an inert atmosphere in the storage and feed tanks, modifications would be required only to maintain an inert atmosphere during pulverizing, pneumatic conveying, and during coal/gas separation in the system baghouse.

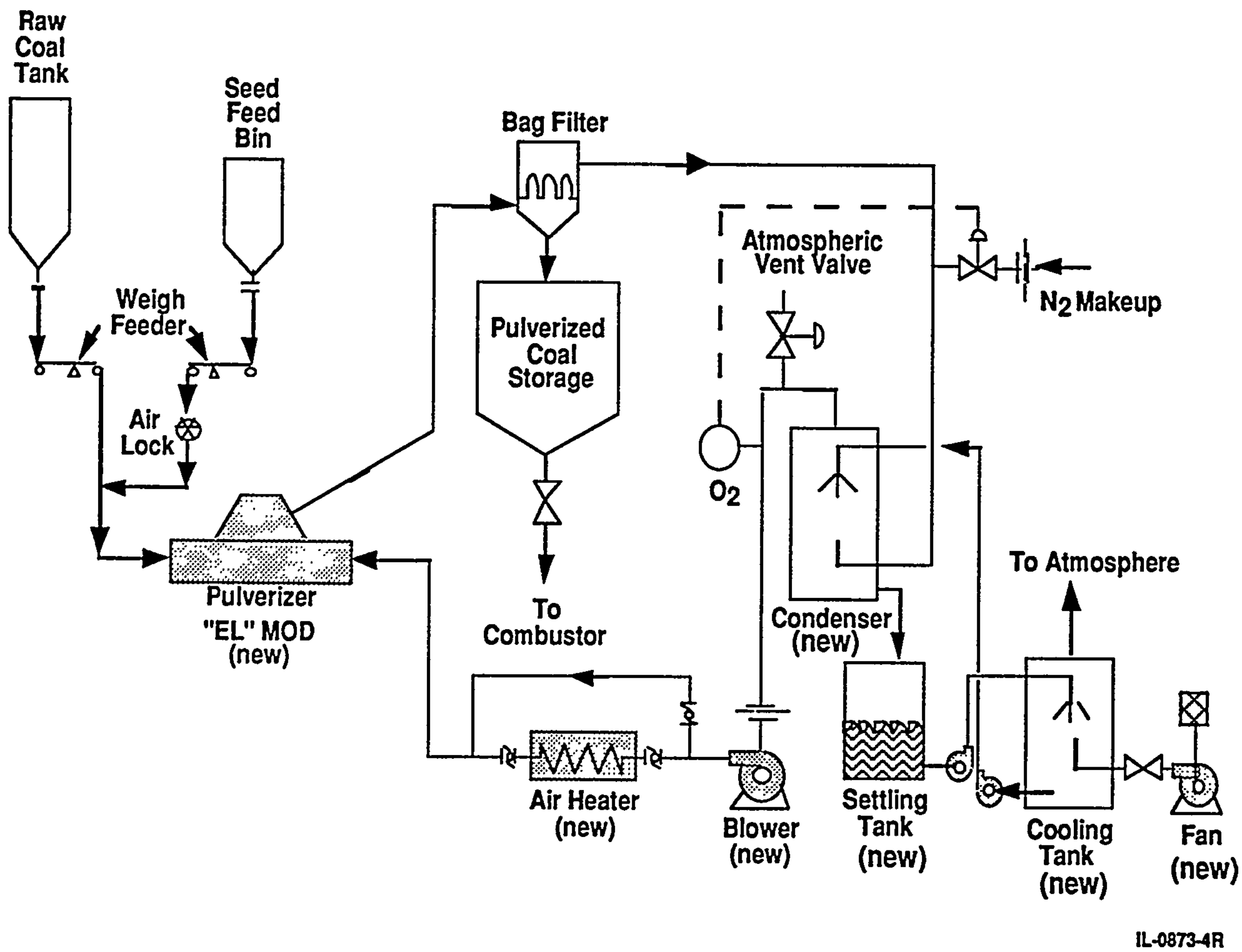



FIGURE 1. Schematic of Western Coal Processing System

Due to the high moisture content of Montana Rosebud coal compared with Illinois #6, more thermal energy is required to dry the coal to acceptable moisture levels. To provide the additional thermal energy, the primary gas temperature entering the pulverizer was increased from approximately 360°F (for Illinois #6) to 550°F (for Montana Rosebud).

Significant drying of the pulverized coal occurs from the pulverizer outlet to the baghouse. For this reason, the pulverizer outlet temperature was increased to 170°F from 130°F (see Figure 2).

Because of material limitations, the E-35 pulverizer could only operate to a maximum inlet temperature of 450°F. Increasing the temperature above this point results in rapid pulverizer deterioration and increased possibility of fire. Therefore, the existing E-35 pulverizer was upgraded to the EL-35 configuration which permits operation at an inlet temperature of as high as 700°F. In addition, the base capacity of the pulverizer is increased from 9,640 pounds per hour to 12,050 pounds per hour.

When air is used as the thermal energy transport medium and carrier gas, and the pulverizer is operated at an inlet temperature of 550°F or greater, the risk of a pulverizer fire increases significantly. To permit high temperature operation, at a much reduced fire risk, an inert gas, such as $N_2$, is required. An existing cryogenic $N_2$ system was already available on site as a supply source. The $O_2$ content of the recirculated gas stream is reduced to below 5% by adding $N_2$ to the system. To minimize $N_2$ usage, the modified coal processing system was designed to recirculate $N_2$ enriched gas. To maintain the drying capability of the inerted gas stream, the moisture in the inerted gas stream is reduced by the direct-contact water cooled condenser system (see Figure 1).

## 3.2 Equipment Selection

The new coal processing system consists of the following major components:

- Forced draft blower to compress the inerted gas.
- Heater to add thermal energy to the gas.
- E-35 coal pulverizer modified to EL-35 configuration
- Bag filter to separate coal and carrier gas
- Coal storage tanks.
- Condenser to remove moisture from the nitrogen

The forced-draft blower (Figure 3) is a higher capacity commercial unit that replaced the existing forced-draft blower. The heater has the capability of transferring sufficient thermal energy to the inerted gas to meet the drying requirements. Based on the requirement of higher pulverizer inlet temperatures and the possibility of operating

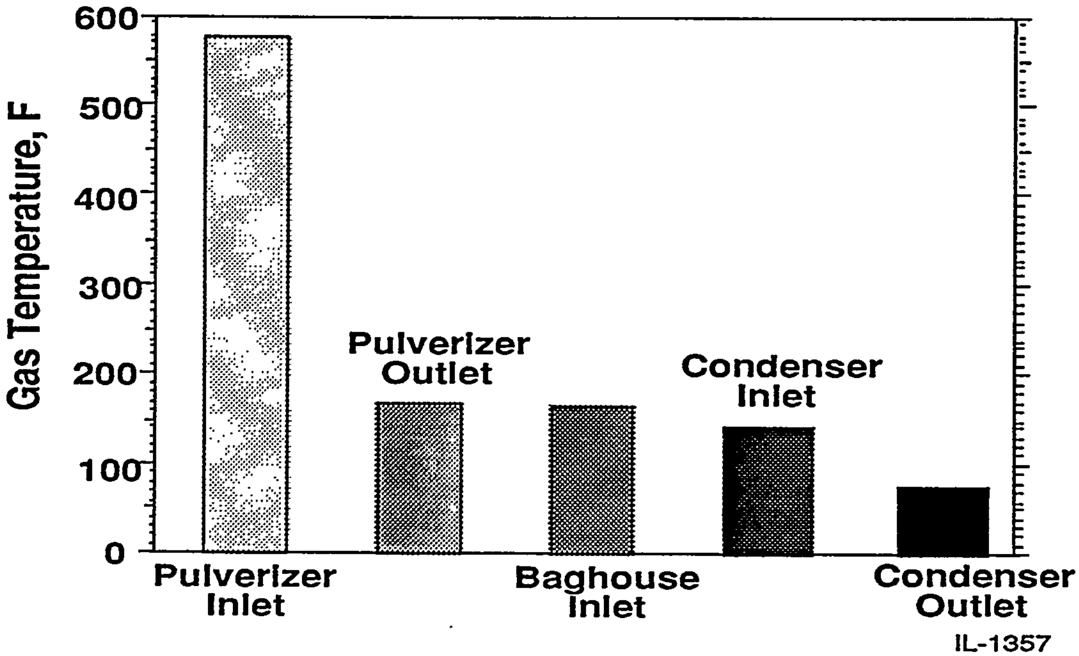



**FIGURE 2. Typical Temperature Profile of Western Coal Processing System**


FIGURE 3.  Lansom Forced-Draft Blower

at higher primary gas flow, a new, higher-capacity air heater was installed (Figure 4). The new air heater is capable of delivering gas at 30,000 lb/hr gas at 700°F. The desired pulverizer inlet gas temperature is achieved by controlling the mixing valves which regulate the fraction of primary gas flow bypassing the heat exchanger (see Figure 1). The mixing valves are used to control the pulverizer outlet temperature to a nominal value of 170°F.

The existing B&W E-35 pulverizer was upgraded to EL-35 configuration. B&W E-35 and EL-35 pulverizers (Figures 5 and 6) are termed "ball and race mills," where coal is crushed between two moving surfaces (i.e. balls and races). An upper stationary race and a lower rotating race hold the balls. To modify the pulverizer, the top and bottom rings, balls, and throat rings were replaced with higher capacity components that were fabricated of materials that could operate at temperatures as high as 700°F. In addition, an adjustable stationary classifier was installed in place of the E-35 rotating classifier. Worn bearings and seals were replaced, and necessary modifications to the pulverizer housing were also accomplished.

The coal system baghouse (PEDCON Cylindrical Dust Collector) was modified for use in the closed-loop system. The bags were replaced and the top was sealed to reduce the loss of $N_2$ to the atmosphere. In addition, a second explosion vent was installed in the unit. Coal and moisture-laden inerted gas are separated when the gas passes through the bags. The filtered gas then exits through the stack at the top of the baghouse where it is ducted to the condenser. Coal exits the baghouse through a rotary valve into the storage tanks.

