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THE LOW MOISTURE EASTERN COAL PROCESSING SYSTEM AT THE UTSI-DOE COAL FIRED FLOW FACILITY

TOPICAL REPORT

Prepared by:

Bruce R. Evans
Eddie S. Washington
Marvin E. Sanders

October 1993

The University of Tennessee Space Institute
Energy Conversion Research & Development Programs
Tullahoma, Tennessee 37388

Prepared For The United States Department of Energy

Work Performed Under Contract No. DE-AC02-79ET10815

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COAL FIRED FLOW FACILITY

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ABSTRACT

A low moisture, eastern coal processing system was constructed at the Department of Energy's Coal Fired Flow Facility (CFFF), located at the University of Tennessee Space Institute in Tullahoma, Tennessee, to provide a metered and regulated supply of seeded, pulverized coal to support magnetohydrodynamic (MHD) power generation research. The original system configuration is described as well as major modifications made in response to specific operational problems. Notable among these was the in-house development of the Moulder flow control valve which exhibited marked improvement in durability compared to previous valves used with pulverized coal. Coal processing system performance parameters are discussed. A summary of tests conducted and significant events are included.

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1.0 INTRODUCTION

The purpose of the coal processing system at the Department of Energy's Coal Fired Flow Facility (CFFF) is to provide a metered and regulated supply of seeded, pulverized coal to a magnetohydrodynamic (MHD) combustor. The mixture is burned in the combustor to provide the high temperature, electrically conducting plasma required for the testing of MHD power generating and pollution control components. The coal processing system was originally designed by the Babcock and Wilcox Company (B&W) for use with Illinois #6, a low moisture eastern type coal, and was installed in the CFFF by the Southeastern Engineering and Development Company. Construction was started in January, 1978 and was completed during the third quarter of 1979. The system was used during tests of the Low Mass Flow (LMF) test train from its construction through test LMF4-V in November, 1990. The coal processing system was completely modified prior to test LMF4-W in May, 1991 to handle the higher volatility and moisture content of western coals. The original system design, major system modifications, and historical data relating to the operation of the system while burning Illinois #6 eastern coal over a nine-year period are described below. A chronological summary of eastern coal tests conducted at the CFFF, duration of each test, and significant events appears in Appendix A.

2.0 DESCRIPTION OF THE ORIGINAL SYSTEM DESIGN

The original coal processing system was designed by B&W to represent the type of system that might be installed at a commercial MHD power generating facility using a bituminous coal similar to Illinois #6 (see Table 1).

TABLE 1. Typical Illinois #6 Coal Analysis (Wt.%)

(Raw coal composite analysis on UTSI sample RC89001, 6-6-89)

	Wt%
Moisture	8-10
Other Components (dry basis)	
Ash	10.19
Carbon	71.66
Hydrogen	4.92
Nitrogen	1.54
Oxygen (by difference)	8.86
Sulfur	2.83

As a result, the following performance criteria were established for system design¹:

- Raw coal and seed would be ground to a size of 70% through 200 mesh and dried.
- Coal and seed would be blended before injection into the combustor. The proportion of seed to coal should be variable.
- The coal and seed would be fed to a combustor operating at pressures up to 6 atmospheres at a mixture flowrate of 3.3 tons per hour for 100 hours of continuous operation.
- The coal and seed would also be fed to a combustor operating at pressures up to 8 atmospheres at a mixture flowrate of 9.2 tons per hour for 2 continuous hours of operation.
- The coal and seed would be injected into combustors of various designs through single or multiple feed ports.
- Air would be used as the transport medium. The amount of air injected into the coal and seed would be minimized to improve combustor performance.
- Combustion would be initiated by injection of coal and seed into the combustor at as low a rate as possible, and gradually increased to the nominal flowrate. The system should be capable of an instantaneous start at the nominal steady-state flowrate if necessary.

The overall system designed by B&W to meet these criteria can be considered as two subsystems for: a) coal and seed pulverizing; b) coal and seed delivery ². Each of these is described below. The system is shown schematically in Figure 1 and pictured in Figure 2. System component specifications are tabulated in Table 2.

2.1 Coal and Seed Pulverizing Subsystem

Raw coal is loaded into a hopper at the base of the coal tower and conveyed to a bucket elevator by means of a screw auger. The bucket elevator then transports the coal vertically over eighty feet, to the raw coal storage tank. Potassium carbonate (K_2CO_3) or potassium sulfate (K_2SO_4) seed material is transported by screw auger from a ground level hopper to the raw seed storage tank located on the coal tower. Operation of the raw coal and seed conveyors is controlled by two level detectors in each of the storage tanks. Conveyor operation is initiated when the lower level detector indicates that the tank is empty. As the tank becomes full, the upper level detector stops the tank loading operation. However, due to the moisture absorbing characteristics of the seed material, the shutdown of the seed conveyor is delayed to

