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**FINAL REPORT
PROOF OF CONCEPT TESTS OF THE
MAGNETOHYDRODYNAMIC STEAM-BOTTOMING SYSTEM
AT
THE DOE COAL-FIRED FLOW FACILITY**

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I. EXECUTIVE SUMMARY

The development of coal-fired magnetohydrodynamic (MHD) power can be viewed as consisting of two parts; the topping cycle and the bottoming cycle. The topping cycle consists of the coal combustor, MHD generator and associated components. The bottoming cycle consists of the heat recovery, steam generation, seed recovery/regeneration, emissions control (gas and particulate), ash handling and deposition, and materials evaluation. The report concentrates on the bottoming cycle, for which much of the technology was developed at the University of Tennessee Space Institute (UTSI).

Because of the complexity of the required technology, a number of issues required investigation. Of specific concern regarding the bottoming cycle, was the design of the steam cycle components and emissions control. First, the high combustion temperatures and the use of large quantities of potassium in the MHD combustor results in a difference in the composition of the gases entering the bottoming cycle compared to conventional systems. Secondly, a major goal of the UTSI effort was to use a variety of coals in the MHD system, especially the large reserves of high-sulfur coals available in the United States.

The Department of Energy developed a "Coal-Fired MHD Preliminary Transition and Program Plan" in 1984 and followed this with an MHD program plan in 1988. One outcome of these plans was the initiation of proof-of-concept (POC) testing.

The first POC test at the Coal-Fired Flow Facility (CFFF) located at UTSI was completed in August 1987 while burning Illinois No. 6 coal for a total of 198 hours. At the conclusion of the Illinois No. 6 POC tests, more than 2687 hours of operation had been accumulated on the low mass flow (LMF) test train at the CFFF. After completing the POC test objectives for the Illinois coal, preparations were made to test Rosebud coal from eastern Montana.

This report will describe the Rosebud coal POC program and the major equipment modifications made on the system. It will also present the results and conclusions of tests with both coals, with emphasis on the differences in performance observed between the two coals.

More than 2000 hours of POC testing were successfully accumulated while firing Illinois No. 6 coal and nearly 1050 hours while firing Rosebud coal. Base test conditions were similar for both coals.

Significant differences in moisture, reactivity and mineral matter composition between the Illinois and Rosebud coals required equipment modifications and led to operating differences. Significant effects are summarized below.

The coal preparation system, modified to produce a dry, pulverized coal in an inert atmosphere while pulverizing the higher moisture, more reactive Rosebud coal, performed very well. It produced a satisfactory coal particle size while providing a uniform coal feed rate.

During the Illinois No. 6 coal tests, the seed and coal were mixed in the pulverizer. This approach worked well, but desired changes in the mixture ratio to the combustor were difficult to achieve. This was due to the long residence time and the mixing that occurred in the storage and feed tanks. The system used for the Rosebud tests, a 47% solution of K_2CO_3 injected with No. 2 fuel oil into the combustor, worked well. This system provided more precise control and the flow rate can be adjusted instantly. This approach does reduce the combustion temperature somewhat. However, it could be adapted to feed a potassium formate solution (from a seed reprocessing plant) or molten liquid to overcome the temperature reduction.

In spite of very high levels of oxides of nitrogen (NO_x) generated in the combustor, emissions from the combustion of both coals (Illinois No. 6 and Rosebud) were controlled to levels well below New Source Performance Standards (NSPS) requirements. Levels were slightly higher for the Rosebud coal, which was attributed to the lower sulfur content (see Reference 22 for additional detail). Sulfur dioxide emissions can be eliminated for all practical purposes by operating with sufficiently high K_2/S levels. The sulfur dioxide (SO_2) levels were generally under NSPS requirements with potassium to sulfur (K_2/S) ratios of about 1.4 and above.

Particulate emissions for the Rosebud were finer, about $0.5\ \mu m$, compared to about $0.8\ \mu m$ for the Illinois coal. The baghouse effectively reduced particulate emissions to levels well below NSPS and Combustion 2000 goals, with emissions as low as 0.0003 and 0.0006 lb/MBtu measured for the Rosebud and Illinois coals, respectively. The dry ESP improved significantly after smaller diameter electrodes, recommended by our consultant, ADA, Inc., were installed. Although the dry ESP met NSPS requirements and original Combustion 2000 goals throughout the program, performance was much more consistent after the electrodes were changed. The complete wet ESP system was not evaluated until the LMF5G test, near the end of the Rosebud coal tests. It met NSPS requirements with 21% of the total flow passing through it and Tennessee regulations with nearly 100% of the gas flow. Time was not available to fully evaluate the wet ESP system, but we believe this system can meet emission regulations. Furthermore, it has a number of advantages in an MHD system using a seed reprocessing approach with a slurry/solution input.

Ash deposition was well controlled during testing of both coals, even though gas lanes were smaller than conventional commercial systems. The coal type had a significant effect on deposit characteristics. The Rosebud coal conditions produced a characteristic blue deposit in the superheater high temperature module (SHTM) tube banks. Although the presence of this material did not adversely affect ash deposition, future work should include a study of the formation and possible effects of this material. Also, because reactions involving solids are very slow, ash deposition should be carefully monitored during controlled conditions over long periods of continuous operation if MHD development is ever reinstated.

Corrosion resistance of metal alloys with potential application in superheaters and intermediate-temperature air heaters increased with increasing chromium content during tests with both coals. During the Rosebud tests, alloys with 20-21% Cr and high chromium to nickel ratios, performed as well as or better than other alloys with higher chromium content but lower Cr/Ni ratios. Four alloys, 316, 304, 253MA and 310, tested with both coals showed considerably lower corrosion with Rosebud coal as compared to Illinois coal, which was attributed to the lower Rosebud sulfur content. However, the corrosion data should be used carefully, because of the differences in test times.

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II. INTRODUCTION

The development of magnetohydrodynamic (MHD) technology has been underway for a number of years. The University of Tennessee Space Institute (UTSI) began work on this subject more than 30 years ago. The first UTSI publication of the results of a diagonal-conducting-wall generator experiment was issued in 1964. Investigators here made significant progress in this technology while testing at UTSI facilities of about 7.5 and 15 megawatt input ratings. UTSI also was one of the first organizations to recognize the need to develop the technology required for designing the steam bottoming cycle for an MHD system, and to investigate pollution concerns and develop techniques for controlling emissions.

There were several major reasons for the concern about designing steam cycle components and emissions control. First, the high combustion temperatures and the use of large quantities of potassium in the MHD combustor would lead to dramatic changes in the composition of the gases entering the bottoming cycle as compared to conventional systems. This, in turn, would affect ash deposition and thus heat transfer, materials performance (corrosion of metals and ceramic materials used in the system) as well as the selection and performance of the particulate control approaches. Second, the very high combustion temperatures produce very high levels of nitrogen oxides, an order of magnitude or more higher than allowed under the NO_x emission rules in effect at that time, especially when operating at or near the conditions planned then. Finally, a major goal of the UTSI effort was to use a variety of coals in the MHD system, especially the large reserves of high-sulfur coals available in the United States.

Under the sponsorship of the Department of Energy, the Coal Fired Flow Facility (CFFF) was built to develop MHD technology and dedicated in 1980. Components were added sequentially over a period of time for budgetary as well as technical reasons. The Department of Energy developed a "Coal-Fired MHD Preliminary Transition and Program Plan" in 1984 and followed this with an MHD program plan in 1988. One outcome of these plans was the initiation of proof-of-concept (POC) testing. The POC effort was to be carried out at three locations for the three major subsystems; the topping cycle, the bottoming cycle and the seed regeneration

cycle.⁽¹⁾ The Coal Fired Flow Facility at UTSI was chosen for the steam bottoming cycle POC testing. The first POC test at the CFFF was completed in August 1987 while burning Illinois No. 6 coal for a total of 198 hours. By November, 1990, 12 more tests and more than 2000 hours of POC testing with Illinois coal were completed. Another test using Illinois coal was completed later under conditions simulating those chosen for a retrofit design plant, Plant Scholz at Gulf Power. At the conclusion of this test more than 2687 hours of operation had been accumulated on the low mass flow (LMF) test train at the CFFF. The Illinois No. 6 coal POC tests were identified as LMF4 tests. The highlights for these tests are summarized below:⁽²⁾

1. *The Low Mass Flow test components were operated for more than 2000 hours while firing Illinois No. 6 Coal. More than 3600 tons of coal were burned during this time and more than 700 tons of slag, ash and spent seed were generated.*
2. *Although the UTSI objective was development of the downstream components, it was necessary to operate MHD components to produce a suitable combustion gas for the downstream. We achieved reliable operation of the combustor, nozzle, diffuser, and the aerodynamic duct used to simulate the MHD generator. These components were required to provide downstream conditions that were representative of larger scale MHD systems. A TRW combustor segment also was successfully tested.*
3. *About 70% of the coal ash constituents were tapped in the primary furnace, just downstream of the diffuser exit, under atmospheric pressure conditions. About 12-15% of the potassium fed with the coal was combined with the slag, but techniques were developed, as part of another program, to readily remove this potassium from the slag, fly ash and insoluble portion of the ash/seed mixture. This process integrated well into almost all seed regeneration processes being considered.*
4. *Major achievements in the POC program at UTSI were in the area of pollution control, in spite of major challenges that existed at the beginning of the program:*
 - *Even though several thousand parts per million of nitrogen oxides are generated by the high temperatures required for MHD, experimental results and kinetic modeling indicated that NO_x emissions of only 1/10 of the NSPS limit, could be*

achieved through control of combustion conditions. In fact, NO_x levels are well below those obtained in many current Clean Coal Programs with virtually no carbon loss.

- Sulfur dioxide was controlled to levels well below NSPS limits. SO_2 emissions could be completely eliminated with K_2/S ratios of about 1.4 and higher.
- Although the average particle size was only $0.8 \mu\text{m}$, particulate emissions well below NSPS limits could be achieved in both the baghouse and the electrostatic precipitator. Emissions as low as 0.003 lb/million Btu and 0.0006 lb/million Btu were measured from the electrostatic precipitator and baghouse, respectively.
- Volatile chloride emissions could be reduced or eliminated by operating with potassium levels slightly above those required to react with the ash and sulfur dioxide.
- Organic Priority Pollutants could not be detected in slag or in solids collected downstream of the secondary combustor. Inorganic Priority Pollutants deposition and distribution appeared to be comparable to conventionally fired boilers.

Nitrogen oxides, sulfur dioxide and particulates were controlled to levels well below the original Combustion 2000 goals for these pollutants. Furthermore, control of volatile chloride and organic priority pollutants was demonstrated.

5. Ash deposition was well controlled during the LMF test periods, even though gas and metal temperatures were above conventional practice for fouling coals and much smaller gas lane spacing was used in the CFFF as compared to commercial plants.

6. Corrosion resistance of the tubes tested was a function of the chromium content of the tubes. Corrosion rates for metals in similar gas- and metal-temperature zones are expected to be similar to those in conventional boilers with similar coals.

7. *A silicon carbide particulate reinforced alumina composite material was identified as a good candidate for use in regenerative air heater development.*

After completing the POC test objectives for the Illinois coal, preparations were made to test Rosebud coal from eastern Montana. A 15-hour test burn prior to beginning the Rosebud POC program (Test No. LMF4-H) was completed while firing the Rosebud coal to obtain data requested by DOE and to gain experience in preparing and firing this fuel. In addition, four pre-POC Rosebud Coal tests were also run in 1991 to establish operating conditions for the POC tests and with primary objectives of evaluating the following new equipment and modifications installed for the Rosebud coal POC tests including:

- A coal handling system modified to pulverize, dry and feed the higher moisture, more reactive Rosebud coal.
- A potassium carbonate solution injection system.
- A wet electrostatic precipitator system, including a drum filter. The filter, which completed installation of the system was installed during LMF5G, which was completely installed.

During these pre POC tests, Rosebud coal was burned for more than 292 hours.

The original goal of the Rosebud POC program was to test for 2000 hours, as in the Illinois POC tests. However, the Rosebud POC test program was terminated after a little over 1000 hours as a result of decisions made to abort the national MHD program. The Rosebud coal tests were identified as LMF5 tests. This report will describe the Rosebud coal POC program and the major equipment modifications made on the system. It will also present the results and conclusions of these tests, with emphasis on the differences in performance observed between the two coals. *It must be emphasized that the Rosebud POC program was terminated after operating only 1000 hours. This prevented acquisition of much of the data required, eliminated many of the chemical analyses planned and precluded completion of much of the data analyses. Therefore, extreme care must be exercised in the interpretation of the Rosebud data.*

III. COMPARISON OF COALS

The analyses of the Illinois No. 6 coal burned during the POC tests indicated it was a medium volatile bituminous coal, according to the ASTM Classification (ASTM D 388), whereas the Rosebud coal is a subbituminous coal. These coals had characteristics that were

significantly different, some of which led to differences in behavior during testing. The primary coal differences were:

1. Reactivity and moisture levels. The Rosebud coal had higher moisture levels and, as is the case with the 'younger' subbituminous coals, contained higher oxygen levels and is more reactive than bituminous coals. The higher moisture levels required higher drying temperatures or longer drying times to achieve the same moisture levels to the MHD combustor. However, the higher reactivity meant higher risk of fire during drying, especially if higher drying temperatures were required. Table III.1 illustrates the major coal composition differences. To accommodate these differences, the coal processing system was modified to increase the air temperature to the pulverizer, the pulverizer itself was modified to accommodate the higher temperatures, and components were procured and installed to inert the drying process to eliminate the risk of fire and/or explosion. The coal processing system modifications will be described in detail in the next section.