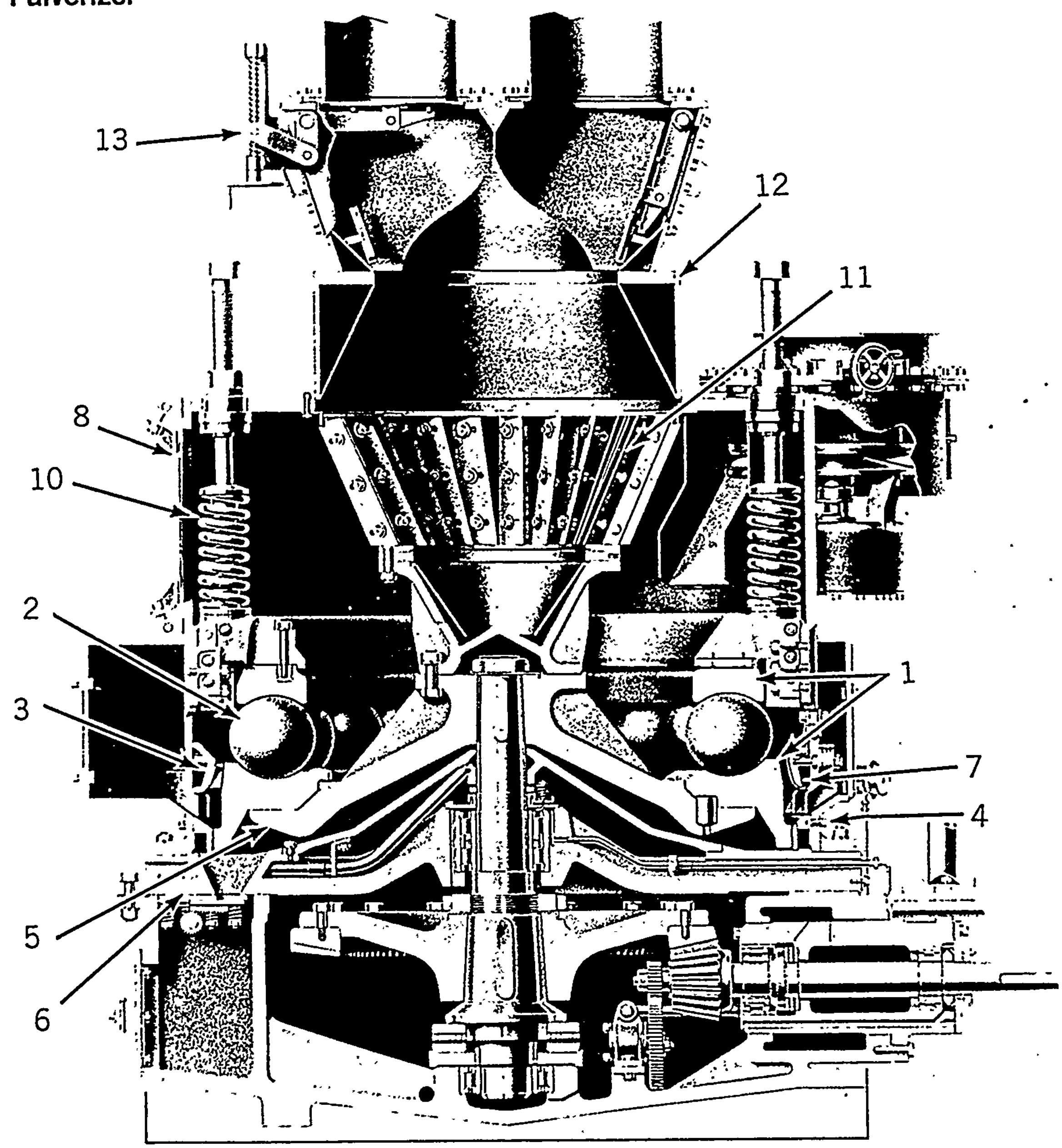
A direct-contact, packed tower condenser (Xerxes/Heil) was installed to dry the recycled gas (Figure 7). Cooling water is sprayed into the top of the condenser, countercurrent to the gas flow. By cooling the inerted gas stream exiting the condenser to below 90°F, the moisture in the recirculated gas stream can be regulated. Moisture that is discharged from the condenser is piped to a settling tank and then to a cooling tower. After the water is cooled, it is then recirculated to the spray condenser. The gas exiting the condenser is returned to the blower where it is pressurized, reheated, and ducted to the pulverizer. A photograph of the completed Western coal processing system is shown in Figure 8.

### 3.3 Safety Systems

One major area of concern was over or under pressurizing the equipment. The coal system baghouse requires near atmospheric pressure operation; therefore, the gas pressure in the system from the baghouse to the inlet to the system blower is maintained at near atmospheric. Since the baghouse required near atmospheric pressure, the condenser could be constructed of fiberglass-reinforced plastic which resulted in substantial cost savings. The equipment and ducts from the blower exhaust

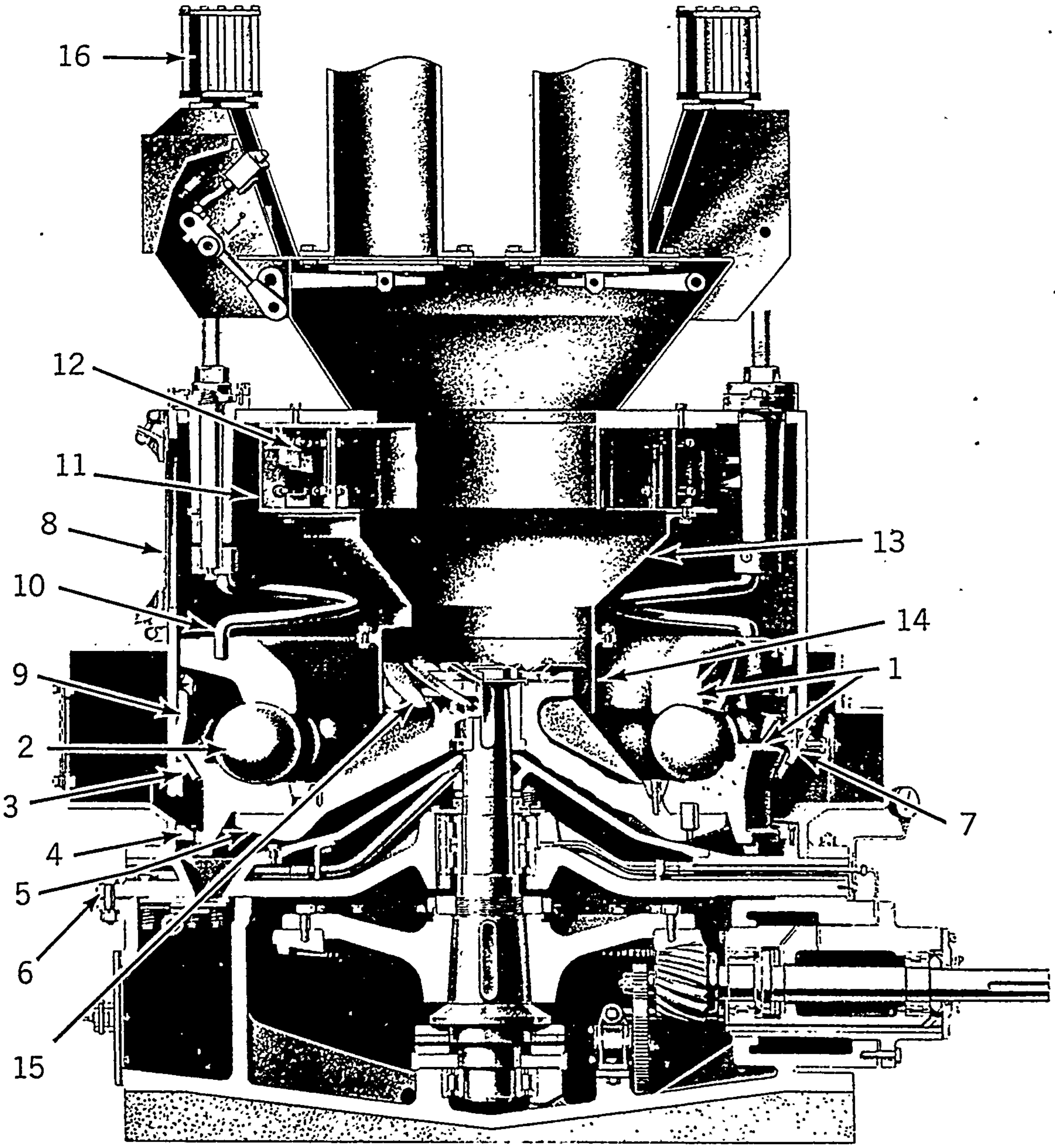
FIGURE 4. Stahl Air Heater

## E Pulverizer




1. Top and Bottom Rings
2. Balls
3. Throat Ring
4. Seal Ring
5. Yoke
6. Top Bearing Plate
7. Relief Gate
8. Access Door
10. Spring
11. Rotating Classifier
12. Intermediate Section
13. Swing Valves

**FIGURE 5. Schematic of B&W E-35 Pulverizer**




1. Top and Bottom Rings
2. Balls
3. Throat Ring
4. Seal Ring
5. Yoke
6. Top Bearing Plate
7. Relief Gate
8. Access Door
9. Housing Unit
10. Spring
11. Stationary Classifier
12. Adjustable Inlet Vanes
13. Cone
14. Tailing Section
15. Tailing Discharge Seal
16. Air Cylinder Valves