FIGURE 1. Schematic of Eastern Coal Processing System

FIGURE 2. Eastern Coal Processing System - Coal Tower

TABLE 2. Eastern Coal Processing System Specifications and Capacities

Component	Manufacturer	Capacity/Specification
Raw Coal Conveyor	Webster Manufacturing Co.	25 tons/hour (50 lb/ft ³ coal)
Raw Coal Tank	Babcock & Wilcox	1400 ft ³ volume; 75 psig design pressure
Pulverizer	Babcock & Wilcox	Model E-35: 9640 lb/hour; 70% through 200 mesh
Pulverizer Motor	Alliance Electric Co.	Louie Allis Model: 75 hp; 300 rpm
Raw Seed Tank	Babcock & Wilcox	150 ft ³ volume; 75 psig design pressure
Seed Weigh Feeder	Merrick Scale Mfg. Co.	Model CF-950: 1 ton/hour (K ₂ CO ₃ or K ₂ SO ₄)
Seed Conveyor	Clemons Elevator Serv Co.	60 ft tubular screw; 6 in diameter
Coal Weigh Feeder	Stock Equipment Co.	8 tons/hour (50 lb/ft ³ coal)
Air Blower	Spencer Turbine Co.	Model #30100-H MOD: 4500 cfm air at 70°F inlet at 90 in. water static pressure
Air Heater	Carl Mayer Corp.	Oil Fired; 4500 cfm air from 70°F to 600°F
Bag Filter	PEDCON	Model No. 96-CTP-144: 4500 cfm air flow at 150°F; 144 bags; 2160 ft ² filter area
Pulverized Coal Reservoir(2)	Babcock & Wilcox	700 ft ³ each volume; 775 psig design pressure
Pulverized Coal Feed Tank	Babcock & Wilcox	900 ft ³ volume; 775 psig design pressure

allow it sufficient time to empty. A panel light in the control room indicates the status of the coal and seed conveyors.

The ratio of seed to coal in the pulverized mixture is set by regulating the flow of each constituent into the pulverizer. Both coal and seed flows are metered with belt type weigh feeders located at the base of their respective storage tanks. The operator selects the desired coal feed rate and percent seed by adjusting the controller set point. The controller will then regulate the operation of the weigh feeders to maintain these values. A change in the coal feed rate will result in a similar change in the seed rate to keep the seed percent constant.

A Babcock & Wilcox E-35 pulverizer (Figure 3) is installed at ground level directly below the coal and seed feeders. The E-35 is a medium speed, ball and race pulverizer consisting of a single row of balls between a stationary upper ring and a rotating lower ring (Figure 4). Grinding pressure is set by adjusting the springs that hold the top ring in position. Raw coal and seed are fed into the grinding zone where they are mixed with partially ground coal. Warm air, supplied by the air blower through the air heater, causes the mixture to circulate through the pulverizer grinding elements until it becomes fine enough to be picked up by the air stream and transported to the bag filter at the top of the coal tower structure. At rated flow, the pulverizer produces a dried coal/seed mixture with a particle size of 70% through 200 mesh.

The temperature of the coal/seed/air mixture at the pulverizer outlet is maintained at 150°F to ensure that the mixture has been sufficiently dried, but is not

FIGURE 3. Babcock & Wilcox E-35 Pulverizer

Scale: |←12"→|

FIGURE 4. Ball Grinding Elements of the Babcock & Wilcox E-35 Pulverizer

hot enough to ignite. For constant coal, seed, and air flow rates, this outlet temperature is regulated by variation of the air inlet temperature in response to changes in coal and seed moisture levels. Air supplied by the blower is routed through or bypassed around the air heater and is blended by means of hot and cold air mixing valves (Figure 5). Since excessive inlet temperatures could damage the pulverizer, the air heater outlet temperature is maintained below 600°F by controlling the fuel and combustion air flow. In the event of high air heater or pulverizer outlet temperatures, loss of coal/seed flow, loss of control air to valves, or loss of electrical power to the valves, the hot air mixing valve will close and both the cold air mixing valve and hot air dump valve will be driven to the full open position. A heater flame detector will cause a shutdown of the heater if combustion air flow is lost.

Pulverized coal and seed are separated from the transport air in the bag filter. The filter is cylindrical in shape and is comprised of 144 dacron bags, 7 inch diameter x 96 inch long. The mixture enters the filter housing tangentially in a cyclonic type flow, depositing coal and seed particles on the outer surface of the bags. Air passes through the bag fabric and exits from the top to the atmosphere. The bags are continuously cleaned by low pressure air directed to the inner bag surface by a rotating plenum (Figure 6). The pulverized coal/seed mixture falls into a conical hopper and passes through a rotary valve to one of the two reservoir tanks.

2.2 Coal and Seed Feed Subsystem

The coal and seed feed subsystem was designed to supply pulverized coal and seed to combustors in the three test bays in the adjacent test building at nominal flow rates of 3.31 tons/hour to Bay #1 continuously for a minimum of 100 hours, and 9.16 tons/hour to Bays #2 and #3 for two continuous hours of operation.

Pulverized coal and seed from the bag filter are stored in the two reservoir tanks installed in parallel between the bag filter and the feed tank. Coal and seed are transported to the test bays from the feed tank by the pressure differential between the feed tank and the combustor. The reservoir tanks, located above the feed tank, are used to refill the feed tank as its contents are depleted. The feed and reservoir tanks are configured to be capable of simultaneously supplying coal to the feed tank from one reservoir, while coal from the bag filter is received by the other reservoir. Transport of coal into and out of the reservoirs and feed tank is regulated by an Allen Bradley programmable logic controller which permits the operation of the 26 system valves (Figure 7) in manual or automatic time sequence modes. Each reservoir has a capacity of approximately 20,000 lbs. The feed tank capacity is 30,000 lbs. All three tanks are ASME rated pressure vessels with a maximum design pressure rating of 775 psig.