Table III.1 Comparison of Coal Analyses (Wt. %)

	Illinois #6	Montana Rosebud
Moisture	8 - 10	23 - 30
(on dry basis)		
Ash	11.62	12.78
Carbon	67.62	66.54
Hydrogen	4.61	4.61
Nitrogen	1.27	0.95
Oxygen (by difference)	11.34	14.42
Sulfur	3.54	0.70

2. Coal impurities/ash constituents. The differences between the Rosebud and Illinois No. 6 coals were more or less typical of differences between many bituminous and subbituminous or lignite coals. The sulfur in the Rosebud coal was significantly lower than the sulfur content for the Illinois coal. The Rosebud coals also had higher concentrations of 'basic' constituents, i.e., calcium and magnesium, but the sodium and potassium levels were somewhat lower than in the Illinois coal. So-called acidic constituents, silicon and iron, were much lower in the Rosebud coal. These differences

resulted in different coal ash viscosities, in differences in the fly ash composition, and in the amount of potassium seed needed to react with the sulfur in the coal.

a. The slag composition differences (see Table III.2) and ash viscosity variations (see Figure III.1)⁽³⁾ resulted in slag tapping differences at the primary furnace as well as differences in slag layer thickness and thermal conductivity of the slag. The fly ash composition differences also led to significant variations in the properties and appearance of ash deposits in the superheater test module tube banks, factors which affect materials performance. However, the differences in corrosion results are also affected by the actual individual test duration, the number of interruptions during the individual tests as well as the overall test duration for both coals. Therefore direct comparison of results was difficult.

Table III.2 Slag Elemental Analyses, % by Weight

Constituent	Illinois Coal Slag LMF4-P	Rosebud Coal Slag LMF5-A
SiO ₂	43.9	42.9
Al ₂ O ₃	13.4	17.5
Fe ₂ O ₃	15.6	2.9
TiO ₂	0.79	0.86
CaO	6.3	20.7
MgO	0.91	3.5
Na ₂ O	0.32	0.22
K ₂ O	16.4	12.9
SO ₃	0.47	0.3
P ₂ O ₅	N/A	N/A

Slag Viscosity, poise

Figure III.1. Slag Viscosities for Illinois #6 and Rosebud Coals

b. The lower coal sulfur content combined with the use of potassium carbonate seed resulted in higher potassium carbonate concentrations in the combustion gases. This appeared to change the ignition characteristics of the combustible gas mixture at the secondary combustor, requiring higher temperatures to assure combustion in the case of the Rosebud coal.

c. The differences in ash composition, the higher ratio of potassium carbonate to sulfate and as well as some differences in ash particle size caused some differences in the performance of particle collection equipment. A wet electrostatic precipitator (WESP) was installed during the LMF5 test program to assure that State of Tennessee emission standards were met and to compensate for apparent deficiencies in the dry electrostatic precipitator and baghouse observed in LMF4 testing. The WESP was operated for the first time during LMF5E, but the full system, including the vacuum drum filter, was not installed until LMF5G, in April, 1993, too late to complete a quantitative evaluation of the system. Some preliminary performance data were obtained and the results indicated that it performed as designed.

d. During earlier tests with low sulfur fuel oil, we observed that sulfur had an effect on nitrogen oxide levels. The Rosebud POC tests confirmed the observed effect of sulfur level, which tended to slightly increase NO_x levels (see Reference 22).

These differences will be discussed in this report along with our assessment of some of the reasons for the differences. Equipment modifications made to minimize the effects of these differences are also described in detail.

IV. MAJOR PHYSICAL PLANT CHANGES

Several major modifications were made to the CFFF equipment before and during the Rosebud POC tests. One was the coal preparation/processing system, which was modified before Rosebud coal was fired in Test LMF5A to accommodate the different characteristics of the subbituminous coals. The major differences that affected operation of the coal processing system were the higher reactivity and moisture levels of the Rosebud coal. The lower sulfur levels of the Rosebud coal in combination with other factors led to another modification, a different

method of adding the potassium seed to the combustion process. Potassium carbonate was fed as a solution to the combustor instead of being mixed with the coal before pulverizing, as was done with the Illinois No. 6 coal. The third major change was the addition of a topping cycle diagnostics access ring that was designed to permit measurement of parameters critical to assure that the upstream simulation was representative of MHD conditions. This system also helped assure that downstream components were evaluated under correct conditions. A final component installed was a wet electrostatic precipitator (WESP) system. This system replaced a badly deteriorated venturi scrubber and was required to assure compliance with Tennessee particulate emission standards in case the dry ESP and the baghouse were operating off design for test purposes or were not operating efficiently.

IVa. Coal Preparation System

Due to the differences between Montana Rosebud coal and Illinois #6 coal (see Table III.1), significant modifications to the CFFF coal processing system were required to process Montana Rosebud coal. The modified system was designed to increase the processing capacity of the system and provide greater operational flexibility. System flexibility was required because the operating conditions were not certain at the time the new equipment was selected.

Whereas Illinois #6 coal had been dried to less than 4% moisture, preliminary flow tests of Rosebud coal had indicated that the moisture content of coal exiting the feed tank should be below 8% to provide stable coal flow to the combustor. Furthermore, a typical utility grind coal was desired (i.e. 70% through 200 mesh).

The O_2 content of subbituminous coal (see Table III.1) is considerably higher than in bituminous coal. Because of the higher O_2 content and the increased reactivity 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 coal system baghouse.

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). A higher pulverizer outlet temperature, 170°F compared to 130°F for the Illinois coal tests, also aided

in the drying which was observed to occur between the pulverizer outlet and the baghouse. A new air heating system consisting of a higher capacity forced-draft blower and a new air heater capable of delivering gas at 30,000 pounds per hour at 700°F was installed.

Because of material and design limitations, the original E-35 pulverizer could operate to a maximum inlet temperature of only 450°F. Increasing the temperature of this pulverizer model 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 was 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 with 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, especially for a more reactive coal such as the Rosebud. 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. Figure IV.1 shows the coal processing equipment modifications. Additional details are provided in a paper by Holt et al.(4)

Figure IV.1. Schematic of Western Coal Processing System

The coal system baghouse (PEDCON Cylindrical Dust Collector) was also 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 moist, 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 routed 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. 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 (Xerxes/Heil). 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, re-heated, and routed to the pulverizer.

A microcomputer based control system was designed and installed to process Montana 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 a IEEE-488 standard instrument bus. Custom software was written in "C" language to implement the control scheme.

IVb. Seed Injection System

During the LMF4 POC test series, which burned Illinois No. 6 coal with a nominal sulfur content of about 2.5 % or more, seed was added in the form of potassium carbonate mixed with the coal in the pulverizer and fed as a dense phase mixture directly into the combustor. The typical flow rate was determined to give a nominal molar stoichiometric ratio, K_2/S , of about 1.1. This provided sufficient potassium to combine with most of the sulfur dioxide and chlorine, and the seed was recovered largely as potassium sulfate, with small amounts of potassium chloride and potassium carbonate, depending on the coal sulfur levels and amount of seed added.

In planning for the LMF5 test series, which was to use Rosebud coal from Montana, a low sulfur coal, there was considerable discussion among the upstream and downstream development teams and the Department of Energy program managers about the appropriate chemical form of seed to use and how to add the seed to the MHD system. The Rosebud coal has a nominal 0.8% sulfur content. If sufficient potassium carbonate were added to provide 1% of the flow as potassium for electrical conductivity purposes, a molar potassium to sulfur ratio of about 4.0 results. This meant that most of the potassium in the combustion gases would have been in the form of potassium carbonate. Deposition of potassium carbonate on the heat transfer surfaces had been found to be a severe problem in Kennecott Copper experiments⁽⁵⁾ and at the U-25 facility in Russia⁽⁶⁾. Furthermore, the limited tests that had been performed during the Illinois POC tests in the CFFF indicated that fouling was more of a problem than when the solids were a potassium sulfate/fly ash mixture. There was some concern that the gas flow passages might become completely plugged while operating with high K_2/S ratios. Further, collection of the carbonate also raised uncertainties. More details of these aspects are given later.

The discussions related to the chemical form of potassium to be added led to consideration of a preliminary concept using a mixture of potassium carbonate and potassium sulfate. In this proposed concept, the total potassium was chosen to give the desired elemental potassium flow rate (nominal 1%) and the split between carbonate and sulfate chosen to give the desired stoichiometric K_2/S ratio, e.g. 1.1. However, the CFFF coal processing system had provisions for metering and adding only one type of seed. The carbonate and sulfate could be mixed in the desired ratio and fed dry from the single seed tank, but this was unwieldy. For this reason, a development effort was initiated to provide an additional method of injection of potassium carbonate seed. This approach would also reduce the sulfur concentration in the combustion gases, a desirable result in operation of both the upstream and downstream components.

Potassium carbonate is not soluble in fuel oil. Therefore a slurry system was investigated. This could have been accomplished, but feeding a water solution is much easier. The water affects the flame temperature achieved, of course, so adjustments in the combustor inputs were made to compensate for this loss. This system was intended for experimental utility only--not for commercial application, although commercial addition of a liquid, molten potassium formate has been considered.

The system as installed is shown schematically in Figure IV.2. The potassium carbonate solution in water (47% carbonate, by weight) was delivered by tanker truck. The seed was

purchased in solution at the same price per pound of potassium carbonate as previously paid for the dry seed. The system pumped it up to a regulated pressure, controlled the flow rate, mixed it with the No. 2 oil at four locations and injected it into the combustor through four oil nozzles. These oil nozzles were routinely used in POC testing to add clean fuel to simulate 100% slag carryover in a commercial sized plant.

Figure IV.2 LMF5 Seed Injection System

This system worked exceptionally well and provided finer control over seed flow rates, and therefore, the potassium to sulfur ratio, than had been possible with the dry seed mixed and fed with the coal. The tests in the LMF5 series were conducted predominantly with potassium carbonate seed only. This decision was based largely on the topping cycle development team's reluctance to introduce more sulfur into the flow than absolutely necessary. However, if it were desired to feed both sulfate and carbonate, the sulfate could be mixed and fed with the coal and the carbonate fed as a water solution with this system.

IVc. Topping Cycle Diagnostics Access Ring

In order to properly evaluate the bottoming cycle components in the LMF5 test series an adequate simulation of the topping cycle gas conditions was needed. Because an MHD generator was not operated for this simulation, a greater access to the simulated plasma stream was available for study. The CFFF LMF5 flow train design of water cooled modules which comprised the "aerodynamic duct" allowed for insertion of a diagnostics module, which was used to evaluate both MHD plasma diagnostics and plasma conditions. This module, called the instrument ring, was installed between aerodynamic duct modules CD-1 and CD-2. The instrument ring was supported with a number of Mississippi State University's (MSU) Diagnostic Instrumentation and Analysis Laboratory (DIAL) diagnostics systems including the laser Doppler velocimeter (LDV), potassium emission absorption system (PEAS), sodium line reversal (SLR), and

coherent anti-Stokes Raman spectroscopy (CARS) system. The LDV measurements indicated that the gas was choked at the instrument ring, giving near sonic gas velocities.⁽⁷⁾ The PEAS measurements provided both gas temperature and potassium species concentrations.⁽⁸⁾ The PEAS system required modification of the separation technique for the emission and transmission signals. A spatial separation was employed rather than the 1 KHz temporal separation normally used with both PEAS and SLR. The SLR measurements were not successful at the instrument ring because of the SLR's inadequate signal separation. CARS measurements of gas temperature were acquired^(7,9), but sufficient optical access was not available for the BOXCARS high spatial resolution technique to be employed. The CARS measurements were acquired with alternating argon and nitrogen optical port purge and this confirmed that argon purge was required to prevent boundary layer interference with the measurements when N₂ CARS was employed. Nitrogen CARS provided better temperature measurements in general than CO CARS which was attempted at the CFFF diffuser to measure temperature and CO concentration. CARS also indicated a substantial increase in particle scattering effects as the seed mass flow increased. The mechanism creating the increase in particle effects is suspected to be due to quenching effects of the seed solution which increases the free carbon in the gas.