**FIGURE 6. Schematic of B&W EL-35 Pulverizer**

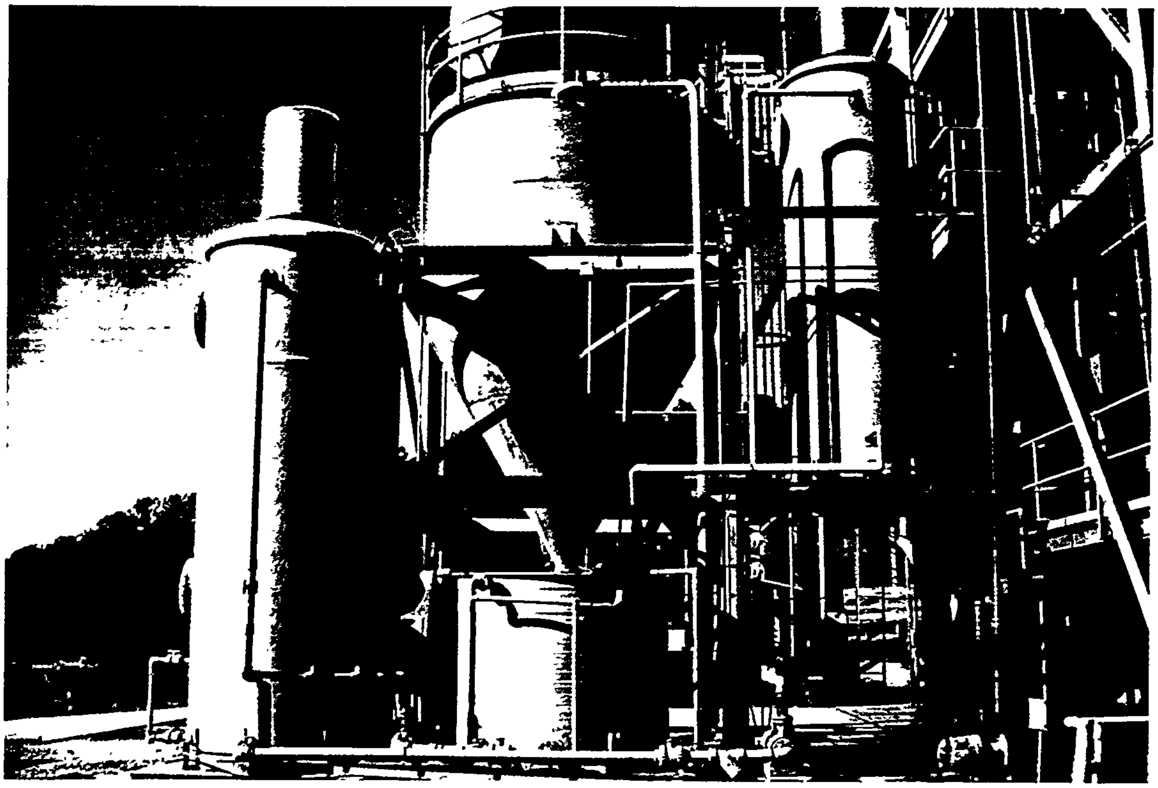


FIGURE 7. Xerxes/Heil Direct-Contact Packed Tower Condenser System

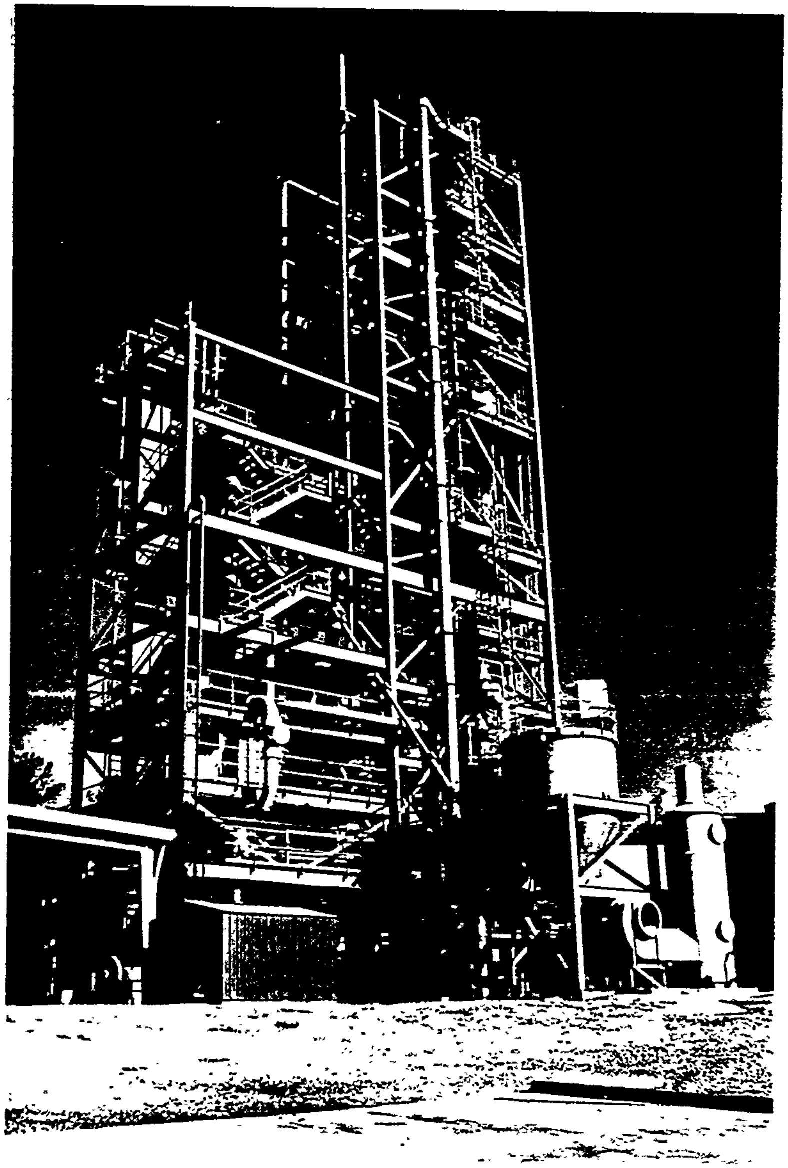


FIGURE 8. Photograph of Western Coal Processing System

to the pulverizer outlet were designed and constructed to withstand at least 5 psig, which is the maximum pressure generated by the blower when the inlet is at 0 psig. A combined pressure/vacuum relief valve was placed in the duct immediately prior to the condenser. The valve is spring operated so that it opens automatically when the limits are exceeded. The vacuum relief portion of the valve opens during startup of the blower, if necessary. The pressure relief valve also opens in the event of a system over- pressure.

An emergency $N_2$ system was installed to maintain an inert atmosphere in the pulverizer in the event of failure of the blower or power failure at the facility. The emergency nitrogen line was connected to the outlet of the cryogenic system so that failure of the nitrogen system isolation valve still would permit maintenance of an inert atmosphere in the pulverizer.

### 3.4 Process Control System

A microcomputer based control system was designed and installed to process Rosebud coal. Additional safety requirements and a more complicated control scheme mandated a change from the primarily manual operation of the Illinois #6 coal processing system. A personal computer with a 80386 processor, ISA bus, and the OS/2 multitasking operating system was installed. An off-the-shelf input/output (I/O) unit with analog-to-digital converter, multiplexers, analog output, and digital I/O was installed to interface to the coal processing system hardware. Communications from the computer to the I/O unit is over an IEEE-488 standard instrument bus. Custom software was written in "C" language to implement the control scheme. The proportional control loops for the western coal processing system are tabulated in Table 2. A detailed discussion of Western coal system control loops can be found in Ref. 3.

## 4.0 COAL PROCESSING AND FEED SYSTEM PERFORMANCE

The CFFF coal processing system was modified to pulverize, dry, and feed Montana Rosebud coal, a western coal. The requirements of the modified system included pulverization of the coal to 70 percent through 200 mesh and drying of the coal to a moisture level of 8 percent. Certain characteristics of western coal cause it to be mo re difficult to process than eastern coals. For instance, Montana Rosebud has a higher heating value that is 15 percent less than Illinois #6. Therefore, more raw coal is needed to obtain the required thermal input, i.e. a higher pulverization capacity is required. In addition, Montana Rosebud has a Hardgrove Grindability Index (HGI) that is 13 points lower than Illinois #6 and a lower HGI also decreases the capacity of the pulverizer. And lastly, the high moisture content of western coal also penalizes the pulverizer since drying capacity can be a limiting factor on system capacity.

**Table 2. Western Coal System Control Loops**

| Process Variable | Feedback | Controlled Variable |
|---|---|---|
| Coal Feed Rate D.C. | Tachometer from weigh feeder drive motor | Coal weigh feeder Driver motor speed |
| Seed Feed Rate | Calculated rate from weigh feeder, weight on belt and belt speed | Seed weigh feeder D.C. Drive motor speed |
| Pulverizer Air Flow | Calculated flow from pitot tube differential pressure, inlet and air temperature | Pulverizer inlet air valve position |
| Pulverizer Air Outlet Temperature | Temperature, pulverizer outlet | Hot/Cold air mixing valve position |
| Air Heater Outlet Temperature | Temperature, air heater outlet | Fuel/air firing rate to heater |
| Gas Dump Flow | Gas Oxygen Concentration | Gas Dump Valve Position |
| Gas $N_2$ Pressure | Condenser Outlet/Pulverizer Inlet Gas Pressure | Nitrogen Pressurization Valve Position |

In addition to the pulverizing and drying of the coal, operations with western coals can require increased handling and greater precautions against fires in storage areas. A high moisture content increases the tendencies of the coal to pack in critical flow areas and can affect the ability of the coal to successful flow through pipes and exit flow angles. Raw coal particle size is also a critical factor since fines can have a detrimental effect on coal handling and on the ability of the system to remove moisture.

The performance of the modified system is discussed below first in terms of the ability of the system to pulverize and dry the coal (coal processing system), and secondly in terms of the ability of the system to properly convey the coal to the combustor (coal feed system). Finally, western coal system operational successes and difficulties are discussed.

## 4.1 Coal Processing System Performance

### 4.1.1 Coal Fineness

One of the objectives of the CFFF EL-35 pulverizer modification was to achieve a standard utility grind of 70% through a 200 mesh sieve. Several factors affect the fineness of pulverized coal from commercial mills. These factors include coal grindability, air-to-coal ratio, pulverizer loading (capacity factor), classifier configuration, and ball spring tension. However, coal grindability is the most important factor to consider when sizing the pulverizer. As seen in Figure 9 (Reference 4), coal fineness can vary with coal grindability and with loading of the pulverizer. The coal grindability index is indicative of the ease of grinding a particular coal and a higher grindability index means that the coal is easier to grind. Since the mean coal grindability index for Montana Rosebud (47) is 13 points lower than Illinois #6, Montana Rosebud is more difficult to grind and the capacity of the pulverizer is decreased when pulverizing Montana Rosebud.

As can be seen from Figure 9, when the pulverizer is operating at base capacity (a capacity factor of 1), a coal fineness of 70% thru 200 mesh is obtained at a coal grindablility index of 50. If the mill is operated at a capacity factor less than 1, the mill will produce finer coal. Under the present arrangement, the rotary valve below the coal system baghouse limits the amount of coal which can be processed. The rated capacity of the EL-35 pulverizer is 12,090 pounds per hour which is higher than the maximum flow capacity of the rotary valve under the coal system bag-house. When pulverizing at the rate of 7500 pounds per hour, the rotary valve can barely pass the amount of coal coming from the baghouse. For reliable operation at high pulverizing rates, a larger capacity rotary valve would be required. The higher capacity operation would allow pulverizer operation at a capacity factor of 1 and this should produce coal of a consistency such that 70% would pass through a 200 mesh screen.

Since increasing the pulverizer loading to full rated capacity to achieve the desired grind was not feasible during LMF5, other pulverizer adjustments were tried in an attempt to produce a coarser grind. The mill performance was tested initially using Illinois #6 coal during Test LMF4-W and the coal was much finer than desired; nearly 95% passed through a 200 mesh screen. Figure 10 shows that a similar size distribution was observed during the first Montana Rosebud test (LMF5-A). The finer coal grind was to be expected since the pulverizer was being operated at only 41% capacity during these tests. Subsequent tests were conducted at a slightly higher capacity factor (51% vs 41%) and the pulverizer did show an increase in average particle size of the coal (see Figure 10).

During the early tests, the pulverizer was operated at the air-to-coal ratio recommended by the load curve for the pulverizer. In order to produce a coarser grind, the air-to-coal ratio was increased above the EL-35 pulverizer load curve (Figure 11).