The flow of pulverized coal and seed to the test bays in dense phase is regulated by feed tank pressure and supply line size. The low mass flow (3.31 tons/hour) line to Test Bay #1 is 0.75 inch schedule 80 pipe with a minimum bend radius of 1.25 feet. The high mass flow (9.16 tons/hour) line to Test Bay #2 was

FIGURE 5. Pulverizer Hot Air Control System

FIGURE 6. Bag Filter Rotating Plenum

FIGURE 7. Pulverized Coal Reservoir Valve Arrangement

planned to be a 1.5 inch double extra strong pipe with a minimum bend radius of 1.5 feet. Piping is routed from the feed tank to an elevated pipe rack that spans the distance between the coal tower and the test building. The only valves in these lines are shutoff valves. A Micro Motion single tube coriolis meter, installed in the low mass flow supply line measures coal/seed flow (Figure 8). (A high mass flow line originally contemplated has not been installed at the CFFF.)

Provisions were made for two optional supply line components if required. A vertical pick up section can be installed in both supply lines, where the lines rise to the overhead pipe rack, to increase the rate of coal flow during system start up. Also, a distribution device can be installed if a combustor requires multiple feed inlets.

3.0 MAJOR COAL PROCESSING SYSTEM MODIFICATIONS

Several major modifications have been made to the original B&W designed coal processing system in response to specific problems encountered during operation. These modifications are discussed topically below.

3.1 Pulverized Coal Pressurization Gas

During LMF0-2, blistered paint on the fluidizing section of the pulverized coal feed tank was observed, indicating the presence of a fire³. Fluidizing air flow was immediately shut off, the feed tank was inerted with nitrogen, and the external surface cooled with a water spray. Pulverized coal and seed, left in a pile from partially emptying the feed tank, caught fire several days later. In order to determine the cause of this fire, the feed tank was instrumented with thermocouples and a series of pulverizing and transfer operations were conducted. One of these resulted in a fire in the bag filter.

Several bench scale tests were also conducted to study the effect of temperature, pressure, and atmosphere on pulverized coal and coal/seed samples⁴. These tests indicated self heating of the pulverized coal occurred when in the presence of air (oxygen) and pressure. The principal recommendation of these studies was to use nitrogen for pressurization of the feed tank and reservoir tanks, as well as for fluidizing flow. This change was adapted for all subsequent tests.

3.2 Coal Line Blockages

One of the first problems encountered during operation of the coal processing system was that of coal line blockages. The coal tube (the section of coal line that is routed through the vitiation heater, terminating at the coal disperser on the combustor disperser plate) became plugged five times during LMF0-1. A post test analysis concluded that the coal line diameter was too large for the lower coal flow rate used for combined oil and coal firing. A new coal line, one-half the diameter required for coal-

**FIGURE 8. Micro Motion Coriolis Metering Installation
(Under Coal Tower)**

only operation, was installed prior to LMF0-2. At the conclusion of LMF0-2, terminated due to the feed tank fire described previously, the combustor was disassembled and inspected. It was discovered that two of the spiral passages in the coal disperser plug were blocked by a solidified material. Coal flow could not be achieved at all during LMF0-3. Disassembly of the combustor revealed that the disperser plug had burned out and the flow passage was completely plugged. Investigation of this problem indicated that the coal disperser plug was being melted during oil-only operation in the combustor. A test was conducted with an instrumented disperser plug to determine the amount of nitrogen purge flow required to keep the plug below melting temperature. Facility hardware was modified (Figure 9) to automatically purge the coal tube when coal is not flowing. One additional modification was made to the coal disperser by drilling out the solid center section after LMF1D-3 to preclude partial blockage by foreign material such as rust flakes (Figure 10).

A coarse strainer was installed in the coal line to prevent blockages due to agglomeration of pulverized coal and seed particles. The strainer, however, became clogged whenever coal flow was initiated. This single strainer was replaced by parallel duplex strainers to allow cleaning of one of the strainers while continuous flow was maintained through the other to the combustor. The duplex strainers had to be cleaned often during LMF0-3A. Procedures were developed for strainer cleaning and some effort was made to reduce moisture in the coal and seed as much as possible. The LMF0-3B test showed improvement in coal flow, but it was concluded that a method of breaking up the clumps of coal/seed before entering the coal line would be required. A motorized shaker (Figure 11) was installed between the bag filter and the reservoir tanks and tested during LMF1-A. After the removal of the duplex strainers prior to LMF1-B, no further problems with blockages due to coal/seed lumps were encountered.

Throughout the series of LMF tests, blockages of the coal line have occurred for a variety of perceived reasons including foreign objects, high coal moisture content, high seed content in the coal/seed mixture, and irregularities in the supply piping. Many of these irregularities were eliminated when pipe sections and synflex hose sections were replaced by smooth tubing during LMF1A-1 and prior to LMF4-O respectively. A summary of coal line blockages (not including blockages due to melting of the coal disperser tube) can be found in Figure 12.

3.3 Nitrogen Pressurizing System Interface

The nitrogen system is used for pressurization of the feed tank and reservoirs, transport of the pulverized coal/seed mixture to the combustor, for instrument purges, and a purge of the entire test train when tests are completed. Reservoir A was inadvertently pressurized during LMF3-B2c through the nitrogen fluidizing valve 8A (Figure 12). The valve was partially open even though the control panel indicator showed the valve closed. This condition went unobserved during the test since coal transfer operations were not taking place. At the conclusion of the test, as the nitrogen system pressure was vented through the test train, the pressure in reservoir A forced

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FIGURE 9. Nitrogen Injection Coal Disperser

FIGURE 10. Helical Coal Disperser

FIGURE 11. Bag Filter Shaker

FIGURE 12. Coal Line Blockages Per Hour on Coal

approximately 9000 lb of the pulverized coal/seed mixture through the partially open valve, and the nitrogen system piping, and into the test train. Action taken to preclude another incident of this type included: a) pretest checkout of controls, valves, and indicators; b) installation of a check valve in the nitrogen supply piping to the coal system; and c) expanded preventative maintenance procedures for coal system control components and instruments.