IVd. Wet Electrostatic Precipitator System

As noted, a wet ESP was added during the Rosebud POC test program. This wet ESP itself was procured from the North American Air Pollution Company and installed in the summer of 1992. It contained a conditioning section, a spray section and a collector section. A rotary drum filter was added to the system during the LMF5G test. The system is shown on Figure IV.3 and Figure IV.4. The system was described in detail by Sheth, Holt, Douglas and Thompson.⁽¹⁰⁾ It was designed to meet Tennessee particulate emission limits of 0.19 lb/MBtu at a flow of 15,000 actual cubic feet per minute (acfm), which was full flow of the low mass flow train. Efficiencies were specified at 99.9% for a flow of 5000 acfm at 350°F and at 99.7% for a flow of 7500 acfm at the same temperature. As noted earlier, the system was installed to replace the venturi scrubber, which was corroded severely. Furthermore, the performance of the venturi was not adequate to meet Tennessee particulate emission standards during LMF start up, when it was operated alone, without the dry ESP or baghouse. The wet ESP also could be used to meet Tennessee Standards when the dry ESP and BH were operated off design for test purposes, were off line or not operating efficiently.

Figure IV.3. Schematic of Wet ESP

Figure IV.4. Wet Electrostatic Precipitator

Wet and dry ESPs differ in operation principally in their mechanism for removing the collected particulate. In a dry system, a timed sequence of mechanical rapping or vibration is used to remove the ash from the collection surfaces. During these rapping periods, the ash drops from the collection plates or discharge electrodes into a hopper. Some reentrainment of particulate into the gas stream occurs at this time, which reduces efficiency. Wet ESPs

typically have very high collection efficiencies for submicron particles. In a wet system, the collected particulate is washed from the collection surfaces with water and little or no reentrainment occurs.

Some of the disadvantages normally associated with wet ESP systems are not applicable in an MHD system. Since the spent seed must be regenerated, and since the seed regeneration processes being considered for commercial application begin with a dissolution step, the solution/slurry exiting from the wet ESP may eliminate one of the processing steps. In addition, for conditions where potassium carbonate and potassium sulfate are present, the system installed at UTSI could be used for separating the carbonate and sulfate. This separation can be effected using a filtration system, since the sulfate has a reduced solubility in the presence of the carbonate.

V. SUMMARY OF TESTING

Testing for LMF5 began in 1991, with pre POC test LMF5A completed in August of that year. POC testing was concluded with LMF5J in September of 1993, with data analyses and chemical analyses of samples continuing after that test. Almost 1340 hours of coal fired operation were achieved during that period. Details of test planning, test operations and results are contained in Test Reports and Test Summary Reports.

Table V.1 LMF5 Test Dates and Duration

<u>Test Number</u>	<u>Date</u>	<u>Duration, hours</u>
<u>Pre-POC Tests</u>		
LMF5A	August, 1991	75.2
LMF5B	August, 1991	60.4
LMF5C	September, 1991	49.8
LMF5D	November, 1991	106.9
<u>POC Tests</u>		
LMF5E	April, 1992	90.8
LMF5F	August, 1992	290.1
LMF5G	September, 1992	313.8
LMF5H	April, 1993	88.3
LMF5I	July, 1993	212.2
LMF5J	September, 1993	52.0
TOTAL-All Rosebud POC Tests		<u>1047.2</u>
TOTAL-All Rosebud Coal Tests		<u>1339.5</u>

Table V.2 Nominal POC Test Conditions

	<u>Illinois # 6 Coal</u>	<u>Rosebud Coal</u>
Thermal Input, MW	19	19
Seed	K ₂ CO ₃	K ₂ CO ₃
Primary Stoichiometry, %	85-90	85-90
Primary O ₂ /N ₂ Ratio	1	1
K, Wt% of Total Flow	1	1
Gas Temperature to SHTM	2250°F	2250°F

VI. SUMMARY OF RESULTS AND DISCUSSION

Via. Coal Processing System

The CFFF coal processing system, after being modified to pulverize and feed Montana Rosebud coal, was used successfully for 1339 hours of combustor operation. Coal moisture during Montana Rosebud testing remained below 8% resulting in stable coal flow into the combustor for extended testing periods. The size distribution, which was originally finer than desired, has been gradually adjusted and the most recent attempt produced coal of 77% through 200 mesh. Additional changes to the pulverizer configuration are possible, which should produce the desired standard utility grind of 70% through 200 mesh. Figure VI.1 illustrates stable combustor coal feed during a typical eight-hour test period.

Figure VI.1. Coal Mass Flowrate During 8-Hour Test Period

A new Fischer-Porter coriolis mass flow meter was evaluated and installed during the Montana Rosebud testing. This single-tube coal flow meter was more accurate and reliable than

the first-generation coriolis meters used for over thirteen years at CFFF. A typical Fischer-Porter coriolis meter calibration curve is shown in Figure VI.2.

Figure VI.2. Fischer-Porter Coriolis Meter Calibration Curve

Due to the process control automation implemented, the operation of the Western coal system required 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.

VIb. Topping Cycle Diagnostics Access Ring

The ring was implemented with a pressure port assembly to determine if flow choking occurred at the ring as suspected from the LDV and PEAS measurements. Periodic pulse purging was used to remove slag build up, but slag blocked the port before pressure readings were taken at the start of the LMF5-1 test. The pressure port was cleaned just prior to ignition on 13 July, 1993 and pressure data was obtained for about 20 minutes after the POC thermal input conditions were established. After this period slag accumulation in the pressure port prevented accurate pressure readings. The good pressure measurements are shown in Figure VI.3, along with continued measurements as the port plugged. Measured pressure was 2.24 Atm, the expected pressure for choked conditions. A 1.7 Atm pressure would be expected for supersonic

flow at the instrument ring to throat area ratio. Thus, these measurements confirm that the LMF5 flow choked at the instrument ring when it was installed. The fact that the diagnostic ring choked the flow had no impact on the downstream POC testing or relevance to MHD generators.

Figure VI.3. Pressure Measurements and Coal Flow at the Instrument Ring

DIAL diagnostics were also employed in the downstream sections of the LMF5 flow train. These diagnostics provided additional gas temperature data, wall temperature data, and gas velocity profiles for comparison with UTSI predicted velocity profiles for heat transfer analysis.⁽¹¹⁾ Details of the DIAL measurements are given in the DOE MSU DIAL reports such as the Final Progress Report.⁽¹²⁾

VIc. Effect of Potassium Compound on Secondary Combustion

During early testing with the Rosebud coal, it was observed that it was somewhat more difficult to ignite the secondary combustor. Test results indicate that this was the result of several factors, including primary stoichiometry, inlet gas temperature and flame suppression by potassium species in the flue gas. Potassium carbonate was supplied to the primary combustor in a 47% solution during the LMF5 series. When seed solution flow was started while the gas temperature entering the secondary combustor was lower than about 1600°F, secondary combustor performance often degraded. With secondary combustor inlet gas temperatures somewhat above 1700°F, combustion appeared to be similar to the LMF4 series. A typical example occurred during LMF5E. Coal firing was established with no seed flow while the secondary combustor inlet temperature was about 1510°F. Seed flow was started at about 1710°F. Prior to starting seed flow, secondary combustor operation was normal; however, immediately after introduction of seed the secondary combustor flame was strongly influenced, increasing downstream CO levels. Normal operation resumed when the seed flow was turned off.

The same phenomenon was repeated on two other occasions during this test and again during LMF5H, when the seed flow was turned on for brief periods. Potassium carbonate solution flow rate and secondary combustor outlet CO concentration during LMF5E are plotted in Figure VI.4. The secondary combustor inlet gas temperature indicated by thermocouples during this period was about 1600°F. The actual gas temperature corrected for thermocouple radiation losses was probably about 1800°F. Secondary air temperature was around 470°F, providing an estimated mixture temperature (not including heat of combustion) of about 1520°F. This is well above the normal minimum ignition temperature for CO, which is about 1250°F. Normal secondary combustor operation with seed flow was established when the indicated secondary combustor inlet gas temperature reached about 1660°F. The impact of this effect on the POC flow train and future commercial plants is that the secondary combustor ignition temperature will be higher when higher K₂/S ratios are used.

Figure IV.4. Effect of Seed Flow on SC Outlet CO Concentration

Suppression of flames by potassium is a known phenomenon, and chemical kinetics studies indicate that both potassium and sulfur can inhibit flame propagation under some conditions. The most likely mechanism for flame inhibition by potassium is

and

where M is a third body, such as N_2 , H_2O , or H_2 . These reactions inhibit CO oxidation by removing OH radicals from the flame.

Equilibrium chemistry calculations indicate that the concentration of KOH in the reducing gas prior to secondary combustion is about 0.2% at 1800°F for typical seed flow rates. The KOH vapor is in equilibrium with condensed K_2CO_3 , and the equilibrium concentration of KOH does not change after secondary combustion, provided that a significant amount of K_2CO_3 remains ($K_2/S > 1.0$). For the case where there is no K_2CO_3 after secondary combustion ($K_2/S < 1.0$), KOH concentration is less than 5 ppm after secondary combustion. The absence of KOH after secondary combustion for low K_2/S conditions provides a possible explanation for the differences in secondary combustor operation observed in the two test series.

The predicted effect of KOH concentration on secondary combustor flame propagation has been modeled using the NASA GCKP84 chemical kinetics code. The system was modeled as an adiabatic plug flow reactor, with the flue gas and secondary air being instantaneously mixed at position $X=0$. The two potassium reactions discussed above were added to a standard set of reactions for CO oxidation. For an initial mixture temperature of 1520°F (1100°K), no ignition delay was predicted; however, for a mixture temperature of 1340°F (1000°K), a significant ignition delay was predicted, as shown in Figure VI.5. It should be noted that in the

Figure VI.5. Calculated CO Concentration as a Function of Distance from Secondary Air Injection Point

real secondary combustor the mixing is not instantaneous and there is significant heat loss to the water-cooled walls from the flame; both of these factors would increase the ignition delay.

Information was gathered on potassium and sulfur reactions for use in secondary combustor chemical kinetics modeling. Kinetics studies of the sodium-sulfur system have been performed, and results are available in the literature. The kinetics of the potassium-sulfur system are expected to be very similar to the sodium-sulfur kinetics, but no study of potassium-sulfur interactions has been performed. Reliable, potassium-sulfur kinetics data is required to accurately predict secondary combustor performance, and potassium-sulfur kinetics is also important in the formation of NO_x and SO_2 . Therefore, bench scale experiments were conducted at UTSI as part of a graduate research project to obtain the required data. The results of the literature study and bench scale tests will be available as a doctoral dissertation by David Pruitt.

VId. Emissions Control

Emissions control was a critical element in the development of technology for the MHD system at UTSI. During the Illinois No. 6 and Rosebud coal tests, major emphasis was on measurements to determine the levels of particulate and gaseous emissions from the combustion gases. These combustion products were characterized by measuring sulfur oxides, nitrogen oxides, and chlorides as well as quantities and characteristics of particulates resulting from the combustion of coal containing ash and seed material. Efforts were then successfully concentrated on control of these emissions by various techniques and control components. Details of the measurements and control efforts are outlined below.

VId.1 Particulate Emissions Control

On-line measurement of particle size distributions

Because coal-fired MHD power generation is encumbered by high loadings of submicron particulates, efforts to evaluate particle removal systems for the Coal Fired Flow Facility MHD exhaust gas were undertaken. This required diagnostics of the particulates entering and leaving the particle removal systems. Standard extractive methods provide particulate loadings and size distributions, but are labor intensive. Standard extractive methods cannot provide on-line near real time measurements needed to evaluate performance during changing operating conditions and to enhance understanding of the physics of the different particulate emissions control

devices. Unfortunately, the extreme number densities of the particulates in the typical MHD exhaust stream ($>10^7$ particles/cm³) and the very small particulate sizes (mass mean diameters of 0.5-1.0 μm) are beyond the capabilities of existing near real time on-line particulate measurement instruments. Attempts to develop an on-line, near real time extractive instrument was unsuccessful due to the "sticky" nature of the potassium compounds which comprise the bulk of the MHD exhaust particulates.^(13,14) To circumvent these difficulties existing commercial optical instruments were modified to allow on-line near real time measurements of both particulate size distributions and loadings as they vary with time. Insittec's *in-situ* optical particle counter, sizer, velocimeter probe (PCSV-P)^(15,16,17,18) was modified to allow measurement of particle size distributions between diameters of 0.2 and 25 μm at loadings up to 3×10^7 particles/cm³ and flue gas velocities up to 100 m/s. This resulted in a new ultrafine probe (PCSV-UFP).⁽¹⁹⁾ In addition, Insittec's *in-situ* optical Transform Method for Extinction Scattering with Spatial resolution probe (TESS)^(19,20) was modified to continuously measure the flue gas particulate concentration as a volume concentration for particulates smaller than about 8.8 μm diameter which includes the bulk of the particulates. A high temperature cooling jacket was developed for both instruments which allows their use at the entrance to the CFFF superheater test module where the gas temperature is about 1550°K and where potassium carbonate and potassium sulfate are still partially in gas and liquid phase. By employing the cooling jacket, information concerning the formation and growth of particles entering and moving through the superheater test module could be obtained.