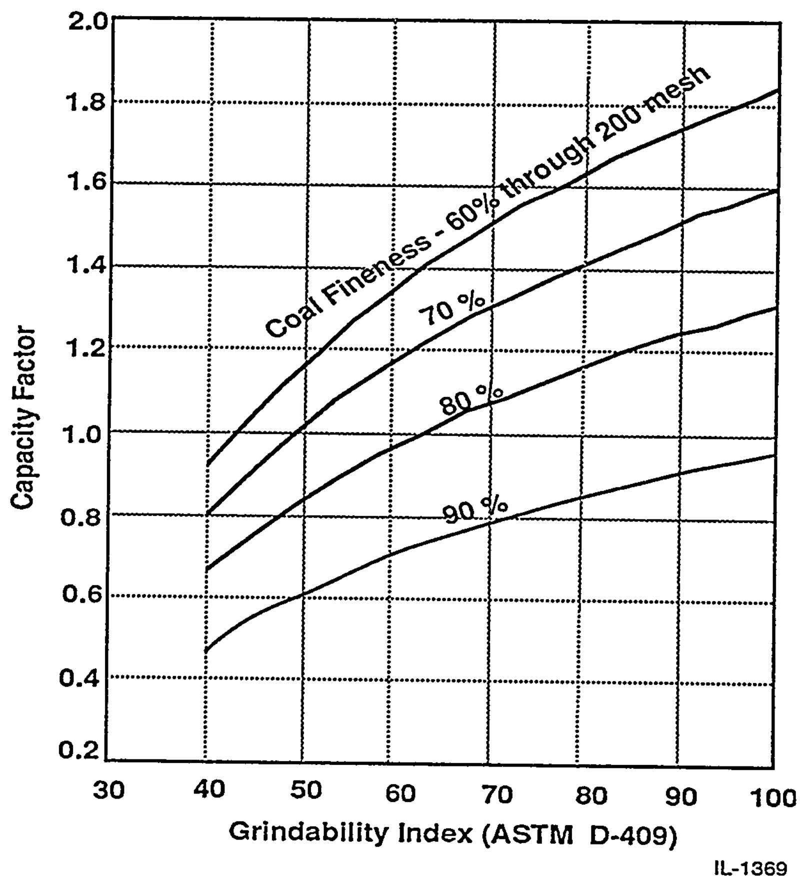



FIGURE 9. Effect of Grindability and Fineness on Pulverizer Capacity

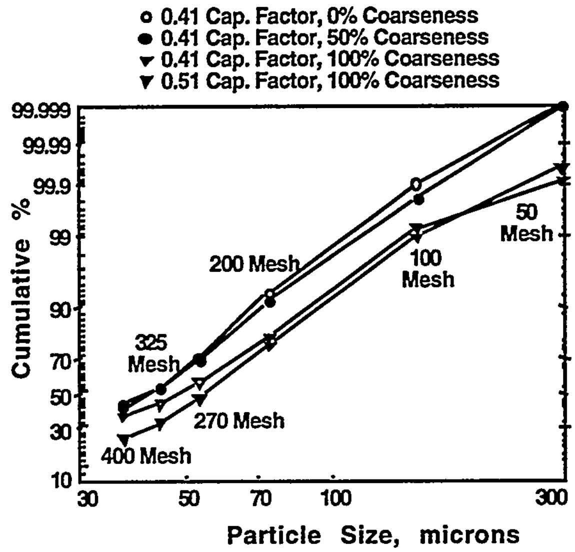



FIGURE 10. Pulverized Coal Size Distribution

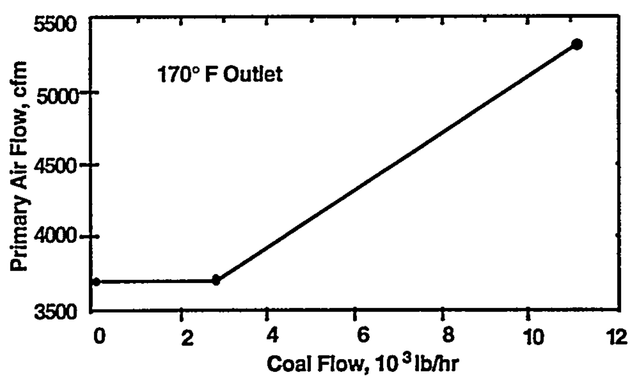



FIGURE 11. B&W EL-35 Pulverizer Load Curve

An increase in airflow will cause larger particles to be entrained in the gas flowing out of the mill. However, at the higher airflows, only a small decrease in the fraction of material passing through 200 mesh was observed. After the first test on Montana Rosebud the classifier vanes were adjusted to the 50% coarseness setting and some increase in average particle size was observed (see Figure 10). Next, the classifier vanes were adjusted to provide the maximum particle size. Again, small increases in particle size occurred. However, with the classifier vanes set at maximum coarseness, increasing the air to coal ratio above that recommended by the load curve had little or no effect.

The effect of reducing ball spring tension was also evaluated. Spring tension on the balls was reduced to 850 pounds from 1350 pounds. Fineness data from samples gathered with ball tension at 850 pounds were compared with data collected at 1350 pounds with no apparent change in the average particle size. Spring tension was then reset to the values that had been set during the pulverizer modification.

The removal of the classifer vanes was the most effective pulverizer adjustment made during Montana Rosebud testing and resulted in a coal grind of 77% through a 200 mesh. B & W has suggested that a larger particle size can be achieved by removal of the "cabbage cutter". The cabbage cutter, or tailing discharge seal, provides additional size reduction after the coal exits the rings. In summary, additional changes to the pulverizer configuration or installation of a larger baghouse rotary valve should produce the desired standard utility grind of 70% through 200 mesh.

4.1.2 Coal Moisture

Coal moisture is not only a design specification of the overall MHD system but excessive coal moisture can seriously hamper CFFF coal handling and feeding. Past experience has shown that high coal moisture levels adversely affects dense phase coal flow and can lead to plugged coal chutes and flow stoppages in the combustor coal feed line. The western coal system was designed to remove the high moisture levels in Montana Rosebud by increasing the capacity of the gas heater and by adding a condenser unit to remove moisture from the recycled gas. The design goal of the western coal modification was to achieve a moisture level of eight percent or less. The average moisture percentages for samples taken from the coal feedtank during Rosebud coal tests are given in Table 3 .

Table 3. Average Feedtank Moisture

| Test | Moisture (wt %) | Standard Deviation |
|---|---|---|
| LMF5-A | 4.70 | 0.62 |
| LMF5-B | 4.76 | 0.38 |
| LMF5-C | 4.85 | 0.49 |
| LMF5-D | 7.39 | 0.98 |
| LMF5-E | 6.28 | 0.54 |
| LMF5-F | 5.29 | 0.67 |
| LMF5-G | 6.45 | 0.63 |
| LMF5-H | 6.56 | 1.10 |
| LMF5-I | 6.92 | 0.79 |
| LMF5-J | 7.23 | 0.58 |

For the first three western coal tests (LMF5-A through LMF5-C), feedtank moisture levels remained below 5% and there were minimal coal handling and feeding problems. However, note that in general the feedtank coal moisture steadily increased during the remainder of the test program and averaged 7.23% during the last test. The elevated coal moisture levels during the last seven Montana Rosebud tests caused significant feeding problems (see Section 4.2.2). The most notable exception to the steady increase in coal moisture during the test series occurred during test LMF5-D when the feedtank coal moisture averaged 7.39%.

During LMF5-D, heavy rains soaked the coal storage pile, with a measured rainfall of over 2.5 inches during the first few days of the test. Raw coal analysis for this test indicated over 30% moisture by weight and it had the appearance of a thick sludge. During this portion of the test, the coal flow was more erratic than in the previous tests. To correct this problem, coal from the bottom of the feedtank was recirculated back through the pulverizer for additional drying. Immediately after completion of recirculation, the coal flow became much smoother. Recirculating the coal reduced the moisture to approximately 6%.

Although 3" X 0" coal was specified during procurement, the delivered raw coal contained a large percentage of fines. The first Western coal shipment was small (354 tons) and required minimal handling during the early portions of the test program. After the first three tests, the shipment and handling of the coal resulted in the production of smaller fragments with a large quantity of fines. Fine coal can contain more surface moisture (due to increased surface area) and is more difficult to dry in a pulverizer since it will have less residence time exposed to high gas temperatures.

The design conditions of the western coal system were achieved in terms of operating the system with a higher pulverizer outlet temperature (170°F) and maintaining a condenser outlet temperature of 90°F (see Figure 2). However, the modified system was not designed to accommodate raw coal with a large percentage of raw coal fines. The large percentage of raw coal fines was responsible for the excessively high pulverized coal moisture levels seen after the first three tests. Future coal procurements should specify that the coal be double-screened to reduce coal fines and avoid the numerous coal handling and feeding problems experienced during LMF5 tests. Some options for processing very wet raw coal have also been considered; including increasing the pulverizer exit temperature to 180°F and/or increasing the gas-to-coal ratio.

## 4.2 Coal Feed System Performance

Conventional pulverized coal processing systems utilize a carrier gas to convey pulverized coal to a combustor in dilute phase. The CFFF coal feed subsystem was designed to use dense phase transport. Pressurized dense phase transport is a method of conveying granular solids which have a high solids to gas ratio and low gas velocities. Because the amount of carrier gas and its accompanying cooling effect is minimized, this method is well suited for MHD applications. The coal feed system for the western coal tests was identical to the feed system used during eastern coal testing. This feed system (Figure 12) conveys pulverized coal from the pressurized feed tank to the combustor in dense phase through a 0.75 x 0.0625 inch stainless steel tubing coal feed line. There are two mass flow meters and a volume fraction meter in the coal transport line, one mass flow meter at the feedtank exit and a second mass flow meter and a volume fraction meter at the inlet to the coal combustor. In order to determine coal line pressure losses and to correlate MHD system pressure oscillations with coal feed, two dynamic pressure transducers were installed in the coal feed line between the two mass flow meters. An assessment of the accuracy of the mass flow measurements and a discussion on the stability of the coal flow is given below.

### 4.2.1 Mass Flow Measurement

The Micro-Motion single-tubed coriolis mass flowmeters have been used since the start of coal fired testing at CFFF and have generally demonstrated good performance. However, intermittent zero-shifts in the Micro-Motion meters were experienced and the meters were outdated and required frequent repairs. A study to identify a suitable replacement for the Micro-Motion meters was undertaken during the eastern coal test series. The candidate designs featured double-tubed coriolis meters from three manufacturers. However, none of these double-tubed meters were successful in measuring pulverized coal flow and erratic output signals were observed from all three meters.