3.4 Coal Storage Tank Operation Control

Control functions for the original Allen Bradley programmable logic controller system were limited to on/off sequencing and programmable timer functions. It was determined during checkouts, however, that satisfactory automatic control of the coal feed subsystem required analog voltage I/O and a high level programming language capability for logic functions and flow calculations. The Allen Bradley system was replaced by manually operated relay logic. The coal system was operated using manual control for discrete functions and automatic control for analog functions. The CFFF Data General computer data acquisition system was used to provide operator feedback of control system variables and safety system alarm monitoring.

3.5 Flow Control

In the original B&W design, pulverized coal and seed were conveyed in dense phase from the feed tank to the combustor utilizing a small amount of fluidizing air (11-13 scfm) introduced at the feed tank outlet (fluidizing air was later eliminated to improve flow stability). Flow was controlled by line size and regulation of feed tank pressure. As stated above, the original 0.75 inch, schedule 80 pipe was replaced after LMF0-1 with 0.75 inch, schedule 160 pipe, and this replaced by 0.75 x 0.065 inch stainless steel tubing during LMF1A-1. Additional problems with flow control encountered during LMF1C-2 and LMF1C-5 resulted in the installation of a sized flow restrictor at the end of the 0.75 inch supply tube. Due to continuing problems with erratic coal flow, a study was conducted after LMF1D-3 to define improved flow control techniques. A remotely controlled, 1.27 inch ball valve was installed in the coal line, successfully tested, and used for the remainder of the LMF1D and LMF1E series of tests.

Prior to the LMF3 test series, the ball valve was replaced by a Clarkson pinch valve (Figure 13). In the pinch valve, a venturi shaped elastomer sleeve is constricted pneumatically, resulting in a smooth, round, and variable flow passage. Although the pinch valve provided improved flow control, abrasion of the elastomer sleeve by coal particles made replacement of the sleeve necessary after approximately 20 hours on-coal. A more durable control valve was designed by Mr. Edward Moulder of the UTSI staff. The Moulder valve (Figure 14) utilizes two rollers (Figure 15) with variable area, semicircular grooves machined around one-quarter of the circumference of each roller. As the rollers are rotated through a 90 degree arc, the circular flow passage is increased or decreased. The rollers are made of hardened 440C stainless steel and have a service life of hundreds of hours on-coal. The Moulder valve was first installed

THROTTLING ACTION

FIGURE 13. Clarkson Pinch Valve Throttling Action

FIGURE 14. Moulder Coal Flow Control Valve

FIGURE 15. Moulder Valve Rollers and Roller Housing

prior to LMF4-J and has demonstrated satisfactory performance for every subsequent LMF test.

4.0 COAL PROCESSING SYSTEM PERFORMANCE

The overall successful performance of the eastern coal processing system can be summarized by stating that pulverized coal and seed were provided for over 2250 hours of LMF series tests. This system was designed to represent the type of system that might be used in a commercial MHD power generating facility. While the pulverizing subsystem utilizes conventional equipment and practices, the coal feed subsystem does not. 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 characterized by 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. Since dense phase transport has not been studied extensively, some discussion of factors related to performance are appropriate.

4.1 Flow Measurement

A Micro Motion single tube coriolis meter has been used to measure coal and seed flow in every CFFF test. This meter consists of a U-shaped tube clamped at the ends which is vibrated at a constant frequency. The mass of pulverized coal/seed mixture moving at a velocity through the tube, which is oscillating with a peak angular velocity, produces a coriolis force perpendicular to two velocities. The forces generated in each leg of the tube are of equal magnitude and opposite direction. The resulting moment produces an angular deflection of the tube about the central axis that is measured optically. This angular deflection is proportional to the mass flow⁵.

Prior to installation in the coal feed system, a study⁶ was conducted to evaluate the Micro Motion coriolis meter with respect to operating characteristics under various pressure and flow conditions, and to develop meter flow calibration methods. The study concluded that the meter was suitable for the measurement of dense phase coal/seed flow over the range of anticipated run conditions at the CFFF.

The calibration method developed for the study consisted of weighing the amount of coal/seed mixture flow through the meter during an interval of time and comparing it to the meter voltage output. This calibration setup (Figure 16) was used through LMF1-C6 when an improved coal calibration tank (Figure 17) was fabricated. The new tank featured weight measurement by load cell and the ability to be backpressured to simulate actual combustor pressures. Calibration methods were also

FIGURE 16. Original Coriolis Meter Calibration Test Setup

FIGURE 17. Improved Coriolis Meter Calibration Test Setup

revised at this time to include computer control of flow times. A typical coriolis meter calibration curve is shown in Figure 18.

Throughout the LMF series of tests on eastern coal, one or more Micro Motion single tube coriolis meters were installed in the coal line as the primary means of measuring coal flow. Generally the meters have given good service and the calibration curves have been reasonably consistent (Figure 19). There have been instances during tests, however, when changes in test train parameters (with no change in measured coal flow) have indicated a step shift in meter output. Various theories have been advanced as to the causes of these apparent shifts, but none of the theories have been proven to date. In an effort to improve coal flow measurement, coriolis meters manufactured by Neptune, Smith, and Endress & Hauser were evaluated as a possible replacement to the Micro Motion meter. These meters were all of the newer dual tube design, but produced an erratic output signal that was impossible to relate to levels of coal flow.

