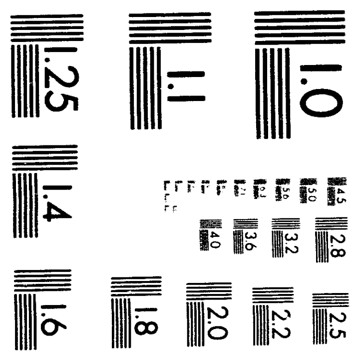
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DOE/ET/10815-223
DIST. CATEGORY UC-112
UTSI-93-08

TECHNICAL PROGRESS REPORT

FOR

THE MAGNETOHYDRODYNAMICS

COAL-FIRED FLOW FACILITY

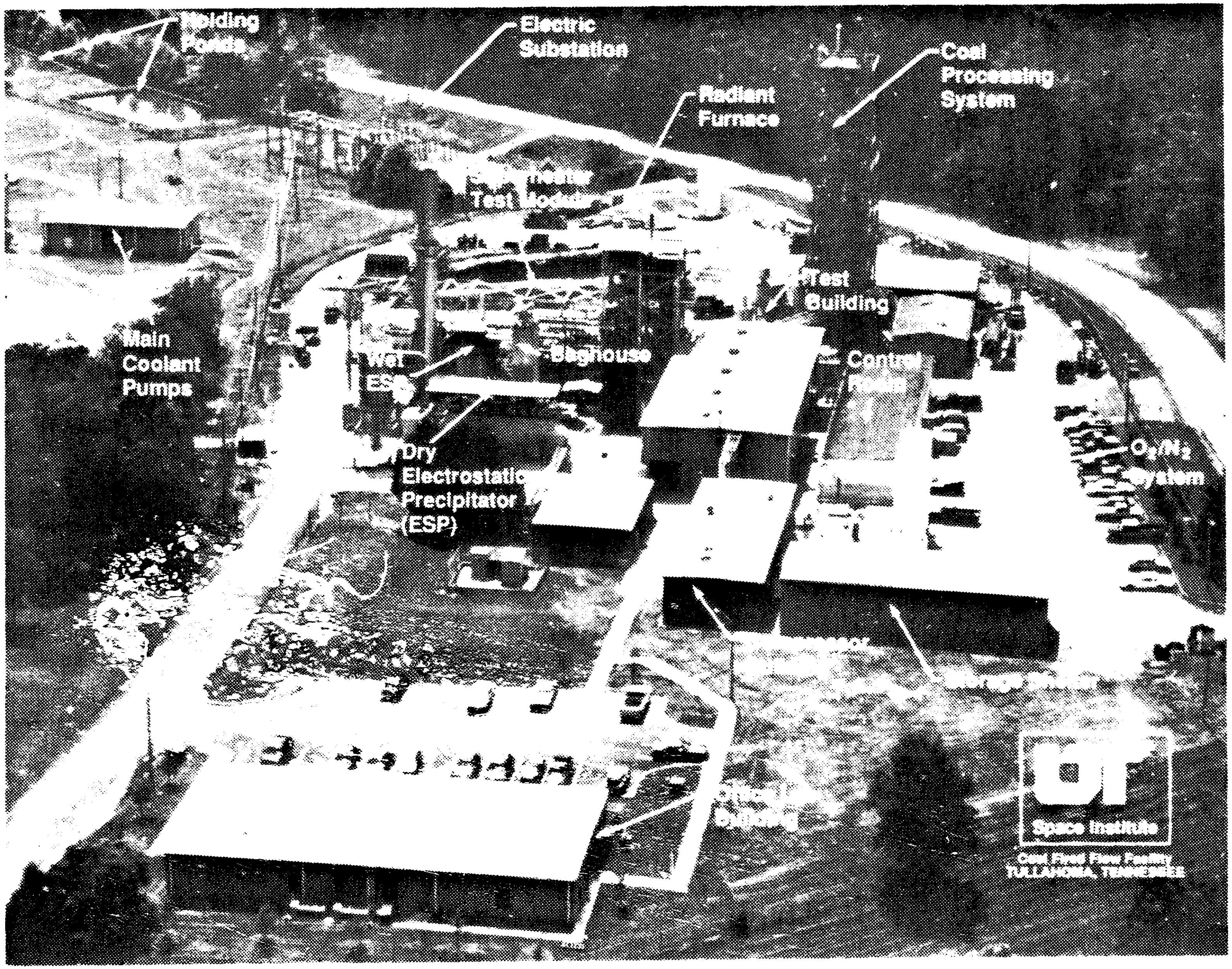
For The Period
April 1, 1993 - June 30, 1993