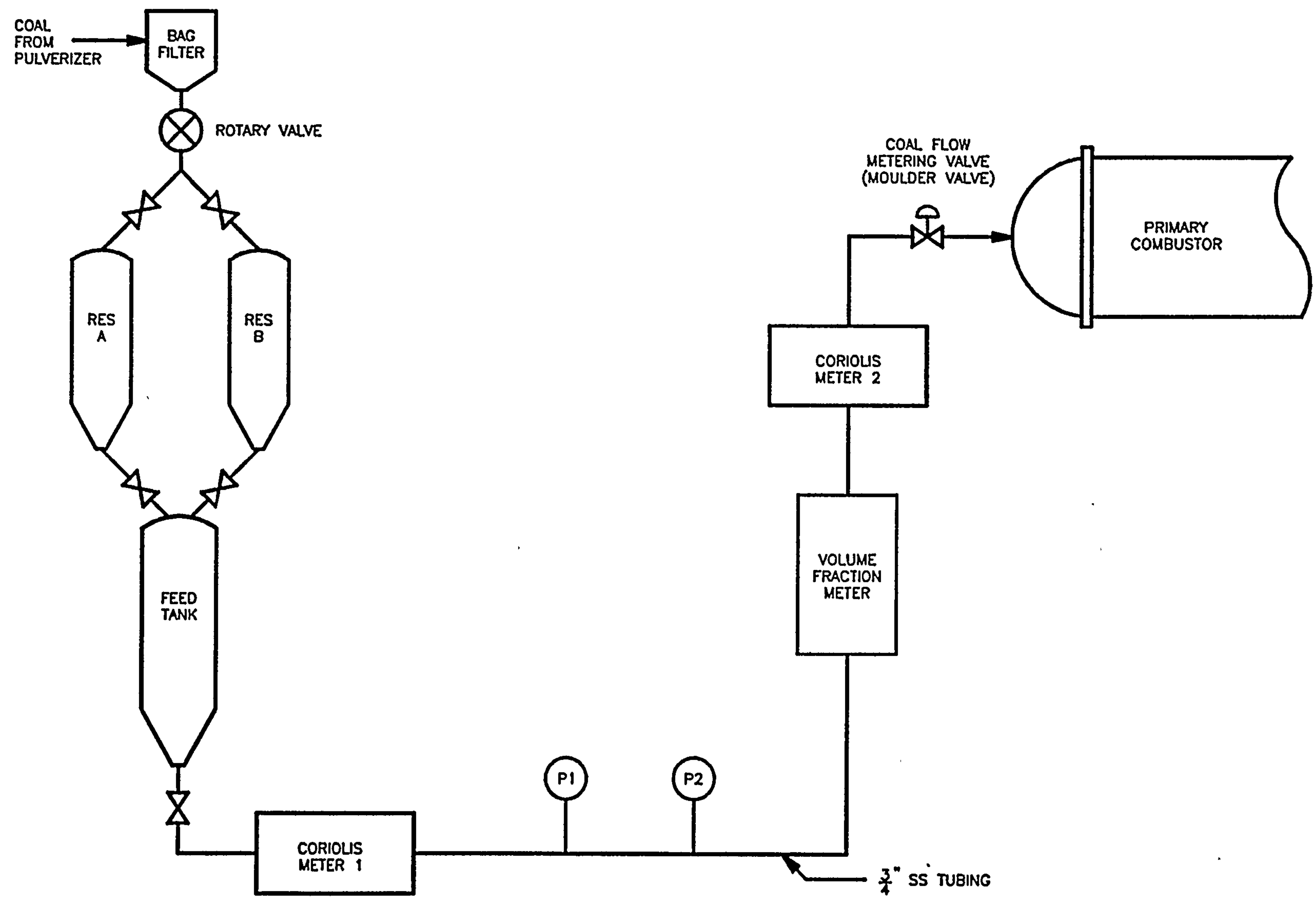



FIGURE 12. COAL FEED SUBSYSTEM

A new Fischer-Porter coriolis-type mass flowmeter was evaluated and installed during the Montana Rosebud testing phase. A comparison of the new Fischer-Porter flowmeter with the Micro-Motion flowmeter can be made by observing the meter calibration data in Figures 13 and 14. The calibration data were obtained by using a load cell to measure the change in weight of the calibration tank over a computer measured time period. This new single-tubed coal flow meter was more accurate and reliable than the first-generation Micro-Motion coriolis meters used for over thirteen years at CFFF (note that the Fischer-Porter meter has a higher correlation coefficient than the Micro-Motion meter). The base condition coal flowrate for test LMF5-I was 0.84 lbs/sec. The LMF5-I calibration data show that the Fischer-Porter meter has an average deviation of less than 2% of the base condition coal flowrate. A photograph of the Fischer-Porter meter is shown in Figure 15.

4.2.2 Coal Flow Stability

The western coal system was used successfully during 1339 hours of combustor operation. Figure 16 illustrates stable combustor coal feed during a typical eight-hour test period. Although stable coal flow was achieved for extended testing periods, coal flow stoppages continued to be a problem during several of the Montana Rosebud tests.

During Illinois #6 tests and Montana Rosebud tests, blockages of the coal line have occurred which caused a temporary shutdown of the test until the coal line could be cleared. During eastern coal tests, many of the perceived causes of the coal line blockages were eliminated such as: 1) removal of lumps and foreign objects by installing a shaker screen beneath the coal system baghouse, and 2) replacement of pipe sections and synflex hose sections with smooth stainless steel tubing in the coal line. Coal moisture during eastern coal tests was generally below 4 percent and as a result very few coal line blockages were experienced during the latter portion of the eastern coal test series (see Reference 2). Therefore, coal flow stoppages were not expected to be a major problem during western coal testing if acceptable coal moisture levels could be maintained.

Further improvements in operations were achieved during Montana Rosebud testing by installing an automatic coal line cleanout system which could be activated by the test operator when a coal line blockage occurred. The automatic coal line cleanout system allowed the operator to continue firing fuel oil temporarily until coal fired testing could resume. The automatic coal line cleanout system consisted of a series of remotely operated valves which shutoff the flow from the coal feed tank and introduced high pressure nitrogen to clear the coal feed line to the combustor. Using this technique, coal flow could normally be restored in less than one minute. Nonetheless, coal line blockages could not be entirely eliminated even with the automatic coal