Coriolis meter coal flow measurements have been periodically verified by comparison to flow rates manually calculated from changes in feed tank weight over a known period of time. The measured and calculated flow rates have generally been in good agreement considering the uncertainties in feed tank load cell data and coriolis meter output. The flow rate comparison shown in Figure 20 for the LMF4-U test is representative.

Using the UTSI automated data acquisition system, a computer program was written that continuously calculates coal flow from the change in feed tank weight over a known period of time. Since the output signal of feed tank load cell fluctuates due to external vibration from operation of the coal processing system, the program uses an average of the first and last 32 data samples in a 3072 second period as the initial and final weights of the time period. Coal flows are frozen for 3072 seconds every time the feed tank is refilled before the calculated flow rate is again updated. During tests, coal flows calculated in this manner generally track well with coriolis meter output.

4.2 Coal Particle Size Distribution

The Babcock and Wilcox Type E pulverizer installed at the CFFF was designed to produce a coal size of 70% through 200 mesh when operating at base capacity. Pulverizer coal particle size distribution can be verified by sieve analysis performed in accordance with ASTM D197-87. Sieve analyses were not routinely conducted during periods of pulverizer operation, however, and much of the available early data are suspect. Valid sieve analyses were performed for feed tank composite coal samples obtained during LMF4-H and LMF4-I and particle size distribution for these two tests closely bracket the 70% through 200 mesh requirement (Figure 21).

FIGURE 18. Typical Coriolis Meter Calibration Curve
(Micro Motion Serial No. 2263928)

FIGURE 19. Composite Coriolis Meter Calibration for Micro Motion Serial No. 22639 (LMF4-O through LMF4-V)

**FIGURE 20. Comparison of Coal Flow by Coriolis Meter and Feed Tank Weight
(Data from LMF4-U)**

FIGURE 21. Pulverized Coal Size Distribution

4.3 Coal Moisture

One criteria for measuring the performance of the eastern coal processing system is the capability to dry coal during the pulverization process. Experience gained during the LMF series of tests indicates that excessively moist coal (greater than 5%) is more difficult to flow in dense phase and more likely to result in a blockage of the coal line. Illinois #6 coal has consistently been dried at the CFFF from a moisture level of 8-10% to less than 4%. The average moisture for feed tank coal samples is shown in Table 3 for the last six eastern coal tests.

TABLE 3. Feed Tank Coal Sample Moisture

Test	Number of Samples	Average Moisture (wt%)	Standard Deviation
LMF4-Q	20	2.81	0.23
LMF4-R	150	2.40	0.45
LMF4-S	62	2.99	0.34
LMF4-T	127	3.15	0.43
LMF4-U	128	3.28	0.32
LMF4-V	111	3.46	0.45
Average	597	3.02	0.55

4.4 Coal Flow Stability

The ability to maintain steady test conditions profoundly affects the quality and usefulness of the test data acquired. Since combustion of pulverized coal is the primary thermal input into the LMF test train, the stability of coal flow is a significant parameter.

Evaluation of coal flow stability is complicated, and appears to be affected by a variety of factors including feed system geometry, flow rate, feed tank pressure, combustor pressure, seed content, moisture, and void fraction. The CFFF coal transport line is sized to obtain line velocities of 10-15 ft/sec. Test experience and mathematical analysis⁹ at UTSI indicate that velocities in the 10-15 ft/sec range will result in more stable flow. Primary indicators of stability are the outputs of the installed coriolis meters, coal line pressure transducers, and the AuburnTM Two-Phase Flow Analyzer. This instrument measures the relative dielectric constant of a two-phase mixture and gives a measure of the volume fraction of the mixture. A rotating sensor field automatically compensates for non-homogeneity of the sample⁷. Secondary indicators include many downstream test train temperatures.

A recent study of the CFFF coal feed system used high frequency measurements to examine dynamic behavior of line pressure, flow rate, and volume fraction measurements during normal system operation⁸. Coal flow fluctuation levels

were calculated for both coriolis meter and line pressure transducer output during a portion of the LMF4-P test. Among other things, the study concluded that: 1) accurate coal flow rates can be measured by coriolis mass flow meters; 2) fluctuations in the coal flow rate are greatest toward the combustor end of the feed line; 3) coal flow fluctuations are not ergodic over 10 second intervals and are not well correlated; and 4) pressure signals in the line have a high degree of correlation with each other.

In an effort to provide an indication of coal flow stability over the operational life of the eastern coal processing system, the standard deviation of coriolis meter output was calculated for a period of time during each test and is shown in Figure 22. Beginning with the LMF1D series, it can be seen that the standard deviation levels are fairly consistent. Although the selection of the data blocks was somewhat arbitrary, an attempt was made to choose representative periods of coal flow for each test when the control system set point was constant. A further caveat, with respect to these data, is that three different Micro Motion coriolis meter models have been used at the CFFF, and records as to which meter was used in a specific location during a particular test are incomplete. It would be expected that the electronics in a newer model would exhibit a lower level of fluctuations than an older model.