During the testing of the MHD bottoming cycle components at the CFFF the PCSV-UFP and the TESS instruments were used to measure particle size distributions (dN/dlogD vs. D) and volume concentrations (C_v) vs. time, respectively, in the inlet ducting to all the particle control systems and in the dry electrostatic precipitator (DESP) outlet ducting. The Insittec *in-situ* probes also measured particle size distributions in the baghouse (BH) outlet ducting and at the entrance to superheater test section 1 (TS1), and measured volume concentrations in the wet electrostatic precipitator (WESP) outlet ducting. Typical CFFF particle control systems inlet and outlet measurements are provided in Figures VI.6 and VI.7. Comparative extractive measurements at the entrance and exit of the particulate control devices are presented, indicating the comparable accuracy of the PCSV-UFP and the TESS probes. The Insittec probe measurements at the superheater test module entrance are given in Figure VI.8. Comparative extractive measurements could not be adequately performed entering the superheater test

module because condensation of the potassium compounds within the extraction hardware could not be prevented.

Figure VI.6. Comparisons of *In-situ* and Impaction Measurements for BH and DESP

a. BH/ESP Inlet

b. DESP Outlet

Figure VI.7. Measured Particle C_v Variations Across the DESP

Figure VI.8. Superheater Test Module Particle Size Distribution Measurements

Figure VI.6 clearly illustrates the good comparison which occurred between the PCSV-UFP in-situ measurements and standard extractive particle collection measurements. The 5 stage cyclone measurements acquired at the particle collection equipment inlet are in excellent agreement with the PCSV-UFP measurements down to the approximately $0.8\ \mu\text{m}$ size limit imposed on the PCSV-UFP by the high loadings of smaller particles. Although they were labor intensive, the 5 stage cyclone measurements were made both before and during PCSV-UFP measurements to increase confidence that time changes in the particle size distributions didn't negate the comparisons. The 7 stage flow sensor DESP outlet measurements and the *in-situ* measurements aren't in nearly as good agreement, but the 7 stage flow sensor measurements were made during a different test period with inadequate DESP performance being noted. Sufficient manpower was not available to repeat the stage flow sensor measurements during the PCSV-UFP measurements which occurred months later and after DESP performance was corrected by modifying the DESP electrode configuration. Earlier PCSV-P measurements attempted at the DESP outlet, when the performance was like that illustrated by the 7 stage flow sensor measurements, showed better agreement; however, those PCSV-P measurements were limited by measurable number density limitations of the probe before UFP modifications.

Insitec's measurements of particle loadings at the DESP and BH outlet were far lower than at the particulate collection equipment inlet ducting, and this allowed the optical *in-situ* PCSV-UFP probe to measure particle size distributions down to $0.31\ \mu\text{m}$. Most of the mass was concentrated in particles less than $6.3\ \mu\text{m}$, so additional time to determine larger particle

loadings was not taken at the DESP and BH outlet locations. Measurement of large particle size loadings was attempted at the BH outlet with the PCSV-UFP, but almost 45 min. of data was acquired with no noticeable change in the measured size distribution, because large particles were not in this flow in measurable quantities.

Measurements of C_v with TESS indicated significant temporal variations in particle loadings. As Figure VI.7 indicates, these variations appear as bursts of increased loading, which might be expected with sootblowing which is occurring upstream of the measurement stations. However, no correlation could be determined between increased loadings and sootblowing cycles. Particle loadings can also be expected to increase randomly as particles randomly shear off upstream walls and heat exchanger surfaces. Multiplying C_v by particle density provides particle mass loadings for the $8.8\ \mu\text{m}$ and smaller particles monitored by the TESS probe. From these measurements, particulate mass removal efficiencies for the DESP and BH were determined to be near 99.80% and 99.98%, respectively. Appropriate measurements could not be made for the WESP since it was not functioning properly when C_v measurements were made during CFFF tests when the PCSV-UFP and TESS were available.

Figure VI.8 shows PCSV-UFP measured particle size distributions at the high temperature superheater test section (TS1) compared to a typical distribution measured at the BH/ESP inlet ducting. Figure VI.8 shows that the TS1 distributions are about two orders of magnitude lower in loadings for a given particle size. Attempts to measure loadings of the larger particle sizes were not continued after about 10 minutes of probe insertion to diminish overheating possibilities for the probe in the $\sim 1550\ \text{K}$ (2330°F) TS1 inlet gas environment. Attempts were made to measure the loadings at TS1 with the 5 stage cyclone apparatus, but even heating the cyclone hardware could not prevent particulate condensation and deposition inside the cyclone system. As a result, the 5 stage cyclone system was coated with condensed potassium compounds, and no comparative measurements were available for the PCSV-UFP measurements in this high temperature environment. The PCSV-UFP measurements were repeated several times, and at slightly different insertion depths into the superheater TS1 module. As would be expected, the small particle loading increased for measurements made closest to the wall where the cooler wall assists the condensation process.

Baghouse

The CFFF baghouse was operated during all Rosebud coal tests although collection efficiency data were not taken during all tests. Emissions from the baghouse ranged from

0.0003 - 0.009 lb/MBtu all of which are well below the NSPS allowable limit of 0.03 lb/MBtu. Efficiencies were almost always 99.9% or greater. Table VI.1 and Figure VI.9 show data from the LMF5 test series.

Table VI.1 Baghouse Emissions - LMF5 POC Tests

TEST NO.	FLOW, ACFM	EMISSIONS, lb/MBTU	EFFICIENCY, %
LMF5B	6670	.0006	99.9+
LMF5D	4440	.006	98.9
LMF5F	5690	.0003	-
LMF5F	5220	.0054	99.9+
LMF5G	4600	.0051	99.9
LMF5G	4990	.0008	99.9+
LMF5H	6470	.0005	99.9+
LMF5H	5640	.0006	99.9+
LMF5I	5500	.0057	99.8
LMF5I	5340	.0036	99.9+
LMF5I	5010	.0092	99.9

Figure VI.9. Baghouse Emissions during LMF5 Tests

As in LMF4 tests, the bags were cleaned during LMF5 using reverse air with sonic horn assist. The nominal filtration velocity through the Gore-Tex bags is 2 ft/min. The initial 24 hours of operation during LMF5E were conducted using oil-firing only which produced a much higher moisture content flue gas than does coal firing. The outlet damper to the baghouse apparently leaked during this period and the bags were soaked with condensate. Since both potassium carbonate and potassium sulfate are water soluble, recrystallization of these salts in the fabric itself resulted in blinding of the fabric.

New Gore-Tex bags were successfully tested during the LMF5F and LMF5G tests. Four of the carbon steel thimbles which attach to the bags at the bottom had corroded to the point of failure just prior to the LMF5F test and were capped and the baghouse was operated with only 26 bags. Replacement stainless steel thimbles arrived prior to the LMF5G test, and the baghouse was once again operated with 30 bags.

After the initial cleaning cycle, short durations between the required cleaning cycles were prevalent during all tests. At 5400 cfm (2 ft/min filtration velocity), the cleaning cycles were required at intervals of less than 30 minutes apart. With tests conducted using the Illinois #6 coal and at much lower K_2/S ratios, 90 minutes between cleaning cycles was normal. The reverse air fan was replaced at the same time as this increase in cleaning cycle frequency; however, the fan is supposedly identical to the previous one. Also, the reverse air ductwork has been replaced with a different design, but this too is not suspected to be causing the problem. The data indicated that the ash was not being removed efficiently from the bags or was being reentrained after the cleaning cycle. After periods when the baghouse was taken off line for several hours for inspection or when beginning a new test, the initial time between cleaning cycles was approximately 90 minutes or longer (see Figure VI.10) continually degraded afterwards. Also, cleaning the bags two or three times instead of only once also improved the bag condition. Gore-Tex recommended reduced reverse air flow, which was tried during LMF5H, but which was not successful. During Test LMF5I the initial cleaning cycle was again long, in this case nearly 3 hours, but the subsequent cycles were typically less than 45 minutes. A slight improvement was achieved by cycling the reverse air poppet dampers from open to shut at intervals of 10 seconds during the 2-minute cleaning cycle. We concluded that higher reverse air flow may be necessary to provide more effective cleaning. However, collection efficiency was very effective, generally at more than 99.9%, and emissions were only a fraction of the current NSPS limit of 0.03 lb/MBtu (13 ng/J).

Dry Electrostatic Precipitator

The dry ESP was operated during the Rosebud POC tests. Performance of the device was marginal during the first three tests due partially to the high gas flow conditions and a measurable decrease in particle size distribution. To meet the CFFF particulate emission operating permit, the dry ESP was forced to process more than 50% of the flow for most tests.

Figure VI.10. Typical Baghouse Operation (LMF5G)

Emissions from the dry ESP during LMF5E, F & G, when potassium carbonate was used, ranged from 0.165 - 0.707 lb/MBtu for gas flows of 8900 - 12600 cfm (see Table VI.2). The

Table VI.2 Dry ESP Performance during LMF5E, F & G

Test No.	Gas Flow, acfm	SCA	Particulate Emissions, lb/MBtu	Efficiency, %
LMF5E	7190	417	0.052	93.2 (coal only)
LMF5F	9880	304	0.165	96.0
	9720	309	0.273	94.2
	12590	238	0.707	87.8
	11130	270	0.617	89.3
LMF5G	11800	254	0.689	82.6
	11140	269	0.572	92.0
	10840	277	0.443	93.8
	11160	269	0.470	96.2
	8900	337	0.656	86.9
	8550	351	0.365	93.3
	7210	416	0.405	93.3

nominal design flow for this ESP is only 6300 cfm; therefore, the efficiency is not expected to be as good when tests are conducted at a much higher throughput. The particle size distribution has shown an increase in the number of small particles using Montana Rosebud with a K_2/S of approximately 4.0 compared with the Illinois coal with a K_2/S ratio of 1.0. The mass mean diameter, as measured by a 5 Stage Series Cyclone sampler, has decreased from 0.7 to 0.2 micrometers, which was considered a possible contributing factor in the low ESP collection

efficiency. This decrease in particle size was assumed to be related to the presence of significant quantities of potassium carbonate in the collected ash.

During the LMF5F test, large deposits of ash were formed on the wires and plates which were not removed by the rappers and vibrators (see Figure VI.11). These deposits are suspected to result from small water leaks which increased the gas moisture content and later absorbed by potassium carbonate in the ash. Prior to the test, a second set of vibrators (pneumatic) was installed directly on the wire rack of each field and these could be operated manually. Post test inspection revealed that these pneumatic vibrators were capable of removing the deposits and capabilities are planned so that either set of vibrators could be used in the automatic timed sequence.

Figure VI.11. Ash Buildup on Discharge Electrodes In the Dry ESP During LMF5F

Research conducted by ADA, Inc., suggested the dry ESP efficiency could be increased substantially and more consistent performance achieved by replacing the discharge wires with smaller diameter wires. Because of the relatively large diameter-electrodes originally installed in the ESP (1/4" round and 5/16" square), ADA concluded that it was difficult to maintain high current conditions necessary for high particle collection efficiencies. Bench scale tests conducted by ADA suggested that most of the corona discharge was at the ends of the electrodes which are outside the usable portion of the ESP. Based on these tests, the electrodes were replaced with 1/8" round wires installed prior to the LMF5H test. The results measured after the installation of the 1/8" wires were the best recorded for the Rosebud coal, indicating that the smaller electrodes were very effective. The results also appeared to be more consistent, although only two sets of data points were obtained before the POC program was

terminated. The results for the LMF5H and I tests are summarized in Table VI.3 and Figure VI.12, below. Although this equipment was designed for a flow rate of approximately 6300 acfm (Specific Collection Area of 475 ft²/kacfm), it performed well after the electrode modification even with higher flow rates. Emissions were controlled to levels below NSPS except for the test condition which had flow rates of more than 10,000 acfm, well above design levels, corresponding to an SCA of only 283.

Table VI.3 Dry ESP Collection Efficiency - LMF5H & I

Gas Flow, acfm	SCA*, ft ² /kacfm	Emission Rate, lb/MBtu	Collection Efficiency, %
6688	449	0.0022	99.97
6746	445	0.0236	99.14
7615	394	0.0116	99.77
7684	390	0.0217	99.58
9719	308	0.0183	99.78
10583	283	0.1828	97.17

*SCA - Specific Collection Area

Figure VI.12. Performance of the Dry ESP

Wet Electrostatic Precipitator

One of the major efforts in pollution control during the latter stages of the LMF5 series was the installation and preliminary shakedown of the wet electrostatic precipitator (WESP). Of particular significance was the fact that a major component of the wet ESP, the rotary drum filter, arrived at UTSI after LMF5G began and was installed and made operational while the low mass flow train was operating.