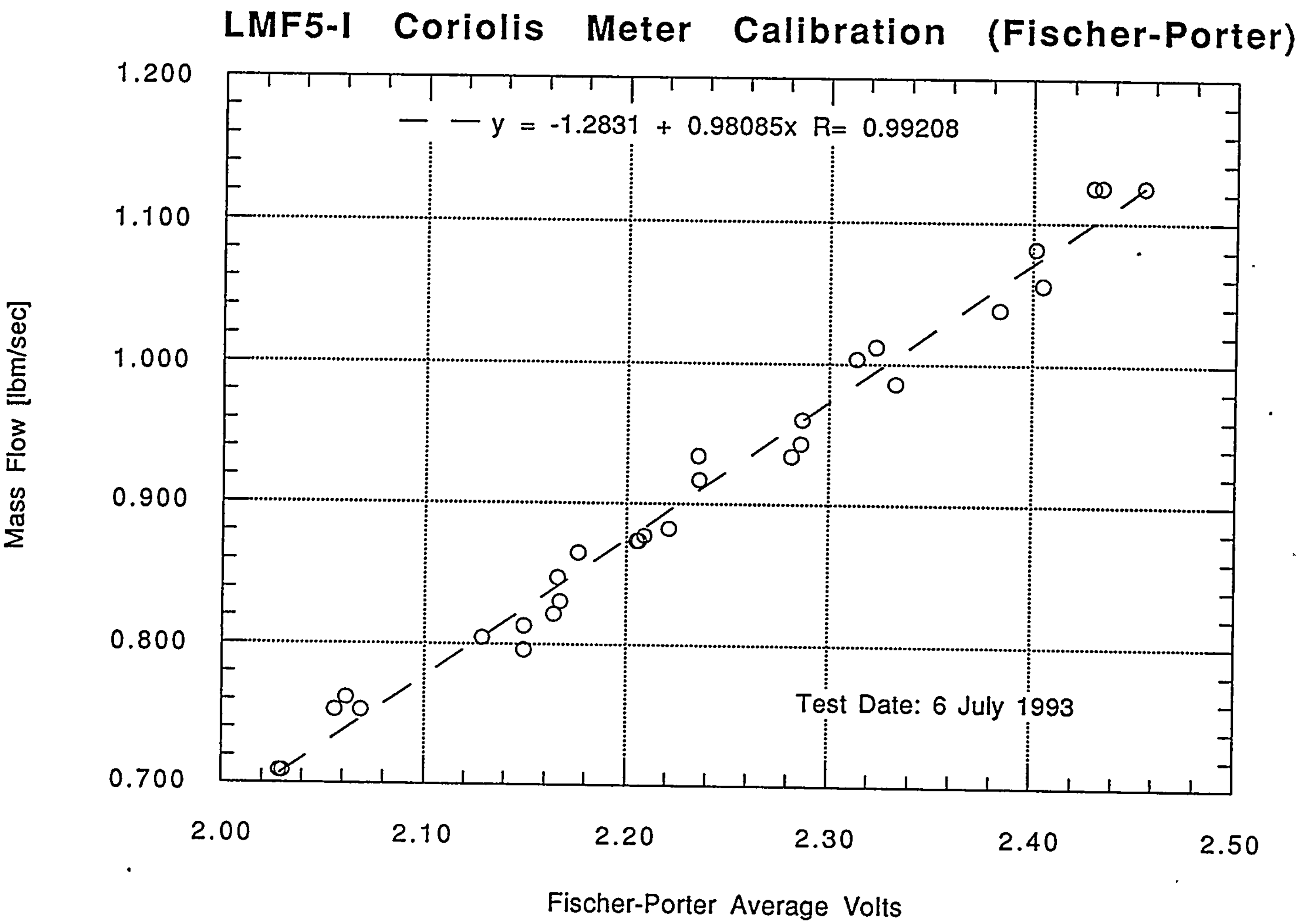



FIGURE 13. Fischer-Porter Coriolis Meter Calibration Curve

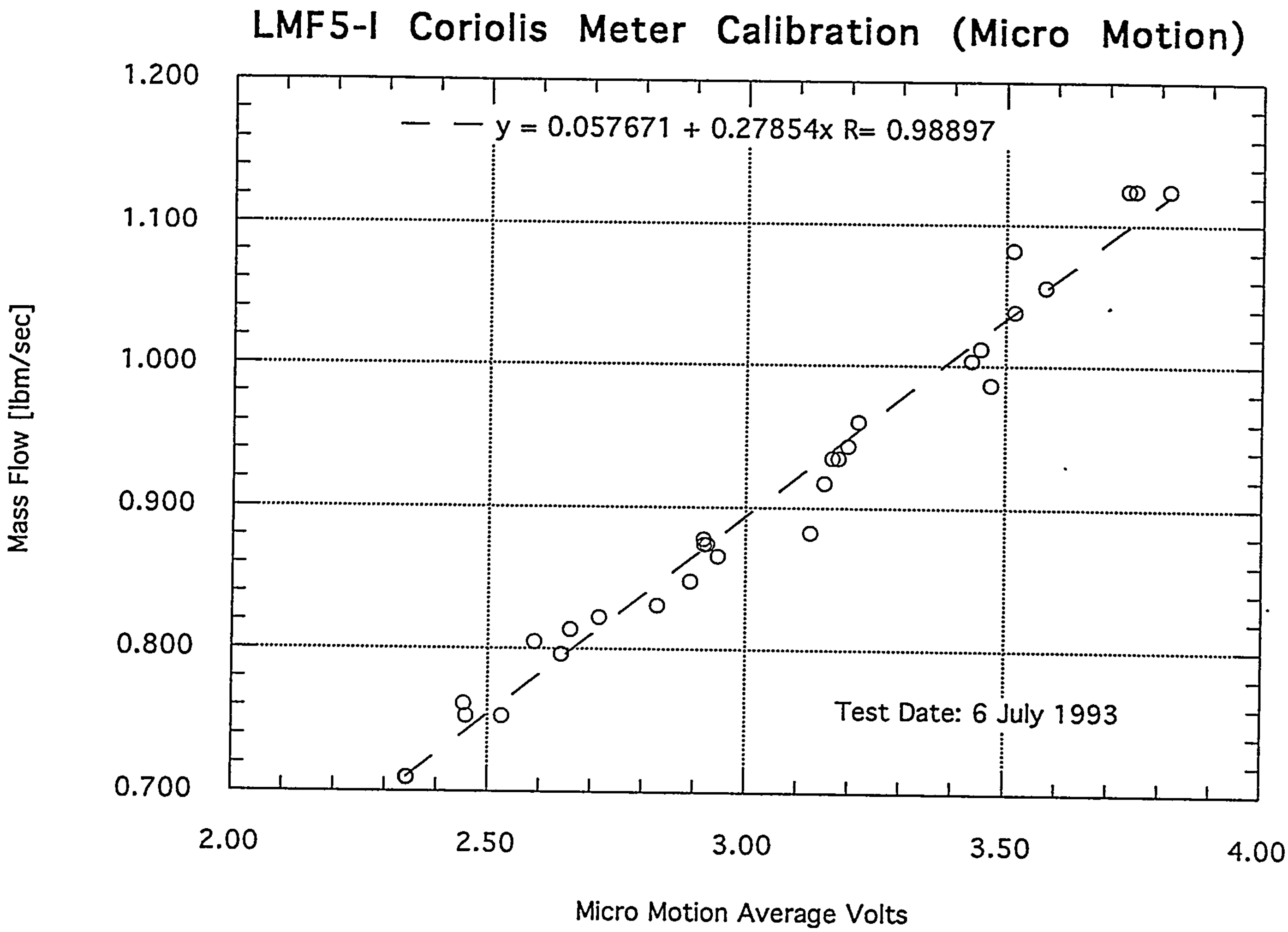



FIGURE 14. Micro-Motion Coriolis Meter Calibration Curve

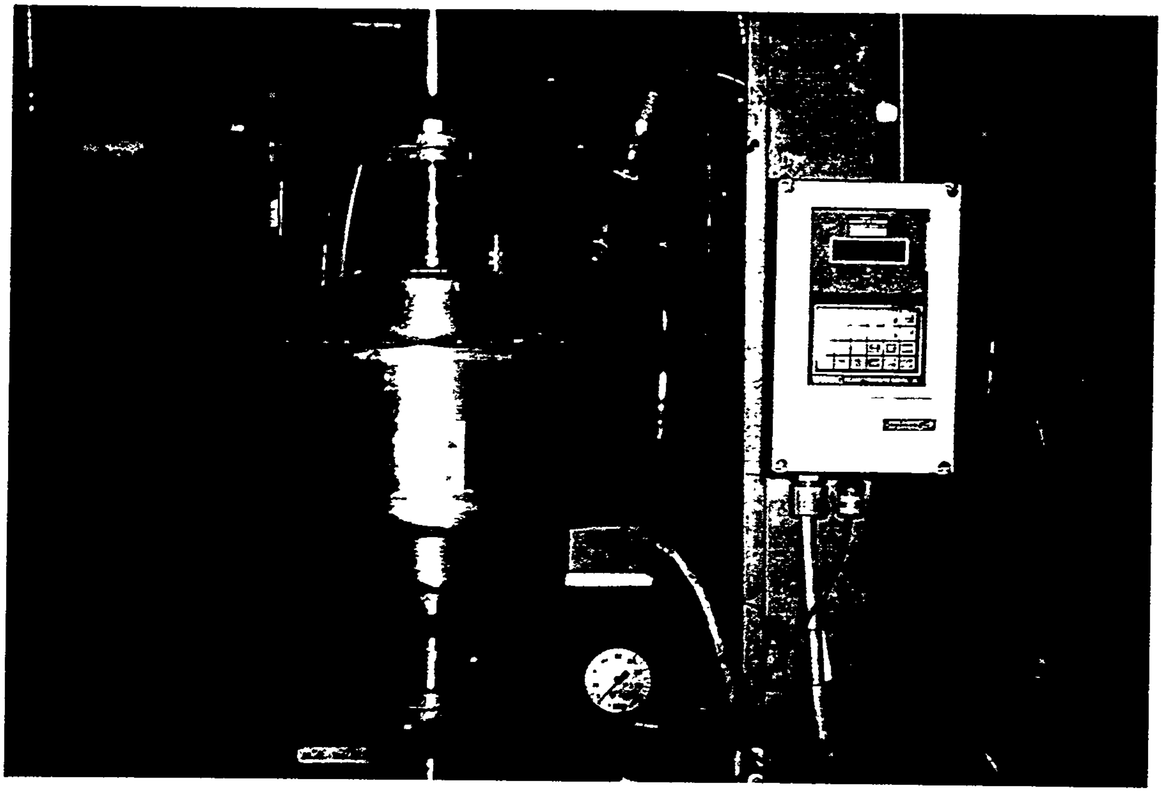


FIGURE 15. Photograph of Fischer-Porter Coriolis Meter

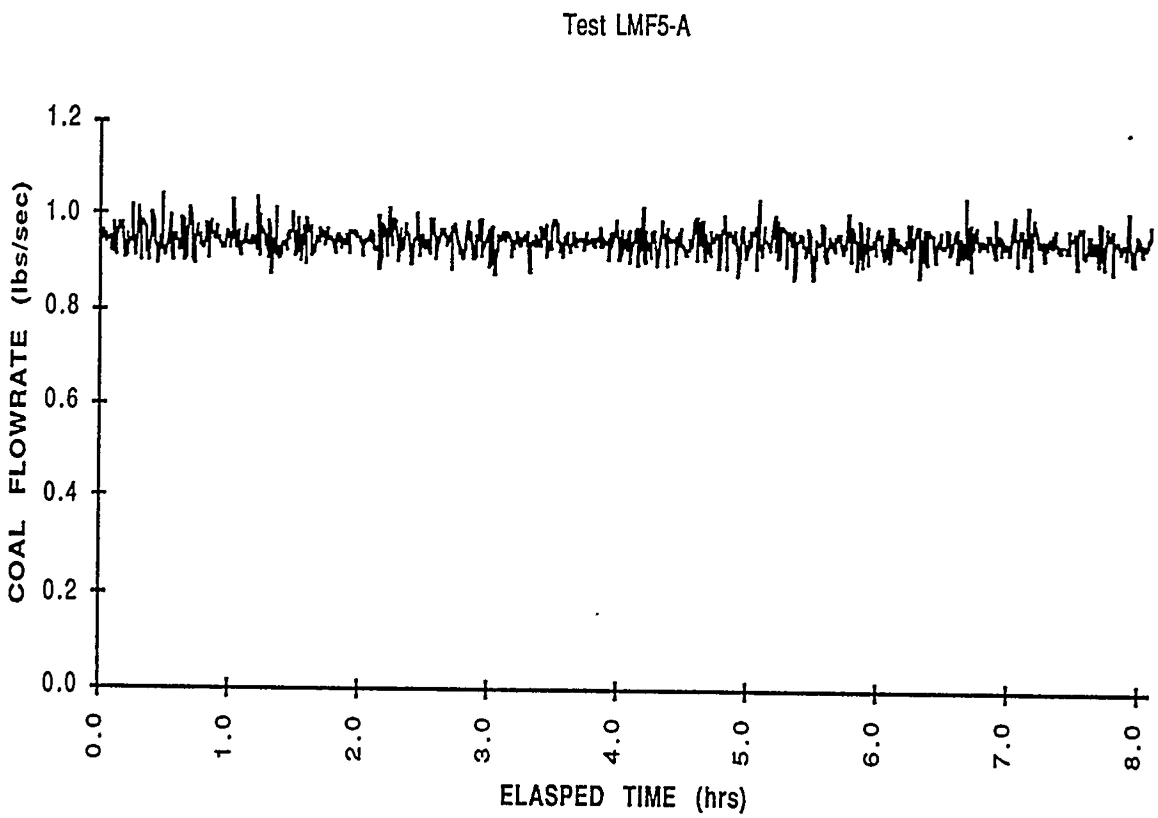



**FIGURE 16. Coal Mass Flowrate During 8-Hour Test Period**

line cleanout system installed; the blockages continued to occur, particularly during periods of high coal moisture.

A plot showing the frequency of coal line blockages for each test is presented in Figure 17. The data show that very few coal line flow blockages were experienced during the first three tests when coal moisture remained below 5 percent. As moisture levels increased above 5 percent, more coal line blockages were experienced. Note that 63 of the 123 coal line blockages occurred during one test (LMF5-D). The problem of coal moisture during test LMF5-D is discussed in greater detail in Section 4.1.2. As MHD systems are scaled up to commercial sizes, coal line plugs should not be a concern if sufficient coal drying ability is available.

During both the latter part of LMF5-F and LMF5-G, a steady coal flow could not be controlled because of abrasive wear of the coal flow control valve (Moulder valve). New ceramic rollers for the Moulder valve were installed for LMF5-H and this eliminated the coal flow oscillations due to wear of the rollers. The effect of worn rollers on the coal flow stability is illustrated in Figure 18.

## 4.3 Coal System Operations

Several minor coal system operational problems occurred during Montana Rosebud testing and many of these problems are documented in Appendix B. The significant coal system operational problem areas included: 1) two coal pulverizer main shaft failures, and 2) power outages at the coal system motor control center which shutdown testing on several occasions. The first pulverizer main shaft failure occurred during test LMF5-F in August, 1992 after more than 672 hours of western coal testing had been accumulated on the modified pulverizer. The pulverizer was completely disassembled and all parts inspected. In addition to the main shaft failure, damage to the main shaft thrust bearing was discovered. Initially, an uneven distribution of coal between the balls and the race was thought to be responsible for the main shaft failure. However, subsequent observations during main shaft replacement revealed that a misalignment between the main shaft and the yoke could also have been partially responsible. The pulverizer was re-assembled with a new main shaft, a new thrust bearing, and the coal chute changed to provide a better distribution of the coal in the pulverizer.

During the LMF5-H test one of the balls in the coal pulverizer fractured (Figure 19) causing another main shaft failure (Figure 20). After the test, the pulverizer was disassembled and inspected. In addition to the failed shaft, the housing wear plates, the bearing and races, the yoke, and the main drive belt pulley were found to have been damaged. Required replacement parts were procured and the pulverizer reassembled and readied for the next CFFF test.