Prior to the LMF1D-2B test, a low bypass filter was installed to reduce fluctuations in the coriolis meter voltage output signal, thereby, stabilizing, to some extent, the indicated coal flow measurement. Figure 23 compares the standard deviation of filtered and unfiltered coriolis meter output using the same data blocks as above. As expected, the standard deviation of the filtered signal is lower than the corresponding signal in each case. As a point of comparison for several of the coal flow measurements used with the eastern coal processing system, statistical data for two different coriolis meters and the coal flow calculated by feed tank weights for a one hour period during LMF4-U is presented in Table 4. The lowest level of fluctuation (standard deviation) is for the newer coriolis meter using a filtered signal, while the highest fluctuation level is for the coal flow calculated from feed tank weights.

TABLE 4. Statistical Comparison of Coal Flow Measurements

	Micro Motion Model B Filtered Output CH 36 [lbm/sec]	Micro Motion Model B Unfiltered Output CH 38 [lbm/sec]	Micro Motion Model D Filtered CH 2172 [lbm/sec]	Feed Tank Weight Change CH 2588 [lbm/sec]
Points	1201	1201	1201	1201
Minimum	0.864	0.802	0.883	0.784
Maximum	0.953	0.955	0.937	1.032
Mean	0.918	0.912	0.910	0.899
Median	0.917	0.915	0.912	0.894
RMS	0.918	0.912	0.910	0.900
Std Deviation	1.136e-2	1.140e-2	7.200e-3	4.628e-2
Variance	1.290e-4	1.967e-4	5.184e-5	2.142e-3

Note: Data are from LMF4-U on 8/11/90 from 01:00:00 to 02:00:01

FIGURE 22. Comparison of Standard Deviation of Unfiltered Coriolis Meter Output

FIGURE 23. Comparison of Filtered and Unfiltered Coriolis Meter Output

5.0 SUMMARY

The original eastern coal processing system was installed at the CFFF to supply a metered and regulated quantity of pulverized coal and seed to a magnetohydrodynamic (MHD) combustor. The system was successfully operated for over 2250 hours of MHD testing prior to reconfiguration for western coal after LMF4-V. Major modifications were made to the original system design in response to specific operational problems. These included:

- the replacement of air with nitrogen as the pressurization gas to prevent feed tank fires;
- installation of a shaker below the bag filter to break up clumps;
- installation of a purge to keep the combustor coal line clear when not flowing coal; and
- development of the Moulder valve to regulate coal flow.

The most significant results observed during operation of the CFFF eastern coal processing system are:

- The system has demonstrated the ability to maintain stable flow conditions for extended testing periods.
- Illinois #6 coal has consistently been dried from a moisture level of 8-10% to less than 4%.
- Particle size distributions have closely bracketed the 70% through 200 mesh requirement set during system design.
- Micro Motion single tube coriolis meters have been used with good result to measure pulverized coal flow in all tests at the CFFF. Methods and hardware were devised to accurately calibrate the coriolis meters and a computer program was written to calculate coal flow from feed tank weights.

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APPENDIX A

SUMMARY OF LOW MOISTURE EASTERN COAL TESTS

**LOW MOISTURE EASTERN COAL PROCESSING SYSTEM
OPERATIONAL SUMMARY**

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
<u>1981</u>			
Mar 21	LMF0-1	1.07	Coal tube plugged 5 times. (hypothesized causes were seed agglomeration in the coal, large coal particles not completely pulverized, debris in feed tank, or discontinuity where the 0.5 inch coal line connects to the 0.75-inch coal tube). Difficulty in setting flow rates due the coal tube being designed for 4 times the flow attempted. The coal tube was dislodged from the disperser plate during preheat. Friction fit was modified for more positive clamping action.
Apr 9	LMF0-2	1.18	<p>Coal line that had a flow area 1/2 half of previous configuration installed prior to test. Test was terminated due to coal combustion in the bottom of the feed tank.</p> <p>Study to determine the cause of the feed tank fire during LMF0-2. There was a question as to whether the feed tank fire was caused by chemical reaction of the K_2CO_3 seed with the coal or self heating of the coal in the presence of the pressurizing and fluidizing air.</p> <p>METHOD & RESULTS: a) feed tank instrumented with thermocouples. Using a 80% coal-20% seed mixture, the temperature rise in the feed tank was measured with several weights of coal in the feed tank and at various air pressures. b) Bench scale tests showed temperature rise with air for certain initial temperatures at elevated temperatures. Little temperature rise with nitrogen.</p> <p>CONCLUSION: Use nitrogen for feed tank pressurization and fluidization.</p>

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
Jul 1	LMF0-3	0.65	Coal Flow was not achieved during initial test due to burned out coal disperser plug (caused by burning oil in combustor during periods of no coal flow). Test performed to determine amount of nitrogen purge required to prevent damage to coal tube during periods of oil only operation. The facility was modified to provide automatic purge of coal tube during oil only operation. Coarse coal line filter replaced by duplex wire strainer (set up so that one strainer could be used while the other one is cleaned).
Jul 22	LMF0-3A	2.28	Line strainers worked but had to be cleaned often (every 5 minutes toward the end of the test). Procedures developed for strainer cleaning, and effort made to reduce moisture in coal/seed mixture as much as possible.
Aug 5	LMF0-3B	2.70	Test showed some improvement in coal flow but coal/seed clumps still a problem. A shaker device was installed between the bag filter and the reservoirs to break up clumps.
<u>1982</u>			
Feb 12	LMF1A-1	0.22	0.75 inch, sch 160 pipe used for coal line was replaced by 0.75 x 0.065 inch stainless steel tubing resulting in a smoother flow passage and coal line velocities of 10 to 20 ft/sec. This reduced coal line blockages and provided in smoother flow. Coal line duplex strainers removed after test.
Feb 19	LMF1A-2	0.00	
Apr 7	LMF1A-3	0.00	
Apr 22	LMF1A-4	0.08	
Apr 30	LMF1A-5	1.12	First successful transfer of coal from a reservoir to the feed tank while testing on coal.
May 27	LMF1A-6	2.88	
Jun 8	LMF1A-7	2.65	
Jun 18	LMF1C-1	4.13	