The original design for the WESP system included a venturi rod deck section where the gas would be humidified and cooled by recirculated water spray. In addition, particles with diameters larger than 5 micrometers would be removed by the venturi rod deck. Initial testing resulted in substantial deposition in the rod deck section which led to blockage of the flow passage. Since the particulate removed by the rod deck section consisted principally of particles larger than 5 microns (which are easily collected by a wet ESP), the rods were removed. The spray system remained in place to humidify the gas.

Initial testing of this system, including the drum filter, began during LMF5H. Dust loading measurements at the ID fan outlet to the stack were .0069 lb/MBtu during this test, well under NSPS requirements, with 31%, 48% and 21% of the total gas flow passing through the baghouse, dry ESP and wet ESP, respectively. This also was well under Tennessee regulations. The wet ESP also met Tennessee regulations with more than 98% (13350 ACFM) of the total flow passing through it. Under these conditions, emissions were 0.138 lb/MBtu, although inlet dust loading was well under normal loadings. At a flow rate of 5230 ACFM, emissions were 0.106 lb/MBtu, above NSPS. Deposition of crystalline K_2SO_4 was observed on the electrodes, which may have been at least partly responsible for the lower than expected performance. The performance of this system could have been improved significantly at the lower flow rates with minor operating condition changes, but inadequate time was available to fully optimize this equipment.

VId.2 Nitrogen Oxides/Sulfur Dioxide Emissions Control

During the LMF5F test, variations were conducted beginning with small quantities of potassium and increasing with time to eliminate the effect of free carbonate. Toward the end of the test, the effect of stoichiometry on NO_x concentration was studied. NO_x levels were generally higher during the entire test than were observed using a higher sulfur coal. Upon shutdown, water leaks were evident and could have contributed to a higher cooling rate of the gas which also would lead to higher NO_x levels. Table VI.4 shows the NO_x emissions during the scheduled stoichiometry variation during the prior LMF5E test.

Table VI.4 Effect of Stoichiometry on NO_x Levels During LMF5E

Thermal Input (MW)	Primary Stoichiometry	NO _x , Lb/MBtu
17.0	0.87	0.19
18.5	0.97	0.80
18.5	0.92	0.26
19.0	0.82	0.16
19.0	0.87	0.18

Throughout the test program, there was evidence that the sulfur level in the fuel influenced the nitrogen oxide levels due to the NO decomposition reaction involving sulfur.⁽²¹⁾ Results reported by Crawford⁽²¹⁾ indicated that a low-sulfur fuel oil produced lower NO_x values than firing a mixture of oil and high-sulfur coal. This was also observed experimentally and analytically during the low-sulfur Rosebud coal tests. Figure VI.13. summarizes tests with the Rosebud and Illinois No. 6 coals and adds data from tests with the Rosebud coal during which sulfur was added to raise the sulfur level to approximately the level of the Illinois coal.⁽²²⁾ A parametric study also included in this paper demonstrated the effect of sulfur on nitrogen oxide formation. These results are shown in Figure VI.14. Tests during LMF5G showed only a minor effect of thermal input on NO_x levels with a primary stoichiometry between about 0.8 and 0.87. A final report by Chapman⁽²³⁾ summarizes the UTSI work on nitrogen oxides.

Figure VI.13. NO_x vs Primary Stoichiometry

Figure VI.14. Parametric Study, NO_x Emissions, Illinois No. 6 and Rosebud Coal Fuels at 85% Stoichiometry, Cooling Rate Approximately 600°F/s - Emissions Index

Additions of potassium carbonate up to a K₂/S molar ratio of about 1.5 continued to eliminate sulfur dioxide. Measurements also confirmed the reaction between potassium and sulfur continues to occur downstream of the secondary combustor outlet instrument and the baghouse/ESP inlet, as shown in Figure VI-15.

Figure VI.15. SO₂ as a Function of K₂/S

VId.3 Air Toxics Emissions Control

As the development of MHD technology progressed, assessment of effluent streams for trace constituents became an essential objective of the UTSI Chemistry Laboratory. By 1987, work had already been done to characterize the coal, slag, seed, spent seed solids, and contact water from Illinois No. 6 Coal POC tests. In 1990, amendments to the Clean Air Act imposed on commercial fossil-fueled facilities required that certain toxic pollutants, designated by the EPA as environmentally detrimental, be carefully monitored. Ultimately, solid, liquid, and gaseous

effluents from tests burning either Illinois No. 6 or Montana Rosebud coal were checked for the presence and behavior of 161 toxic parameters, the applicable compounds as listed in the amended Clean Air Act. Samples of potassium carbonate seed and raw coal were measured for trace inorganic content and included in this assessment to construct an analytical mass balance. Also, an attempt was made to compare our preliminary data to that reported in studies conducted on effluent samples collected from conventional coal-fired technologies, even though different coals, higher temperature combustion and the presence of potassium seed made direct comparisons difficult.

The MHD effluent streams were checked for trace levels of the 13 inorganic metal elements, 35 volatile and 113 semi-volatile organic compounds (161 total). Both the collection and analyses of effluent samples from the CFFF were accomplished using EPA-approved sampling devices and procedures. Atomic absorption and atomic emission spectrophotometric methods were used to quantify the inorganic constituents of effluents from the MHD facility. Organics were measured by gas chromatography/mass spectral techniques. Internal and external laboratory quality control measures were taken to maintain the validity of the analytical results. Representative samples were often sent to International Technology Corporation (ITC) located in Knoxville, Tennessee, or another commercial laboratory for comparison. Samples of the various effluents were collected from several relatively long duration MHD tests from the LMF4 series burning Illinois No. 6 coal, including tests I, K, V, and W. Samples were also collected during the LMF4H and LMF5I tests while burning Montana Rosebud coal. Values from the analyses of solid effluent samples were reported on a dry, sulfur-free basis, so that a better comparison could be made with the information gathered from conventional coal-fired operations. The units used in these analyses are those that are used in the EPA protocols for that analysis. Mg/kg and ppm are equivalent. Mg/liter is used for contaminants in water. Mg/m³ is used to represent solids in a gas.

It had been theorized that the naturally occurring complex organic constituents of coal could not survive the high temperature of an MHD system. However, it seemed possible that some organics could reform during the subsequent cooling of the ash and gases in downstream components. If reformation (or rearrangement) and concentration were to occur, the resulting organic or organo-metallic-containing material could be classified as undesirable, and contaminate the otherwise acceptable effluents. Also, certain virgin inorganic elements in the coal could be volatilized and released into the atmosphere via the gaseous effluent, or

concentrated and then recondensed onto the spent seed ash. Either situation could create costly process waste remediation or disposal problems for a commercialized MHD coal-fired facility. It was hoped that the findings from this study would prove that effluent from the low mass flow train was environmentally cleaner than that from conventional coal-fired plants already in operation. Extraction Procedure (EP) Toxicity tests performed by a commercial laboratory on samples of spent seed and slag from the CFFF had already shown that all MHD solid effluents met the criteria to be landfilled by permit, although coal ash is exempt from these standards.

Air Toxics - Inorganics:

Throughout this investigation, data from the inorganic analyses of coal, slag, and spent seed solids stayed relatively consistent with those results which had been gathered in the earliest portion of this study. Table VI.5 depicts past and the most recent data on the 13 toxic inorganics quantified in samples from tests on Illinois No. 6 coal. It was interesting to note certain distinct depositional trends in successive flow train components when compiling the trace metals data from tests conducted on both Illinois No. 6 and Montana Rosebud coal.⁽²⁴⁾ There was substantial fractionation of metals in downstream components of the MHD flow train, yet the resulting concentrations were generally less than values reported from the analyses of solid effluents from conventional coal-fired facilities. The potassium carbonate seed was tested for the some of the same inorganics to ascertain whether seed could be a source of introduction of any of these toxic elements. Although the presence of just 8 of the 13 toxic metals included in the rest of the survey was checked, only thallium and lead were present at levels above 1.0 mg/kg (reported at 3.0 and 8.0 mg/kg respectively). These low concentrations did not significantly add to the quantities found in the feed tank coal.

All 13 EPA-listed inorganic metals were quantified in samples of slag tap and cyclone water. Table VI.6 shows that there were no levels detected above 3.6 mg/L of any toxic metal included in the study.

One of the last phases conducted in this survey of inorganics was collection and measurement of the same 13 toxic metals in the gaseous effluent. Represented in Table VI.7 is the average data from the assessment of vapor (0.05 micron-sized) and particulate material (averaging 0.85 micron) in the gaseous effluent during combustion of Illinois No. 6 coal. The

highest concentrations of inorganics in the two-phased effluent were found in the vapor, perhaps because of the greater surface area of the smaller-sized particles to which these metals could attach.

Table VI.5 Inorganic Pollutants in Illinois No. 6 Coal and Post-Combustion Solids (mg/kg)

	Seeded Coal		Slag		Spent Seed Solids	
	Maximum Past	Average Present	Maximum Past	Average Present	Maximum Past	Average Present
Ag	1.5	2.3	3.2	7.5	2.6	7.4
As	5.9	16	0.6	<0.1	9	26
Be	6.4	4.7	16	4.6	3.6	5
Cd	6.2	6	4.1	4.9	4.8	6.4
Cr	(Not reported due to possible contamination from refractory)					
Cu	42	46	57	9.6	190	63
Hg	1.4	3	0.2	0.3	0.3	0.3
Ni	32	85	54	64	41	68
Pb	94	72	565	18	150	114
Sb	0.5	1	<0.1	0.1	1.3	0.1
Se	4.4	5.6	0.3	0.7	7.3	15
Ti	28	63	53	36	44	47
Zn	244	265	15	77	465	170

Note: 'Past' values represent the maximum concentrations in previous studies on samples collected from other tests burning Illinois No. 6 coal.

Table VI.6 Inorganic Pollutants in Contact Liquids

<u>Element</u>	<u>Slag Quench Water</u>	<u>Cyclone Water</u>
Ag	0.2	0.8
As	0.1	0.02
Be	0.02	0.1
Cd	0.1	0.4
Cr	1	3.6
Cu	0.4	1.4
Hg	0.6 µg/l	25. µg/l
Ni	0.6	2.5
Pb	0.7	3.2
Sb	1.4 µg/l	0.3 µg/l
Se	0.1	0.8
Ti	0.7	3.3
Zn	0.5	1.3

Note: Concentrations in mg/liter unless otherwise noted as µg/liter

Table VI.7 Inorganic Pollutants in Gaseous and Particulate Effluent
(micrograms per cubic meter)

	<u>Vapor Phase</u>	<u>Particulate Material</u>	<u>Total</u>
Ag	<1.0	ND	<MQL
As	2.5	0.4	3.
Be	<0.1	ND	<MQL
Cd	5.7	0.4	6.1
Cr	53.	4.1	57.
Cu	0.6	0.6	1.2
Hg	0.18	NA	0.18
Ni	21.	1.7	23.
Pb	58.	<5.0	58.
Sb	<0.1	ND	<MQL
Se	13.	<10.	13.
Tl	<0.5	<5.0	<MQL
Zn	8.9	5.	14.

ND = Not detected at method detection limit.

<MQL(method quantification limit) = Below level at which value can be confidently quantified according to method.

NA = Not analyzed

Integrating the data collected from the gas phase study of inorganics provided the previously missing information needed to attempt a mass balance of the 13 toxic metals in the MHD system. Table VI.8 lists the results of the mass balance these inorganics over an average

Table VI.8
Mass Balance of Trace Inorganic Pollutants
[Concentration flow rate, mg/min]

	Total Input (Seeded Coal)	Quenched Slag (H ₂ O + Solids)	Cyclone (H ₂ O + Solids)	Spend Seed (BH/ESP)	Gas (Vapor & Particulates)	Total Output	% Recovery (Output/Input x 100)
Ag	24.0	17.6	2.45	0.13	<MDL	20.2	84
As	56.4	0.03	4.76	45.6	1.01	51.4	91
Be	17.9	10.7	1.88	8.75	<MDL	21.3	119
Cd	24.5	11.4	1.38	11.2	2.16	26.1	107
Cr	385	337	64.3	357	20.1	778	202
Cu	165	22.6	33.1	110	0.43	166	101
Hg	0.23	0.07	0.01	0.05	0.06	0.19	83
Ni	314	150	32.8	119	7.95	310	99
Pb	272	42.0	43.5	200	20.5	306	113
Sb	12.3	2.00	4.50	1.80	<MDL	8.30	68
Se	61.3	1.60	3.74	26.3	4.72	36.4	59
Tl	220	84.4	13.6	82.5	<MDL	181	82
Zn	943	181	342	298	4.88	826	88

MDL = below method detection limit

operation time of 163 hours on Illinois #6 coal during the LMF4 test series. Enclosures showed most species falling into the 80% to 120% recovery range, and were considered satisfactory due to the trace levels which were quantified.