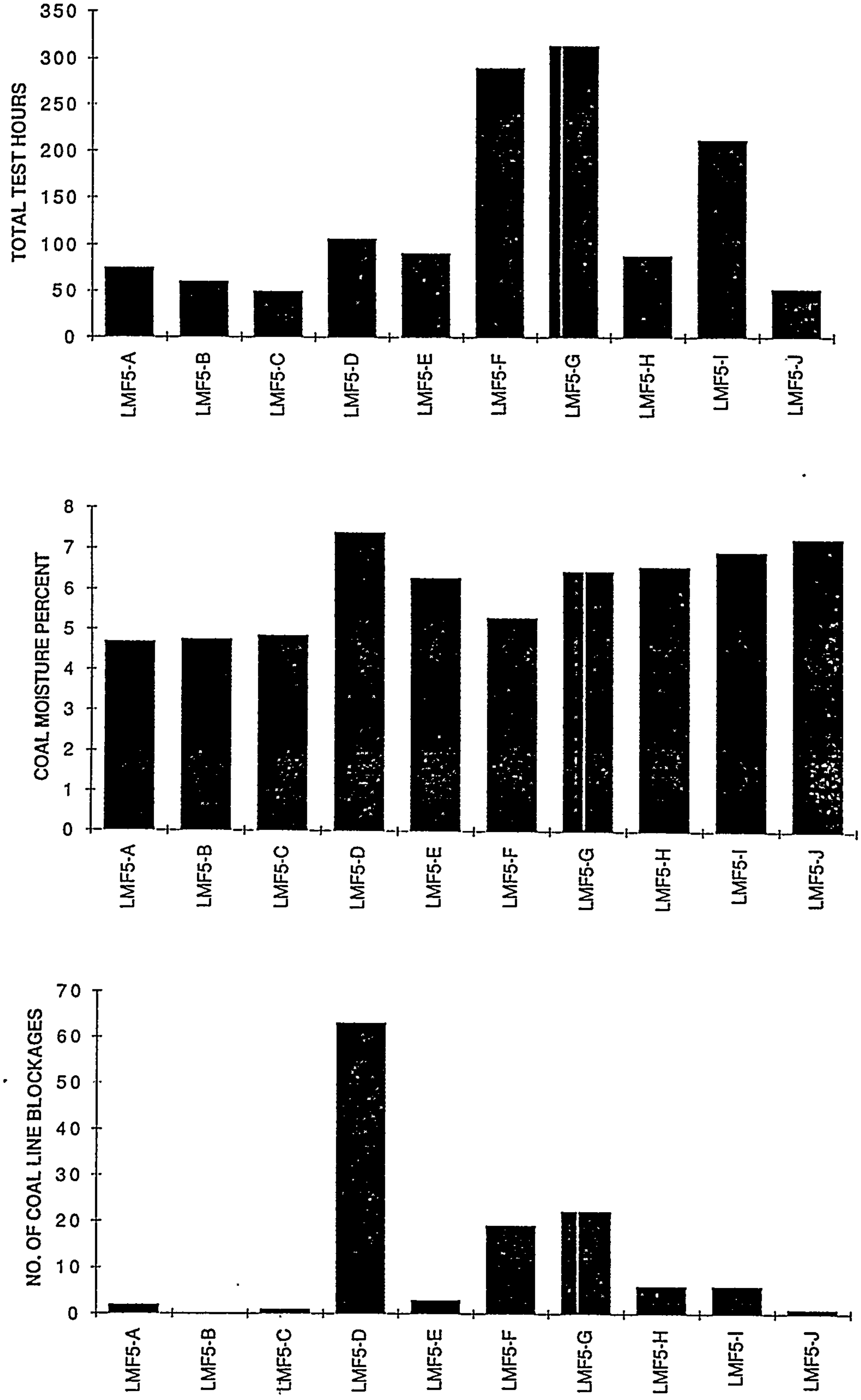
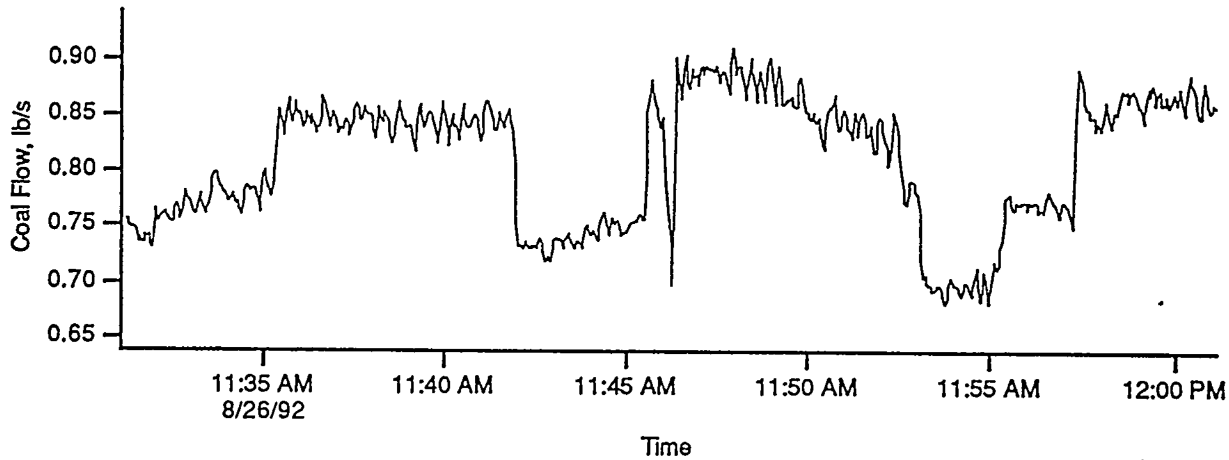
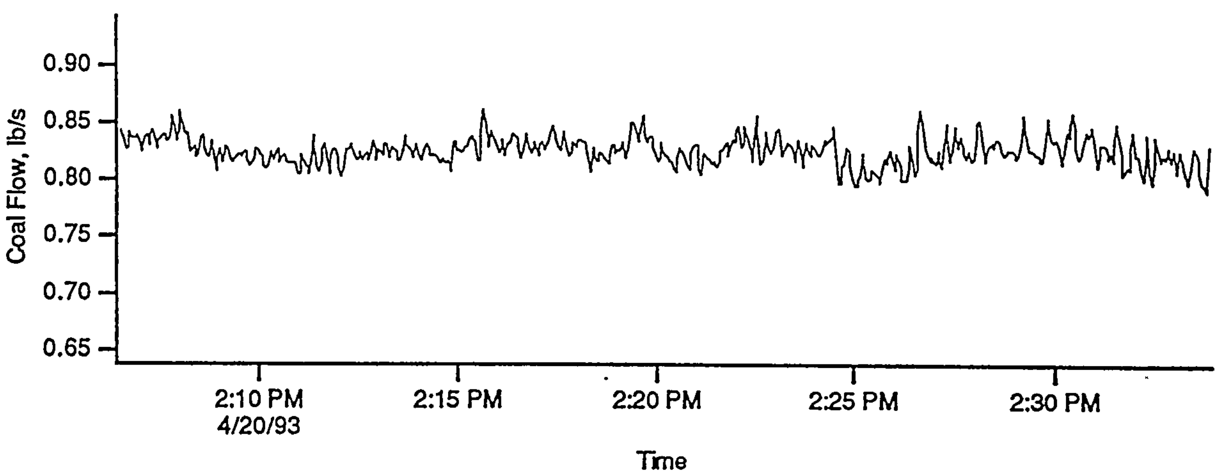



FIGURE 17. Coal Line Blockages




a. Coal Flow with Damaged Moulder Valve




b. Coal Flow with Repaired Moulder Valve

FIGURE 18. Moulder Valve Effects on Coal Flow

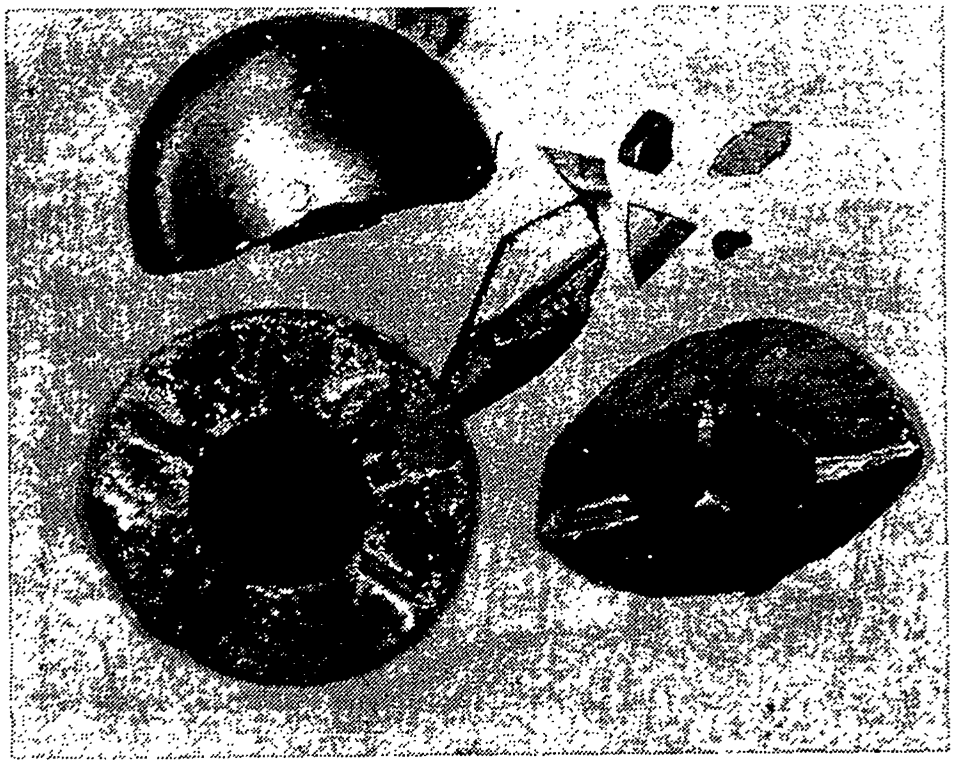
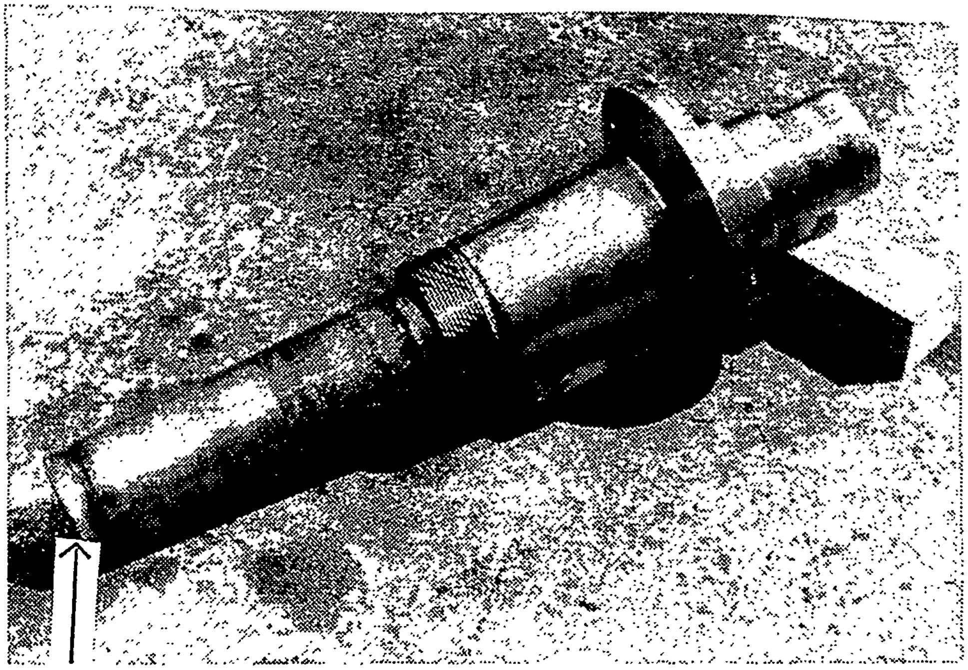


FIGURE 19. Fractured 9-Inch Pulverizer Ball



Break Point

a. Pulverizer Shaft

b. Pulverizer Shaft Section Showing Break Surface

FIGURE 20. 3-1/2 Inch OD Pulverizer Shaft Failure

The circuit breaker for the coal processing system motor control center tripped out at the unit substation and caused a shutdown of the test during LMF5-E. After the first power outage, the circuit breaker was readjusted to it's upper limit but tripped again during test LMF5-G. A new trip module was installed for test LMF5-H but coal flow was lost four times because of coal system power outages. Current readings from the coal system motor control circuit indicated that intermittent overloads were occuring during these tests. This suggests that the power outages may have been related to the pulverizer main shaft failures; where mechanical interferences such as misalignments, a broken ball, or uneven coal distribution in the pulverizer could intermittently increase the pulverizer motor load and place too large a demand on the circuit. After the final pulverizer shaft rebuilt, no further instances of coal system power outages occurred.

The modification of the CFFF coal system was successful in terms of achieving the system design conditions. The design pulverizer outlet temperature of 170°F was achieved, the oxygen concentration of the inerted gas was less than 5 percent, the inerted gas stream exiting the condenser was 90°F, and system static pressure control was maintained with a vacuum breaker/overpressure valve. The new system has the flexibility to increase production of pulverized coal and to change the desired operating temperatures and flows. However, due to the process control automation implemented, the operation of the Western coal system requires no additional manpower over the prior, less complex system of processing Illinois #6 coal. A detailed discussion of the effectiveness of the automatic process control system can be found in Reference 3.

## 5.0 SUMMARY AND RECOMMENDATIONS

The original eastern coal system was modified to process Montana Rosebud, a western coal. The modified system was successfully operated for over 1339 hours prior to the completion of the MHD Proof-of-Concept (POC) testing of the integrated bottoming cycle at CFFF. All of the design conditions for the western coal system were achieved and the design goal of a standard utility coal grind (70 percent through 200 mesh) was nearly achieved. The most recent particle size distribution adjustment produced coal of 77% through 200 mesh. A minor change to the coal system, installation of a larger baghouse rotary valve, should produce the desired standard utility grind of 70% through 200 mesh.