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
Aug 24	LMF1C-2	3.77	Baghouse fire during pretest pulverizing required the replacement of the bags. It is believed that the fire was caused by inadvertently flowing 1200 lb. of wet coal/seed mixture into the baghouse one week prior to the test. It appears that this mixture collected on the bags and the sides of the baghouse and then self ignited when 160°F pulverizer outlet air was blown into the baghouse when pulverizing was started. Operational procedures were revised to prevent wet coal/seed from being fed to the baghouse. Some problems due to improperly sized coal line configuration; restrictor installed at the end of the coal line.
Sep 10	LMF1C-3	3.77	
Sep 17	LMF1C-4	2.92	
Oct 8	LMF1C-5	3.77	Some problems due to improperly sized coal line configuration; restrictor installed at the end of the coal line.
Nov 16	LMF1C-6	6.90	Previous coal calibration method: flow into a bucket. Prior to LMF1D tests a new calibration set-up was installed which included: a) coal calibration tank with load cell and ability to backpressure tank; b) computer control of calibration times. Coal meter calibrated prior to LMF1D tests and during tests. Most calibration curves were slightly different. Coal flow as indicated by the meter was lower than the level indicated by gas analysis and secondary combustor temperatures. Coal flow study conducted. Results: a) It was determined that fluidizing flow would be used only to initiate coal flow and then turned off. Fluidizing flow tended to have a destabilizing effect on flow; b) Pressurize feed tank from top rather than from the bottom. This is faster and appears to result in smoother flow.
<u>1983</u>			
Apr 12	LMF1D-1A	1.70	
Apr 15	LMF1D-1B	6.96	Erratic coal flow. Rust scale found lodged in flutes of coal disperser. Perceived 10% error in coriolis meter.

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
May 12	LMF1D-2A	1.73	Sieve (0.1875 in openings) installed in bottom of feed tank prior to 2A. Erratic coal flow due to blockage of sieve in the bottom of the feed tank. Sieve removed at end of test.
May 19	LMF1D-2B	8.02	In-line sieve installed in coal line at inlet to vitiation heater prior to 2B. Two coal line plugs during test. In-line sieve removed during test. Smooth coal flow for the remainder of the test. Rust scale again found lodged in one of the coal disperser flutes.
Jun 2	LMF1D-3	5.04	Erratic coal flow experienced. Test train shutdown to unplug disperser flutes. Coal flow study conducted. Results: a) 0.75 inch coal line; b) Remotely controlled 1.27 cm ball valve installed at inlet to coal tube to allow variation of flow rate without changing the coal line configuration (previously, coal flow was varied by feed tank pressure changes, a very slow process); c) Coal disperser center body drilled out to prevent plugging. Nitrogen injection was added to compensate for the reduced dispersion angle. This new configuration was tested in plexiglas enclosure and proper coal dispersion observed. It was observed that meter shifts were induced by twisting forces transmitted to the coriolis meter each time the fittings to the meter were retightened. This was resolved by isolating the coriolis meter end connections. No subsequent shifts observed in the LMF1D/E test series.
Jul 15	LMF1D-4	5.00	Improved coal flow program and nitrogen coal disperser worked well
Jul 20	LMF1D-5A	5.60	Unstable coal flow due to obstruction at feed tank. (Thermocouple bundle lodged in the top of the pick-up tube at the bottom of the feed tank).
Aug 8	LMF1D-5B	5.95	Stable coal flow.
Aug 10	LMF1D-6A	3.01	
Aug 19	LMF1D-6B	5.43	
Sep 8	LMF1E-1	5.94	
Sep 15	LMF1E-2	5.71	Smooth, stable coal flow.

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
Sep 22	LMF1E-3	6.27	Rough, unstable coal flow. (Due to restrictions caused by over-tightening of Swagelok® fittings).
			The 1.27 cm ball valve was replaced by a Clarkson pinch valve prior to the LMF3 test series.
<u>1984</u>			
	LMF3-A1	0.00	
	LMF3-A2	0.00	
Aug 2	LMF3-A3	1.96	
Sep 27	LMF3-B1	6.88	
Oct 25	LMF3-B2a	2.80	
Nov 15	LMF3-B2b	7.91	
Dec 6	LMF3-B2c	0.20	Reservoir A was inadvertently pressurized during the test by means of the reservoir fluidizing valve 8A. The valve was partially open although the control panel indicator showed the valve closed. At the end of the test, as the nitrogen system was vented through the test train, the pressurized reservoir forced pulverized coal through valve 8A into the nitrogen system and the test train. Action taken to preclude another incident of this type included: a) pretest checkout of all controls and indicators; b) a check valve was installed in the nitrogen supply line to the coal system; c) expanded preventative maintenance procedures for coal system instrumentation and controls.
<u>1985</u>			
May 31	LMF4-A	3.60	
Jul 12	LMF4-B	6.30	The coal tube nitrogen solenoid valve failed to close when coal flow was initiated. Approximately 50-60 SCFM was injected through the coal tube for the entire test period on coal. The feed tank was inadvertently depressurized during transfer of coal from a reservoir.
Aug 1-2	LMF4-C	16.30	
Nov 7	LMF4-D	7.30	
Dec 11	LMF4-E	9.10	