Air Toxics - Organics:

Of the 148 compounds included in the survey (the original 161 less the 13 inorganic compounds), no harmful organics were ever detected in the MHD post-combustion solid effluents. In a few composite samples of LMF4 series baghouse/ESP ash collected after burning Illinois #6 coal, n-paraffins were found. These innocuous waxes, probably condensed onto the solid particles after cooling. Samples were also sent to ITC for dioxin/furan analyses. The results showed no such contaminants present at the 0.05 ppb (50 ppt) level.

A limited number of cyclone process contact water samples contained low levels of phenols when extracted and concentrated into an acid medium. However, there were no pre-test samples collected to prove that this type of compound did not come from another source of contamination, or that the concentration detected was not cumulative from other previous MHD tests.

Because of the high temperatures of the primary furnace, as well as the oxidizing conditions after the secondary combustor, it was not anticipated that the MHD gaseous effluent would contain any volatile, uncombusted constituents. But the presence of potentially carcinogenic organic compounds in stack effluent and waste gas condensate from conventional coal-fired facilities was documented in the late seventies and early eighties^(25,26). After procuring the necessary sampling equipment and making modifications to existing laboratory instrumentation in order to accommodate gas trapping cartridges, a qualitative look at samples from a test burning Illinois No. 6 coal showed the presence of low levels of benzene. Gaseous effluents from a later MHD test (LMF5-I), burning Montana Rosebud coal, was sampled using methods to test for the presence of both volatile and semi-volatile organic components. Follow-up quantitative analyses showed that only minuscule amounts of 4 volatile species, out of 35 EPA-listed toxics, were detected in the MHD gaseous effluent. The low nanogram-per-liter level presence of these compounds (benzene, chloromethane, methylene chloride, and bromomethane) was verified by a representative sample which had been sent to the air toxics division of Triangle Laboratory, located in Research Triangle Park, North Carolina. Also detected in the gas phase samples from the LMF5-I test, but not quantified, were low levels of

semi-volatile phthalates, phenols, diols, and aldehydes. The appearance and/or reappearance of these organics in the cooler combustion gases, possibly due to the recombination of low molecular weight radicals which somehow escaped the combustion processes, could have been catalyzed by the addition of potassium seed. However, the fate of the most of the naturally-occurring complex organics in coal when volatilized, even with such a short residence time in the high temperatures of the MHD system, was complete destruction. Overall, the low-level quantities of the few organic components which were detected and quantified in the effluent streams resulting from tests at the CFFF are notably less than those reported by Griest and Bezacinsky^(7,8) in the effluents from plants using conventional coal-fired combustion techniques.

Air Toxics - Summary of Findings

Results from this study (Reference 24) generally established that MHD solid combustion products contained lower concentrations of toxic inorganic species than combustion products from conventional coal-fired power plants. However, specific comparisons while burning the same coal in conventional boilers were not available. Post-combustion depositional trends at various locations along the MHD flow train illustrated that the behavior of trace elements in Illinois #6 and Montana Rosebud coals were similar. Considering the low levels of inorganic constituents detected in the MHD system's effluent, mass balance closures of most species falling into the 80% to 120% recovery range were considered acceptable. Extraction Procedure Toxicity test results indicated that all specified parameters, both inorganic and organic, were below the maximum allowable concentration necessary to allow land filling of solids by permit. No toxic organic species were detected in MHD solid effluents.

Process contact water from the slag tap and cyclone was found to have concentrations of less than 4 mg/L of any of the inorganic species included in the survey. Low levels of organic phenols were detected in a limited number of cyclone water samples collected during a long duration test on Illinois No. 6 coal. However, there was no pre-test sample taken to show proof that the results were not from another source of contamination, or cumulative effects from other previous MHD test contact liquid.

Vapor and particulate material from the MHD system's stack gases were found to contain only trace levels of inorganic pollutants. The greatest concentration of inorganics in this two-phased effluent was found in the vapor state, probably because of its characteristically

smaller-sized particles and consequently, greater surface area. Low nanogram-per-liter levels of 4 toxic volatile organic compounds were quantified in stack gas samples from the LMF5-I test burning Montana Rosebud coal. Although low concentrations of a few other semi-volatile organics were detected in the gaseous effluent, the estimated quantities were far less than what had been reported in stack gases and condensate from conventional coal-fired plants. In summary, the results from this survey seemed to prove that nearly all of the organic matrix of coal is destroyed when introduced into the high temperature furnace. The flow is then exposed to the post-secondary combustor oxidizing conditions of the MHD system.

VIe. Ash Deposition/Superheater/Air Heater Materials Performance

VIe.1 Monitoring Superheater Inlet Conditions

A major component of this test series was testing for ash deposition and tube corrosion in an MHD superheater configuration. Therefore, the superheater inlet temperature needed to be maintained during testing near the appropriate temperature of 1500°K (2250°F). But at this level gas temperature measurements are encumbered by significant radiative heat transfer effects. Radiation losses from gas temperature probes such as sheathed thermocouples can produce errors as great as 9 to 15% of thermocouple readings^(27,28) in this temperature range. To circumvent this problem a radiometric (using gas species radiation) line reversal gas temperature monitor was developed and is illustrated schematically in Figure VI.16. As indicated in Figure VI.16 the line reversal components are external to the superheater environment, and thus not subject to fouling by gas stream species or particulates. Although 1500°K gas temperatures are about 300°K lower than typical for application of line reversal gas temperature measurements, system design allowed successful application to gas temperatures as low as 1200°K (1700°F). Radiation shielded thermocouples employing high velocity aspiration to enhance convective heating (*i.e.*, multiple-shielded high velocity thermocouple or MHVT probes) can measure within a few degrees of these gas temperatures,^(9,10,29) but plug quickly in this particle laden environment. This is not a problem with the non-intrusive line reversal technique in this dirty coal combustion environment. Near continuous day long operation of this line reversal system was part of system design, allowing use of the instrument not only for problem diagnostics, but also use as the CFFF Superheater inlet gas temperature monitor to set and maintain operation at desired conditions.

Figure VI.16. Superheater Line Reversal Schematic

Figure VI.17 illustrates a time history of the line reversal temperature and transmission measurements along with sheathed thermocouple measurements and coal flow measurements. The line reversal is shown to respond immediately (within the 0.33 Hz temporal resolution of Figure VI.16) to small coal flow variations and to provide a continuous monitoring of gas temperature for the hour time frame of Figure VI.17. Simple sheath protected thermocouples, due to their thermal inertia, don't respond as rapidly to gas temperature changes. Aspirated shielded thermocouples, which respond more rapidly, have passages between the shield and thermocouple which plug with the high CFFF particulate loading in about 20 minutes, making them unsuitable as a continuous inlet temperature monitor. Also, aspirated thermocouple operation requires continual operator adjustment of the aspiration flow rate and cooling water flows, while line reversal operation required only short window cleanings every 24 to 48 hours. Gas transmissivity in the potassium species emission line used by the line reversal system is also provided in Figure VI.17, indicating reasonable gas species optical absorption for line reversal is provided by the high potassium concentration in the CFFF gas stream.

Because the gas temperatures are lower than usual for line reversal application, the accuracy of the single wavelength line reversal system was examined by comparing the line reversal temperature readings with short duration simultaneous MHVT measurements acquired adjacent to the line reversal lamp port location. Figure VI.18 shows a time trace of the simultaneous line reversal and MHVT measurements, along with sheathed thermocouple measurements at different vertical positions just ahead of the superheater steam tubes and 0.94 m downstream of the MHVT location. "Unaspirated MHVT" refers to measurements made with the MHVT probe used only as a shielded probe (i.e., without gas aspiration across the MHVT

Figure VI.17. TS1 Coal Flow/Line Reversal/Thermocouple Comparisons

Figure VI.18. Comparison of Gas Temperature Measurements

sensor to enhance probe convective heating as added compensation for sensor radiant cooling.) The larger level changes ($>100^{\circ}\text{F}$) seen in the TS1 gas temperature correspond to atypical jumps in coal flow which fortuitously provide slightly different "steady" mean gas temperatures for line reversal accuracy examination. Unfortunately, the second pair of the four MHVT measurements obviously was taken while the coal flow and mean gas temperature were unsteady, and the slow MHVT response negates the usefulness of this measurement. The three MHVT measurements made during "steady" gas temperature periods are typically 60°F less than the simultaneous line reversal measurements. As indicated by the differences in vertically separated sheathed thermocouple measurements, the 0.37 m position difference between the lower line reversal and the MHVT results in a gas temperature difference between the line reversal and MHVT. Assuming the same temperature profile exists at the line

reversal-MHVT and the sheathed thermocouple axial positions, linear interpolation from the thermocouple temperature profile indicates the gas at the MHVT should be approximately 25°F cooler than the gas measured by the line reversal. The remaining 20°K (35°F) difference between line reversal and MHVT measurements at TS1 is less than the expected measurement uncertainty of either typical line reversal or MHVT measurements, and well below the originally expected uncertainties for this low temperature line reversal application. This indicates an uncertainty of about $\pm 2\%$ of the line reversal readings. Obviously, the low temperature CFFF line reversal system provides as accurate a gas temperature monitor as the best available thermocouple configuration, but without susceptibility to rapid plugging in the high particulate loading environment of the CFFF.

Because of its accuracy and continuous operation capability, the low temperature line reversal system was considered for use as a control sensor for CFFF operation. However, the high frequency response of the line reversal results in small, rapid fluctuations in gas temperature readings, and when displayed digitally as a control parameter these small fluctuations need to be filtered out. To do this a 30 second running average of the high frequency line reversal measurements was provided, resulting in a useful CFFF manual system control parameter. As shown in Figure VI.19, this control parameter provides both a more accurate gas temperature level, and a more appropriate response to condition changes than previously used sheathed thermocouples in the approximately 2250°F CFFF superheater entrance gas temperature environment.

Figure VI.19. TS1 Gas Temperature Control Parameters

The CFFF superheater entrance line reversal was also compared to an MSU Diagnostics Instrumentation and Analysis Laboratory multicolor pyrometer probe system (MCPPS)⁽³⁰⁾. The MCPPS was developed to allow accurate wall surface temperature measurements in hot particle laden environments like the CFFF superheater test module. Measurements from both systems, along with sheathed thermocouple measurements, are compared in Figure VI.20. The MCPPS measured wall emissions at a location 2.1 m upstream of the line reversal. Since radiation is a significant portion of the heat transfer at the CFFF superheater inlet, the refractory insulated hot side wall surface temperatures should closely correspond to the line reversal temperatures, and this is the case as shown in Figure VI.20. The improvement over sheathed thermocouple probes for both these radiometric measurement systems is obvious in Figure VI.20.

Figure VI.20. Line Reversal vs. MCPPS Measurements at CFFF Superheater Entrance

Furthermore, modifications of the line reversal apparatus can be implemented to allow measurement of gas phase sodium or potassium concentrations and to correct the measurements for particle scattering⁽³¹⁾ and particle emission-absorption influences⁽³²⁾ without increasing the line reversal non-simultaneous sampling error.⁽³³⁾

The CFFF TS1 line reversal could be operated at any visible wavelength corresponding to distinct gas phase species emission lines. To determine the preferred detection wavelength the line reversal apparatus was used to obtain spectral emission/transmission scans over the near visible spectrum for different LMF5 test conditions. Figure VI.21 shows several spectral scans starting with a scan for an average superheater gas temperature of 1530°K (2295°F) and a 1% potassium seed addition giving a $K_2/S = 4.2$ with Montana Rosebud coal. At this "average" condition a strong potassium doublet was identifiable, whereas the weaker sodium doublet

appeared as a single line because the CFFF line reversal spectrometer resolution was limited to provide a sufficiently strong signal at the low emission levels of the small sodium concentration in the TS1 gas. Nevertheless, the sodium lines were sufficiently strong and resolved to allow valid line reversal temperature measurements at a gas temperature of 1530°K.

Figure VI.21. Visible Spectra for Different LMF5 TS1 T_g Conditions, K₂/S = 4.2

The potassium emission signal levels are not only stronger than the sodium signals at the higher superheater temperature condition, but potassium emissions are detectable at lower temperature conditions where weak or no sodium emissions are detectable, such as shown in Figure VI.15c. Furthermore, potassium emissions at lower potassium carbonate seed flow rates still provide stronger signals than sodium emissions. The low sodium emissions cause concern because a modest decrease in gas temperature could make them undetectable and thereby negate accurate sodium line reversal measurements. Sufficient gas phase potassium emissions were detected by the CFFF low temperature line reversal apparatus with a gas temperature of only 1190°K. This temperature is well below the temperatures for which line reversal is generally considered applicable, and about 200°K below the sensitivity limitation for sodium line reversal at the CFFF superheater.