October 1993

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

Prepared for:
The United States Department of Energy

Prepared by:
The University of Tennessee
Space Institute
Energy Conversion Research and Development Programs



COAL-FIRED FLOW FACILITY

PREFACE

The purpose of this report is to provide the status of a multi-task research and development program in coal fired MHD/steam combined cycle power production. More detailed information on specific topics is presented in topical reports. Current emphasis is on developing technology for the Steam Bottoming Cycle Program. The approach being taken is to design test components that simulate the most important process variables, such as gas temperature, chemical composition, tube metal temperature, particulate loading, etc., to gain test data needed for scale-up to larger size components.

Previous reports have provided comprehensive data on NO_x and SO_x control, radiant heat transfer, particulate control (baghouse and wet and dry electrostatic precipitators), environmental monitoring, and analyses of test data on the convective heat transfer components (superheater and air heater) with eastern, high sulfur coal firing. For this quarter, continued analyses of the data for previously completed eastern coal testing and western coal proof-of-concept (POC) tests are reported. Detailed data analyses will be contained in test reports, topical reports or technical papers.

By the use of these quarterly technical progress reports, MHD program participants and others interested in the technology will be able to gain the knowledge necessary for the confident design of a scaled-up steam bottoming plant.

ABSTRACT

In this quarterly technical progress report, UTSI reports on progress on a multitask contract to develop the necessary technology for the steam bottoming plant of the MHD Steam Combined Cycle power plant. A Proof-Of-Concept (POC) test was conducted during the quarter and the results are reported. This POC test was terminated after 88 hours of operation due to the failure of the coal pulverizer main shaft. Preparations for the test and post-test activities are summarized.

Modifications made to the dry electrostatic precipitator (ESP) are described and measurements of it's performance are reported. The baghouse performance is summarized, together with actions being taken to improve bag cleaning using reverse air. Data on the wet ESP performance is included at two operating conditions, including verification that it met State of Tennessee permit conditions for opacity with all the flow through it.

The results of experiments to determine the effect of potassium seed on NO_x emissions and secondary combustion are reported. The status of efforts to quantify the detailed mass balance for all POC testing are summarized. The work to develop a predictive ash deposition model are discussed and results compared with deposition actually encountered during the test. Plans to measure the kinetics of potassium and sulfur on flames like the secondary combustor, are included. Advanced diagnostic work by both UTSI and MSU are reported. Efforts to develop the technology for a high temperature air heater using ceramic tubes are summarized.

Significant accomplishments, findings and conclusions are highlighted by bold type in Section II of this report and include:

- **A draft Topical Report, "The Low Moisture Eastern Coal Processing System at the UTSI-DOE Coal Fired Flow Facility," was issued.**

- **The CFFF test, LMF5-H, a long-duration, proof-of-concept (POC) test on western coal was conducted during April 1993. This test was terminated after 88 hours on coal due to the failure of the main shaft in the coal pulverizer.**

- **An additional 200 hours of POC testing in the CFFF was authorized by DOE. A 350-hour long-duration test is scheduled for September 1993. This will increase total testing in FY93 to 655 hours for a grand total of 1350 hours on western coal.**

- **A FINAL Topical Report, "Ash Deposition During Illinois #6 Coal Proof of Concept Testing at the Coal Fired Flow Facility," was issued.**

- **A study of the optical properties of the MHD furnace was completed.**

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SECTION I

OBJECTIVE AND SCOPE OF WORK

Under Contract No. DE-AC02-79ET10815, the overall objective is to advance the technology of direct coal-fired MHD components and systems required for MHD power generation operating under conditions simulating those of central power stations.