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
<u>1986</u>			
Apr 2	LMF4-F	0.00	(Oxidizing air compressor checkout)
Apr 29	LMF4-G	2.03	(Western coal)
Jun 5	LMF4-H	14.04	(Western coal) Modification of the bulk seed handling system was completed prior to the test. In the original B&W installation, seed material was manually loaded into a hopper located in the seed drum storage building, and then conveyed to the raw seed tank by means of an auger. In the modified system, seed is pneumatically loaded from a truck into a storage tank located at the base of the coal tower, and then augered to the raw seed tank.
Aug 18	LMF4-I	77.28	
<u>1987</u>			
Jul 29	LMF4-J	5.77	Clarkson pinch valve replaced by Moulder valve prior to test. Binding of the Moulder valve experienced during the test (stainless rotors to stainless casing). This was remedied by machining 1/16 inch from the casing walls and teflon seals installed.
Aug 23 - Sep 5	LMF4-K	198.33	Blockage of seed weigh feeder rotary valve caused incorrect coal/seed mixture for the last 1.5 days of the test. Perceived drying problem.
4th Qtr			Modifications to the seed weigh feeder included utilization of a new belt material, installation of new belt guides and belt tensioning device, and the installation of a 2-inch heated air line from the pulverizer inlet to the seed weigh feeder to reduce moisture absorption and caking.
Dec 2-6	LMF4-L	63.34	Erratic behavior of the coriolis meter (twice indicated loss of coal flow when coal was still flowing). Plugging of bag filter may have been due to the venting of nitrogen through the bag filter. Separate bag for venting proposed.

<u>DATE</u>	<u>TEST</u>	<u>TIME ON COAL (HRS)</u>	<u>SIGNIFICANT EVENTS</u>
<u>1988</u>			
Feb 2-19	LMF4-M	56.55	<p>Erratic behavior of the coriolis meter. Meter returned to manufacturer for service after the test. Chip on seed weigh feeder was replaced during the test (was giving erroneous belt speed). Blockage of feed chute to pulverizer caused by leakage of cool, moist air into the feeder through a partially opened valve. The coal line plugged 5 times during the test.</p> <p>Installed teflon liner in seed feeder inlet chute to reduce the effects of condensation on seed flow. Returned three Micro Motion coriolis meters to the manufacturer for reconditioning.</p>
Apr 26 - May 8	LMF4-N	184.60	<p>Erratic behavior of the coriolis meter throughout the test. The meter readings did not track well with feed tank weights and superheater test module temperatures. Coal line blockage due to screw head becoming lodged in the Moulder valve. The coal weigh feeder motor was overheating during the test (high current demand); the power supply was replaced. The motor armature was rewound after the test. There were some indications that the new coal pile contained a greater quantity of fines which resulted in higher moisture levels in the pulverized coal/seed mixture.</p>
Aug 15 - Sep 2	LMF4-O	252.10	<p>Synflex hoses in the coal line replaced by hard tubing prior to the test. Coal flow was generally smoother than in the previous three tests. Pulverizer belts and a bearing in the seed auger gear box were replaced during the test. The coal auger jammed once. The coal weigh feeder motor was overheating during the test; a fan was used to cool it.</p>
Nov 8-12	LMF4-P	101.30	<p>The chute between the coal weigh feeder and the pulverizer clogged once. The coal weigh feeder motor overheated due to high current (the cover was removed for the remainder of the test).</p> <p>Construction of raw coal storage slab and drain system was completed. (This will prevent contamination by dirt and rocks)</p>

DATE	TEST	TIME ON COAL (HRS)	<u>SIGNIFICANT EVENTS</u>
<u>1989</u>			
May 29 - Jun 1	LMF4-Q	40.84	Discrepancy noted between calculated seed percentage on the display screen and the results of chemical analysis. The seed feeder calibration was verified and coal samples reanalyzed (same result). Some damage to coal nozzle noticed after the test. Three coal line blockages.
Aug 16 -31	LMF4-R	263.38	Generally smooth coal flow. The two coriolis meters tracked well together and with gas sampling and pulverizing data (except for one 3-hour period).
Nov 29 - Dec 8	LMF4-S	134.63	4 coal line blockages experienced after coming back on line from shutdown due to cold weather. Coal system valves 4A, 4B, & 2A operated sluggishly and required manual assistance at temperatures below 20°F. Boot rupture due to inadvertent pressurization of reservoir with valve to feed tank open.
<u>1990</u>			
May 29 - Jun 12	LMF4-T	216.88	1 coal line blockage. The coal/seed chute from the weigh feeders to the pulverizer plugged once. One documented coriolis meter shift. The secondary meter at some point was reading 4.08 lbm/sec coal flow. Appeared to be good agreement between primary coriolis meter coal flow and coal flow calculated from feed tank weights.
Jul 30 - Aug 13	LMF4-U	251.55	2 coal line blockages.
Nov 6-16	LMF4-V	240.50	2 coal line blockages. The Alkon moisture meter was installed near the bottom of the coal system baghouse. The meter appears to give good readings if the rotary valve is shut off for three minutes so that coal can accumulate on the sensor. Good agreement between primary coriolis meter and coal flow calculated from FT weights.
<u>1991</u>			
May 4-11	LMF4-W	85.77	Western coal modification made prior to the test.

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