Operation of the potassium line reversal at the CFFF superheater during the LMF5 tests showed that gas temperatures down to 1200°K can be routinely measured by the line reversal with adequate sensitivity to provide reasonable accuracies. Potassium line reversal measurements provided monitoring of superheater gas temperatures shortly after ignition of the CFFF flow train while sodium measurements were not possible for almost 40 min. (until the flow train warmed sufficiently). Potassium line reversal also provided accurate monitoring of special low superheater temperature test conditions such as high primary stoichiometry, where gas temperatures were too low for accurate sodium line reversal monitoring. The system operated continuously on either the sodium or the potassium lines for the duration of the last five LMF5 Proof of Concept CFFF tests.

VI.2 Ash Deposition

The Rosebud POC test series had two significant differences from the Illinois coal tests that influenced ash deposition. First, the Rosebud coal ash composition is significantly different from the Illinois coal ash. Second, the higher potassium to sulfur ratios result in a large excess of potassium carbonate, which has significantly different characteristics than potassium sulfate. The second difference was probably of more importance in the relatively short tests run in the low mass flow train. In the very long exposures of thousands of hours of continuous operation expected in commercial boilers, the coal ash composition may play a more important role than in the LMF tests. This is in part because of the normally slow reactions involving deposit solids.

The results of the Rosebud tests resulted in several observations. First, the deposits were significantly different in appearance and composition. One physical difference was the characteristic blue color of the deposits, as shown in Figures VI.22 and VI.23. A significant amount of work was spent trying to identify the reason for this color, but no firm conclusions were drawn. We do not believe it had any significant affect on properties that influence ash deposition. This topic is discussed in more detail below. Second, at higher deposit temperatures, the deposits were relatively friable compared to Illinois coal/sulfate deposits. Sootblowers were effective in maintaining deposition equilibrium throughout the SHTM, even through 'quiet periods', when sootblower operation was suspended to allow data collection requested by The Babcock & Wilcox Company (B&W). Deposit removal was also successfully controlled using a computer program to operate the sootblowers.

Figure VI.22. Ash Deposition TS1

Figure VI.23. Ash Deposition TS3 and TS2

Ash deposition was relatively consistent and well controlled during the entire period when Rosebud Coals were fired. Figure VI.24, illustrates that gas temperatures were maintained at the desired levels during the nearly 300-hour LMF5F test. Results for the other tests were similar. Furthermore, as shown on Figure VI.25, the overall gas pressure drop through the SHTM was stable through this test, indicating that no significant accumulation of deposits occurred.

Figure VI.24. Average Gas Temperature In SHTM

Figure VI.25. Overall SHTM ΔP

Representative deposits from TS1 and TS3 are shown in Figures VI.22 and 23. These distinctive blue deposits were observed during the first tests with Rosebud coal. It was recognized that very small quantities of impurities can produce very strong colors, and an effort was made to identify the material causing the blue color. There was concern by some that one possible compound that might be responsible for the blue color is formed under reducing conditions. However, this seemed unlikely since conditions downstream of the secondary combustor are oxidizing, as confirmed by flow measurements and multiple CO₂ and O₂ analyses. Analyses of the deposits confirmed that oxidizing, not reducing conditions did indeed exist. X-ray diffraction analyses, which provide a semi-quantitative measurement of crystalline compounds present, were made by Oneida Research Services, Inc. These analyses indicated that the major crystalline compound was 2K₂CO₃·3H₂O (Potassium Carbonate, trihydrate). No minor compounds or reduced forms were identified. Calculations made using ash deposit analyses indicated that there was 1.35% excess carbonate above that required to account for the potassium not reacted with sulfur.

Analyses were also performed on 5-stage cyclone samples collected to determine particle size distribution. In these samples, it was observed that the blue color become more prominent as the particle size decreased. Potassium, sulfur and carbonate levels also increased as the size decreased. When samples were ashed at 1382°F (750°C) in an oxidizing (air) atmosphere, the blue color became more prominent. Addition of water to the ashed sample produced an immediate change of color to a pink/red. When the sample was dried, the color changed to white. Upon heating to 1382°F (750°C) in air, the blue color returned. Thermogravimetric analyses of the samples indicated that the blue color developed at about 1292°F (700°C), but there was no appreciable weight gain or loss. Based on these analyses, we concluded that the blue color was not caused by reducing conditions and that the blue color is not a result of hydration, since there is no significant weight loss when the color developed. Additional work will be required to determine the reason for the color, but is not planned.

Another significant effort related to ash deposition was that concerned with computer control of the soot blowing operation. This was accomplished using the gas temperature drop across each of three control zones for determining the blowing requirements in each zone. The gas temperature drop across each zone was used as an indicator of the extent of fouling since the last cleaning cycle (i.e., increased fouling = less heat removed from gases = lower differential between gas temperature entering and leaving that zone). By using running averages to

determine the changes in gas temperature drops across a zone, the program was less sensitive to operating changes such as thermal input. The averages were then compared with set point references to determine when fouling had reduced the cooling efficiency to the point where sootblowing was desired. Set points were empirically derived and improved as operating experience was gained. The purpose of soot blowing is to remove deposits and improve the heat transfer in a specific zone. However, blowing in one zone also affects gas temperatures and heat absorption patterns in downstream zones. Therefore, these effects were being considered as operating experience and data were obtained.

Ash Deposition Modeling

A comprehensive 2-D real-time engineering model for ash deposition/heat transfer effects under specific conditions on superheater (or air heater) tubes was under development late in the LMF5 series. The specific capability would be very useful for relating to pilot plant data and predicting ash deposition in a future boiler retrofit application, or for optimizing design/operation details for a new, first-of-a-kind power-plant design. The model is designed to predict variations in superheater deposit shape and heat exchanger performance as functions of time. It is the only model available to simultaneously consider factors lacking in other studies:

- a. gas and particle size distribution and velocity,
- b. tube diameter,
- c. particle density,
- d. deposit shape,
- e. elemental composition of the ash,
- f. ash viscosity,
- g. changes occurring as a function of time and deposit removal through soot blowing and load changes,
- h. particle deceleration on impact.

Boiler design specifics, load, coal properties, boiler operational choices, and locally-entrained ash characteristics are input in terms of superheater tube diameter, steam temperature, flue gas temperature, gas and particle velocity, gas and particle density, gas viscosity, multiple deposition time increments, particle diameter distributions, and dust loadings with elemental analyses for multiple narrow-range particle diameter bins plus calculated viscosity for impacting particles. A coal ultimate analysis input is used to calculate flue gas composition and flue gas viscosity. Particle size distribution data from a five-stage

cyclone measurement made downstream from the MHD secondary superheater location, and elemental analyses of the stage-collected fly ash particles represent the major fuel-related input data. Data from particles significantly larger than the fifth stage of the cyclone were not available and therefore not included in the engineering model input.

Output of the UTSI model calculations included two-dimensional deposit shape as a function of time, and location of impaction on the fireside surface as a function of impacting particle diameter. Details of the model are contained in a Dissertation by X. Yan⁽³⁴⁾ and a paper by C. Wagoner et. al.⁽³⁵⁾

The calculated deposit shape and size were determined for a number of variables, including gas velocity, superheater tube diameter, particle loading and others. Figure VI.26 illustrates the effect of gas velocity for two tube diameters. The effect of fly ash particle size is demonstrated on Figure VI.27. This data was calculated using data from Test LMF5F, when Montana coal only was fired for about 8 hours and coal plus seed was used for the remainder of the test. Fly ash particle size was larger while firing coal only than while using potassium seed with the Rosebud coal. The modeling results can be compared directly with the actual superheater deposits generated during the combustion test that supplied the five-stage cyclone samples, or deposit shapes can be calculated for other site-specific locations (larger or smaller scale, as desired) assuming the same fly ash particles were present at the other site. Initial comparisons for deposit thickness, made during LMF5J, are shown in Figure VI.28. The calculations are in very good agreement with experimental results. Calculations of deposit width did not agree as closely, primarily due to the lack of complete particle size data in one case. Within the period evaluated, the deposit rate was linear with respect to time.

The inertial-impaction module is one of several mass transfer mechanisms included in the UTSI model that was under development when the program was terminated. The site-specific nature of the calculation is useful for scaling test data to other sizes and designs of equipment, and for relating pilot and full scale data. Results were very promising when the tests were terminated. The engineering calculations were being developed to be applicable to MHD conditions which frequently can include molten surfaces on deposits on a superheater tube located in the higher gas temperature zones. More complete particle size data is required, which we believe would further improve the correlation between theoretical calculations and experimental measurements. In addition, the model was being designed to be applicable to conventional coal-fired equipment.

IL-1609

Calculated deposit growth during a 6-hour period on a clean MHD superheater tube shown with 1-hour steps for fly ash particles from Montana Rosebud coal plus seed, 1478 K [2200°F] flue gas and 866 K [1100°F] tube metal.

Figure VI.26. Combined Effect of Tube Diameter & Gas Velocity on Deposition Rates

IL-1610

Calculated deposit growth on clean KMHD superheater tube during an 8-hour period, shown with 1-hour steps, for Rosebud coal alone and Rosebud coal plus seed, 63.5 mm tube OD (2.5"), with 18.3 gas velocity (60 ft/s), 1478 K [2200°F] flue gas and 8676 K [1100°F] tube metal.

Figure VI.27. Effect of MHD Seed vs. Firing Coal Only

Figure VI.28. Calculated and Measured Thickness on Ash Deposit Probe, LMF5J

VIe.3 Performance of Superheater/Intermediate Temperature Air Heater Tube Materials⁽³⁶⁾

Iron-based and nickel-based alloys covering a broad compositional range were exposed during six test runs denoted LMF5E through J with individual on-coal and on-seed run times of 38.6, 287.6, 312.9, 87.6, 207.4, and 51.3 hours totaling 985.4 hours to conditions simulative of fire-side superheater and intermediate temperature air heater service in MHD power generating plants burning relatively low sulfur, high ash, and high volatile Montana Rosebud coal. Test alloys and their nominal compositions are given in Table VI.9, while placement in the test sections is given in Figures V1.29 and VI.30. They were in the form of 7.5 feet long pendant u-shaped tubes mounted in three duct modules called test sections (TS), located in regions of successively lower gas temperature, averaging about 2200°F for TS1, 1600°F for TS2, and 1277°F for TS3. Steam cooling was used to maintain maximum metal temperatures of 1400°F at TS1 and TS2 and 1100°F at TS3. Along the tube length, metal temperatures ranged from about 700°F to the controlled maximum.

During testing, deposits containing approximately 35% potassium sulfate, 30% potassium carbonate, and 30% flyash formed on the tubes. After exposure, corrosion of tube samples was evaluated in terms of scale thickness and depth of internal penetration, comparison of remaining wall thickness with initial ultrasonic thickness measurements, and qualitative microscopic evaluation of scale, penetration, and deposit morphologies. Pre-exposure wall thicknesses were measured ultrasonically at 6 inch intervals and at every 45 degrees around the tube. Remaining wall thicknesses for TS1 and TS2 were measured either microscopically

Table VI.9 Nominal Composition of Test Alloys (in Weight %)

	Cr	Ni	Cr/Ni	Fe	Mo	W	V	Nb	Ti	Mn	Si	P	S	Al	C ²	N
SA192	-	-	-	Bal.	-	-	-	-	-	0.45	0.20	0.03	0.03	-	0.15	-
T11	1.25	-	-	Bal.	0.50	-	-	-	-	0.45	0.75	0.03	0.03	-	0.15	-
T22	2.50	-	-	Bal.	1.00	-	-	-	-	0.45	0.50	0.03	0.03	-	0.15	-
T9	9.00	-	-	Bal.	1.00	-	-	-	-	0.45	0.40	0.03	0.03	-	0.15	-
316	17.0	12.0	1.42	Bal.	2.50	-	-	-	-	2.00	1.00	0.05	0.03	-	0.07	-
347	18.0	11.0	1.64	Bal.	-	-	-	0.70	-	2.00	1.00	0.05	0.03	-	0.07	-
RA85H	18.0	14.0	1.29	Bal.	-	-	-	-	-	0.50	3.50	-	-	1.00	-	-
304H	19.0	9.00	2.11	Bal.	-	-	-	-	-	2.00	1.00	0.05	0.03	-	0.07	-
MA 956	20.0	-	-	Bal.	-	-	-	0.50	-	-	-	-	-	4.50	-	-
800H	21.0	32.5	0.65	Bal.	-	-	-	-	0.38	0.80	0.50	-	-	0.38	0.08	-
253MA *	21.0	11.0	1.91	Bal.	-	-	-	-	-	0.80	1.70	0.04	0.03	-	0.10	0.17
Temp A3	22.0	15.0	1.47	Bal.	-	-	-	0.70	-	1.37	0.40	0.03	0.01	-	0.05	0.19
556 **	22.0	20.0	1.10	Bal.	3.00	2.50	-	-	-	1.00	0.40	-	-	0.20	0.10	0.20
310	25.0	20.0	1.25	Bal.	-	-	-	-	-	2.00	1.50	0.05	0.03	-	0.25	-
HR3C	25.0	20.0	1.25	Bal.	-	-	-	***	-	2.00	1.50	0.05	0.03	-	0.08	0.10
HR-160 *	28.0	Bal.	0.74	4.0	-	-	-	-	-	0.50	2.75	-	-	-	0.05	-
IN 690	29.0	Bal.	0.47	9.0	-	-	-	-	-	-	-	-	-	-	-	-
CR30A	30.5	Bal.	0.62	17.7	2.10	-	-	-	0.18	0.20	0.27	-	-	0.14	0.06	-
CR35A	35.0	Bal.	0.76	18.2	-	-	-	0.50	-	-	0.07	-	-	-	0.07	-

* Contains 0.05% Ce ** Contains 18.0% Co, 0.6% Ta, 0.02% La, 0.02% Zr *** 1% Nb+Ta * Contains 27% Co

Figure VI.29. Placement of Alloys in TS1 and TS2

through the deposit. Natesan⁽³⁷⁾ showed the active deposit species to be K_2SO_4 , and that corrosion is substantially greater with deposits than without. While compact, protective oxide scales are produced on appropriately chosen heat resisting alloys exposed solely to oxidizing combustion gases, the presence of sulfate salt deposits changes the corrosion mechanism from purely oxidation to oxidation/sulfidation. This results in porous, thicker, often multi-layered and spalled scales of lowered protectiveness.