Coal moisture during Montana Rosebud testing remained below the design goal of 8% resulting in stable coal flow into the combustor for extended testing periods. For the first three tests, coal moisture remained below 5 percent and very few coal flow interruptions were experienced. During the remainder of the program, the coal moisture increased because of a high percentage of raw coal fines, and as a result, the number of coal line blockages also increased. Future coal purchases should specify double-screened coal to reduce the percentage of raw coal fines and keep coal moisture levels below 5 percent.

A new Fischer-Porter coriolis-type mass flowmeter was evaluated and installed during the Montana Rosebud testing phase. This new single-tubed coal flow meter was more accurate and reliable than the first-generation coriolis meters used for over thirteen years at CFFF.

Due to the process control automation implemented, the operation of the western coal system requires no additional manpower over the prior, less complex system of processing Illinois #6 coal. The new system has the flexibility to increase production of pulverized coal and to change the desired operating temperatures and flows.

## 6.0 REFERENCES


1. "Integrated MHD Bottoming Cycle Task 1 Modification of the Existing Pulverizer and Dryer System," submitted to the U. S. Department of Energy, PETC, by Babcock & Wilcox and Hudson Engineering Companies, June 8, 1989.

2. DOE/ET/10815-207, "The Low Moisture Eastern Coal Processing System at the UTSI-DOE Coal Fired Flow Facility," B. R. Evans, E. S. Washington, and M. E. Sanders, submitted to the United States Department of Energy by the University of Tennessee Space Institute Energy Conversion Research and Development Programs, October, 1993.

3. Holt, J. K., Reksten, E. L., and Frazier, J. W., "Design and Control of the CFFF's Closed-Loop Coal Pulverizing System To Process Montana Rosebud Coal," Proceeding of the 30th Symposium on Engineering Aspects of Magnetohydrodynamics, June, 1992.

4. Steam/Its Generation and Use, Babcock & Wilcox Company, April, 1991.

# APPENDIX A

## WESTERN COAL TESTS SIGNIFICANT EVENTS

## WESTERN COAL TESTS SIGNIFICANT EVENTS

| DATE | EVENT |
|---|---|
| January 1990 | Preliminary flow tests of western coal to determine suitable moisture levels. |
| December 1990 | Started western coal system modifications. |
| January 1991 | Started installation of new coal system blower. |
| February 1991 | Started installation of new condenser system. |
| April 1991 | Started checkout of Stahl air heater. |
| May 1991 | Started converting pulverizer from E-35 to EL-35. |
| July 1, 1991 | First western coal shipment arrives (354 tons). |
| July 8, 1991 | Started checkout of full coal system. |
| July 15, 1991 | B&W checkout of pulverizer modifications. |
| July 25, 1991 | Coal system modifications completed and system is checked out pulverizing coal. Eastern coal is used during this checkout as a precautionary measure since it is less likely to cause fires. |
| July 28, 1991 | First western coal pulverized. |
| August 12-20,1991 | Second western coal shipment arrives (1245 tons). |
| August 2-Sept. 4, 1992 | Third western coal shipment arrives (1625 tons). |

# APPENDIX B

## SUMMARY OF HIGH MOISTURE WESTERN COAL TESTS

## SUMMARY OF HIGH MOISTURE WESTERN COAL TESTS

| DATE | TEST | TIME ON COAL (HRS) | SIGNIFICANT EVENTS |
|---|---|---|---|
| **1991** | | | |
| May 4-11 | LMF4-W | 85.77 | Most of the major western coal system modifications are completed prior to this test. The condenser system is not operational or required for this test since low moisture Illinois #6 coal is fired. |
| Jul 30 - Aug 3 | LMF5-A | 75.33 | Introduction of dry potassium sulfate using raw seed storage and feed system.<br><br>Liquid potassium carbonate system checked and working properly. No operational or hardware problems occurred with the system and flow control was excellent.<br><br>Automatic coal line cleanout system installed and operated for first time.<br><br>On-line computer program which calculates coal flow from feed tank weights installed.<br><br>Two (2) coal line blockages. Encountered difficulties cleaning coal system baghouse; new higher horsepower motor is needed to overcome this problem. Leakage of gas through the raw coal tank caused higher than desired makeup nitrogen flow rates necessary to maintain the static pressure at the condenser at ambient levels. Raw coal tank leakage controlled somewhat by maintaining a full tank of coal in raw coal tank. A valve located between the raw coal tank and the bucket elevator may be necessary to maintain an adequate seal. Large quantity of very fine coal found in the pyrite trap. |
| Aug 25-29 | LMF5-B | 60.38 | The classifier vanes in the pulverizer were removed before the test in order to produce a courser grind. The vane removal was successful and the percent through 200 mesh decreased from 85% to 80%.<br><br>Potassium carbonate added to the primary combustor as a 47% solution. Potassium sulfate not added during pulverization but approximately 25,000 pounds of previously pulverized potassium sulfate seeded coal was burned at the start of testing.<br><br>No coal line blockages. No operational problems were encountered with the wet carbonate injection system; flow was maintained steady through the test and control of flow |

| DATE | TEST | TIME ON COAL (HRS) | SIGNIFICANT EVENTS |
|---|---|---|---|
| Aug 25-29 (cont'd) | | | and seeding rate was excellent. The coal system baghouse rotary arm blower chain broke causing a high pressure drop across the baghouse. Coal system controls induce coal flow oscillations. |
| Sep 22-25 | LMF5-C | 49.75 | Potassium carbonate added to the primary combustor as a 47% solution. Potassium sulfate and iron oxide added to the coal during pulverizing.<br><br>One coal line blockage. Difficulties controlling coal flow; ruptured diaphragm in Moulder valve E/P. Heavy rain in area on September 24. |
| Nov 17-24 | LMF5-D | 106.60 | Seed introduced as dry potassium carbonate with the coal, and the ratio of coal to combustor oil increased as much as practical. About 7000 pounds of previously pulverized coal containing iron oxide and potassium sulfate was burned at the start of testing. Feed tank coriolis meter is not operational.<br><br>With coal pulverization rate at 6500 pounds per hour and the inert gas heater exit temperature at 775 deg F, the hot gas modulating valve was operating at 90-95% which indicates that this is near the maximum pulverizing rate for these conditions.<br><br>Sixty-three (63) coal line blockages. Plots of the coal feed line pressures indicated that many of the coal line blockages were upstream of the transducers. The coal flow blockages are apparently due to a slightly higher moisture content in the coal/seed mix (7-8%). Pulverization rate as high as 7000 lb/hr of raw coal which is 40% higher than some of the rates used previously. Moulder valve has 0.5" diameter rollers installed. Pulverizer lubricating oil replaced with a higher temperature synthetic oil; however, pulverizer oil pressure dropped during test. Primary coriolis meter shifts 0.1 lbm/sec on November 19. Pulverizer motor has excessive vibrations; suspect bearings are going bad. The coal baghouse rotary valve and shaker trip out when one of the shaker arms becomes loose and causes excessive vibrations. At 7000 lb/hr pulverization rate, the coal grind is 77% through 200 mesh. Erratic coal flow caused by heavy rains on coal pile. The testing was stopped in order to further dry the coal by recirculating coal through the pulverizer. Coriolis meter shifts reported on November 22 for both primary and secondary meters. Decreased coal pulverization rate to 5500 lb/hr on November 23; moisture levels remained high. Raw coal feed auger is plugged with coal mud. |

| DATE | TEST | TIME ON COAL (HRS) | SIGNIFICANT EVENTS |
|---|---|---|---|
| **1992** | | | |
| Apr 22-30 | LMF5-E | 90.78 | Raw coal tank inlet isolation valve installed to prevent leakage to inert gas from coal pulverization system. Pulverizer oil pump pressure relief orifice removed and capped in order to maintain higher lube oil pressure.<br><br>Three (3) coal line blockages. Good agreement noted between feed tank weight calculated coal flow and the coriolis meter indicated values. The circuit breaker for the coal processing system tripped at the unit substation and causes a shutdown of the test. Speculation is that the addition of the pit blower put to much demand on this circuit. Coal system baghouse temperatures reading 10 degrees above normal; reduced pulverizer inlet temperature to bring temperatures back to normal. Examine the electrical load to the coal processing circuit to insure that pulverizing at normal rates will not cause a power outage as occurred during the test. |
| Aug 13-27 | LMF5-F | 290.12 | Fischer-Porter coriolis meter (serial number 92W340854) installed in test building and #1 Micro-Motion meter (serial number 22639) moved to coal tower.<br><br>Nineteen (19) coal line blockages. Dirty strainers in condenser system cause reduced water flow to cooling tower and condenser; the condenser pump, cooling tower pump, and the blower were turned off and the strainers self-cleaned. Raw coal screw auger not operating because coal elevator plugged with wet coal. Coal flow was erratic during the test.<br><br>Coal pulverizer main shaft is broken. A build-up of wet coal at the outlet of the raw coal chute caused raw coal to accumulate on the inside of the pulverizer. |
| Sep 28-Oct 14 | LMF5-G | 313.83 | Replaced main shaft of pulverizer prior to test.<br><br>Twenty-two (22) coal line blockages. Raw coal auger tripped out several times during pre-test refractory warmup. During this time, all electrical power to the coal tower was lost when the coal system motor control center breaker tripped out at the unit substation. Erratic coal flow during early portion of test. The coal pulverizer bleed valve inadvertently actuated; the valve was disconnected and blocked. Large threaded nut found inside pulverizer clean-out door. Replaced raw coal auger motor during test. Lost power to coal tower during test. Leak started in water recirculating pump in coal condenser system. Coal flow is |

| DATE | TEST | TIME ON COAL (HRS) | SIGNIFICANT EVENTS |
|---|---|---|---|
| Sep 28-Oct 14 (cont'd) | | | erratic so test is shutdown to inspect Moulder valve; found excessive wear on Moulder valve rollers. An unintentional Cardox system dump occurred when the raw coal elevator chain broke and damaged a heat sensor. During the test, the coal system power circuit breaker was at its' upper limit; the breaker will be readjusted before the next test to avoid this problem. |
| **1993** | | | |
| Apr 20-24 | LMF5-H | 88.25 | Installed new ceramic rollers in Moulder valve.<br><br>Started installation of pulverizer hot air line insulation.<br><br>New coal tube installed in the primary combustor.<br><br>A new trip module for the coal system motor control center is installed prior to test.<br><br>Six (6) coal line blockages. New trip module is ineffective; lost coal flow due to loss of power to the coal tower four times. Coal tower power losses lead to speculation that a fault exist in the line between the coal tower and the unit substation since the circuit breaker is rated at 600 amps and measurements indicate that we are only pulling 400 amps during operations.<br><br>Very loud noise from coal pulverizer is found to be split pulverizer ball. After consulting with B&W, ball is removed and pulverizer is restarted with one ball missing. Pulverizer shaft drive pulley belt was misaligned causing pulley to rub against the drive system housing. Main pulverizer shaft broken again; the shaft failure most likely caused by failure of one of the large pulverizing balls in the coal mill. |
| Jul 8-19 | LMF5-I | 212.13 | Coal pulverizer refurbished with new shaft, bearings, balls and associated parts.<br><br>Six (6) coal line blockages. The nitrogen makeup to the pulverizing system is only running 0.05 lbm/sec, down from 0.2 lbm/sec a year ago; sealing the valve above the raw coal tank has eliminated most of the leakage in the system. Best overall performance of the coal system in many tests. The pulverizer repairs were apparently successful. A long continuous run of over 88 hours was achieved. |
| Sep 20-26 | LMF5-J | 52.02 | One (1) coal line blockage. Coal tube appears to be plugged between the isolation valve and the disperser plate. |