2. No liquid phase corrosion occurred, as from the complex alkali trisulfates such as $K_2Fe(SO_4)_3$, responsible for potentially severe conventional coal ash corrosion. Such compounds should not normally be present in MHD as a result of low SO_2 and SO_3 concentrations in the flue gas.
3. Many of the corrosion characteristics in these tests were similar to those occurring in liquid phase coal ash corrosion. These similarities included having the same corrosion precursor (K_2SO_4), the same type of scales, the same migration of iron into the deposit, and precipitation of iron oxide near the outer boundary of the diffusion zone as a result of decreasing sulfur partial pressure and increasing oxygen partial pressure.
4. Corrosion resulted in mostly oxide scales containing a small amount of sulfur either in solution or as discrete sulfides. Sulfur penetration of the scale resulted in enhanced outward metal ion migration and production of Cr-Fe scales often having multiple layers. Much separation of these scale layers and scale fracturing occurred, augmented by the relatively large number and intensity of thermal cycles which occurred. The red phase containing iron and sulfur, assumed to be $FeSO_4$, between the scale and the deposit formed by migration of iron into the deposit constituted not only a loss of tube metal but also a brittle phase prone to spalling and to contributing to scale spalling. Since the scale damage would enhance further corrosion, this process could eventually reach a break-away stage wherein scales of adequate protectiveness were no longer maintained due to subsurface chromium depletion and rapid attack would occur. However, cyclic conditions producing scale spalling were far more severe in these tests than would be expected in actual service.
5. Internal penetration of most of the austenitic stainless steels occurred as a result of inward migration of oxygen and sulfur being faster than the outward migration of cations. This penetration resulted in subscale sulfides in some cases, in transgranular

oxidation/sulfidation of the surface grains, and intergranular penetration to a depth of several grains, depending upon the chromium content.

6. Resistance to corrosion generally increased with increasing alloy chromium content. Alloy CR35A with 35% Cr was the most resistant of those tested. See Figures VI.31-VI.33. A statistical ranking of scaling and penetration performance of pass 1 alloys from best to worst was: CR35A, 310, 556, MA956, 253MA, HR3C, HR-160, CR30A, RA85H, and CR-800H. For pass 2, the performance ranking from best to worst was: 253MA, 310, 304H, 347, 316, Temp A3, 690, and chromized T9. The rankings show the importance also of high chromium to nickel ratio. Alloys MA956 and 253MA, with 20-21% Cr and high Cr to Ni ratio, performed as well or better than some other alloys with considerably higher chromium content. Wall thinning data in Figures VI.32 and VI.33 does not take into account either internal penetration or scaling on the tube ID.
7. Monotonically increasing corrosion with temperature was not generally observed due to the ability of high chromium alloys to produce more protective surface scales at high temperatures than at lower temperatures.
8. There was little difference in corrosion between TS1 with a gas temperature of around 2250°F and hard, thick deposits, and TS2, with a gas temperature of about 1700°F and friable deposits. There was, however, evidence of more scale spalling at the higher gas temperature.
9. There was little or no dependence of corrosion on angular position around the tube. Higher frontal heat flux to the tube deposits was offset by thicker, more insulating frontal deposits so that there was no consistent pattern of temperature relative to angular position.
10. The four alloys (316, 304, 253MA, and 310) tested in both the prior LMF4 test series with Illinois #6 coal and the present LMF5 test series with Montana Rosebud coal showed considerably lower corrosion with the Montana Rosebud coal (see Table VI.10). The difference was assumed to be due to lower sulfur content in the Rosebud coal and in the tube deposits.

Figure VI.31. Corrosion Scale Thickness and Penetration Depth (in micrometers) for CFFF Superheater/ITAH Tubes Exposed to 991 Test Hours (except as noted) Under LMF5 Conditions

Figure VI.32. Fireside Tube Surface Recession (micrometers) (averaged at a given cross-section) Plotted Against Average Metal Exposure Temperature (°F)

Figure VI.33. More Fireside Tube Recession (micrometers) (averaged at a given cross-section) Plotted Against Average Metal Exposure Temperature (°F)

Table VI.10 Comparison of Average Corrosion Rates (mm/yr) in LMF5 Tests with Montana Rosebud Coal to LMF4 Tests with Illinois #6 Coal

a. Linear												
Alloy	TS1						TS2					
	LMF4				LMF5		LMF4				LMF5	
	500 hrs.		1500 hr.	2000 hrs.	1000 hrs.		500 hrs.		1500 hrs.	2000 hrs.	1000 hrs.	
	Pass 1	Pass 2	Pass 1	Pass 1	Pass 1	Pass 2	Pass 1	Pass 2	Pass 1	Pass 1	Pass 1	Pass 2
316	1.02	0.32	0.97	0.49	-	0.12	1.41	1.02	1.09	-	-	0.20
304H	0.62	0.18	0.75	0.47	-	0.07	2.10	0.38	1.10	0.77	-	0.17
253MA	0.33	0.14	0.33	0.19	0.16	0.05	0.70	0.41	0.49	-	0.28	0.07
310	0.11	0.44	0.32	0.11	0.21	0.06	0.53	0.15	0.65	0.35	0.22	0.13
b. Parabolic												
Alloy	TS1						TS2					
	LMF4				LMF5		LMF4				LMF5	
	500 hrs.		1500 hr.	2000 hrs.	1000 hrs.		500 hrs.		1500 hrs.	2000 hrs.	1000 hrs.	
	Pass 1	Pass 2	Pass 1	Pass 1	Pass 1	Pass 2	Pass 1	Pass 2	Pass 1	Pass 1	Pass 1	Pass 2
316	0.24	0.08	0.40	0.22	-	0.04	0.34	0.24	0.45	-	-	0.07
304H	0.15	0.04	0.31	0.23	-	0.02	0.50	0.09	0.46	0.37	-	0.06
253MA	0.08	0.03	0.14	0.09	0.05	0.02	0.17	0.10	0.20	-	0.10	0.02
310	0.03	0.03	0.13	0.05	0.07	0.02	0.13	0.04	0.27	0.17	0.07	0.04

VII. CONCLUSIONS AND RECOMMENDATIONS

The first eleven comments are based on the specific results of the UTSI MHD program and their relation to the UTSI objectives.

1. More than 2000 hours of POC testing were successfully accumulated while firing Illinois No. 6 coal and nearly 1050 hours while firing Rosebud coal. Base test conditions were similar for both coals.
2. Significant differences in moisture, reactivity and mineral matter composition between the Illinois and Rosebud coals required equipment modifications and led to operating differences. Significant effects are summarized below.
3. The coal preparation system, modified to produce a dry, pulverized coal in an inert atmosphere while pulverizing the higher moisture, more reactive Rosebud coal performed very well. It produced a satisfactory coal particle size while providing a uniform coal feed rate.
4. During the Illinois No. 6 coal tests, the seed and coal were mixed in the pulverizer. This approach worked well, but desired changes in the mixture ratio to the combustor were difficult to achieve. This was due to the long residence time and the mixing that occurred in the storage and feed tanks. The system used for the Rosebud tests, a 47% solution of K_2CO_3 injected with No. 2 fuel oil into the combustor also worked well. This system provides more precise control and the flow rate can be adjusted instantly. This approach does reduce the combustion temperature somewhat. However, it could be adapted to feed a potassium formate solution (from a seed reprocessing plant) or molten liquid to overcome the temperature reduction.
5. The MHD upstream simulation components performed well throughout testing with both coals, including one test during which a TRW combustor segment was installed. A Topping cycle diagnostic access ring was successfully installed and pressure measurements were made, confirming that the LMF5 flow choked at the location of the ring.
6. Excess potassium carbonate in the combustion gases (due to the lower Rosebud sulfur content) increased the secondary combustion ignition temperature compared to the Illinois coal tests. Adequate procedures were developed to compensate for these differences.

7.
 - a. The particulate emissions were slightly finer for the Rosebud coal than for the Illinois coal (about 0.5 μm or less compared to 0.8 μm , respectively).
 - b. The baghouse was effective in reducing particulate emissions to levels well below NSPS and Combustion 2000 goals, with efficiencies generally above 99.9%. Levels as low as 0.0003 and 0.0006 lb/MBtu were measured at the baghouse outlet for the Rosebud and Illinois coals, respectively.
 - c. The dry ESP performed erratically during the POC tests with both coals. The problem was resolved after smaller diameter electrodes were installed on the recommendation of ADA, Inc. Even with erratic performance, emissions during the Illinois Coal test well below NSPS requirements and original Combustion 2000 goals were achieved during some tests. After the electrode change, emissions were consistently below NSPS goals at rated flow rates.
 - d. The final component of the wet ESP system, the rotary drum filter, was not installed until the LMF5G test. It was designed to replace the wet scrubber, to take all the exhaust flow and meet permit requirements (20% capacity). The wet ESP met NSPS requirements with 21% of the total gas flow passing through it. It also met Tennessee regulations with more than 98% of the gas flow passing through it. At about design flow conditions, emissions were above NSPS but did meet the Tennessee permit regulations for which it was designed. Test time was not available to fully evaluate this system, but it is our belief that this system can meet emission requirements. It also has a number of advantages in a system employing a seed reprocessing approach using a solution or slurry input.
 - e. An economic evaluation of the three systems evaluated is required to select the optimum cleanup device.
 - f. No EPA toxic organic compounds were detected in the MHD solid emissions. Inorganic toxics were well below the allowable limits for landfilling of solids. Vapor and particulate emissions contained only trace levels of inorganic pollutants. The study showed that nearly all of the organic matrix is destroyed in the MHD system.
8. In spite of very high levels of NO_x generated in the combustor, emissions for both coals were controlled to levels well below NSPS requirements. Levels were slightly

higher for the Rosebud coal, which was attributed to the lower sulfur content. Sulfur dioxide emissions can be eliminated for all practical purposes by operating with sufficiently high K_2/S levels. The SO_2 levels were generally under NSPS requirements with a K_2/S ratio of about 1.5 and above.

9. A radiometric line reversal gas temperature monitor, a non-intrusive device, was successfully developed to measure temperatures at the SHTM inlet.
10.
 - a. Ash deposition was well controlled during testing of both coals, even though gas lanes were smaller than conventional commercial systems. The coal type had a significant effect on deposit characteristics. The Rosebud coal conditions produced a characteristic blue deposit in the SHTM tube banks. Although it did not adversely affect ash deposition, future work should include a study of the causes of this blue color. Also, because reactions involving solids are very slow, ash deposition should be carefully monitored during controlled conditions over long periods of continuous operation if MHD development is ever reinstated.
 - b. A comprehensive model, considering factors lacking in other available studies, related well to experimental data. It is recommended that work continue on this model for MHD as well as for conventional boiler applications.
11. Corrosion resistance of metal alloys with potential application in superheaters and intermediate-temperature air heaters increased with increasing chromium content during tests with both coals. During the Rosebud tests, alloys with 20-21% Cr and high chromium to nickel ratios, performed as well as or better than other alloys with higher chromium content but lower Cr/Ni ratios. Four alloys, 316, 304, 253MA and 310 (see Table VI.9 for composition) showed considerable lower corrosion with Rosebud coal than with Illinois coal, which was attributed to the lower Rosebud sulfur content. However, the data should be used carefully, because of the differences in test times. Additional data must be acquired to provide design information for commercial plants. Information must also be acquired to develop design data and evaluate performance of materials (metallic & ceramic) for application in the primary furnace reducing zone.

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