The specific objectives of the DOE Coal-Fired Flow Facility (CFFF) are to resolve experimentally and analytically the key technical areas of concern which have been identified or which may be found to occur in direct coal-fired MHD systems with moderate to high ash carryover. The key areas involve (l) combustor performance, (2) ash/seed particle collection efficiency from the exhaust gas stream, (3) effects of plugging, fouling and corrosion during normal operation, (4) performance of candidate materials in a direct coal fired MHD environment and (5) the operation, conditions, procedures and equipment needed to meet pollution control requirements.

The overall scope of work is summarized under each of the following TASK headings. No modifications were made in the scope of tasks of this contract during the reporting period.

TASK 1 - CONSTRUCTION OF THE CFFF

This task was completed under a prior contract.

TASK 2 - DESIGN AND FABRICATION OF THE 8 LB/SEC TOTAL GAS FLOW, HIGH SLAG THROUGHPUT TEST EQUIPMENT

Provides for specification, design, fabrication and installation of the air heater, superheater, baghouse filter, and electrostatic precipitator. All of these components are installed and have been functionally tested.

TASK 3 - BASE OPERATIONS FOR THE CFFF

Provides for the operation of the CFFF and supporting laboratories and services which, in addition to management of the facility organization, includes: a) Safety, b) Engineering Services, c) Test Control and Support/Data Processing and Documentation, d) Analytical and Chemistry Laboratory Services, e) Environmental Monitoring and Compliance, f) CFFF Mechanical Maintenance Operations, g) Instrumentation and Control, h) Quality Assurance, i) CFFF Preventive Maintenance and j) Graphics Support Services.

TASK 4 - OPERATION AT 8 LB/SEC TOTAL GAS FLOW, HIGH SLAG THROUGHPUT TEST

Encompasses the testing of CFFF equipment and designed components, test data collection, analyses and reporting. A total of 695 hours of long-duration, proof-of-concept (POC) testing on western coal was achieved during FY92 and 88 POC hours to date for FY93. In addition, a cost performance model for the MHD/Steam Power Plant to evaluate the technical and economic significance of test data obtained from current MHD experience will be maintained and improved upon as appropriate.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

Provides for the testing of DOE supplied components.

No specific activity was scheduled for FY93.

TASK 6 - MODIFICATIONS TO THE CFFF

Provides for major facility modifications which included conversion to a western coal processing system, molten ash handling system and a wet electrostatic precipitator (ESP).

The Babcock & Wilcox Company (B&W) and UTSI designed and specified the necessary equipment/hardware that would allow the CFFF to process western coals. This sub-bituminous coal has a much higher moisture content than eastern coals and requires modified handling and processing techniques. UTSI completed the installation of this equipment and it is being used during long-duration, POC testing with western coal.

B&W and UTSI also designed an automated seed/ash handling system as part of the Integrated MHD Bottoming Cycle program. UTSI procured, installed and made all necessary facility modifications required to integrate the new equipment with existing hardware. This included providing proper interfaces for all utilities (electrical, instrument air, cooling water, etc.) as well as any piping and structural modifications required. This system was operational during FY92 testing.

The high temperature air heater (HTAH) materials evaluations, reoriented toward determining the feasibility of using a recuperative air heater instead of the original plan of developing a regenerative air heater, will be continued with the evaluation of tube test specimens made from promising composite materials.

A separate seed injection system to inject a 47% solution of K_2CO_3 directly into the combustor, as opposed to adding seed to the coal during pulverization, was developed and installed. The system will allow for a significant improvement in the control of the amount of seed added during combustion and of the molar potassium-to-sulfur ratio. This system for separate seed injection has been upgraded and utilized for more automatic control during FY93 CFFF testing.

The molten ash/seed handling system was installed and has been undergoing evaluation during testing. Refinements or changes were made during FY92 to improve the system's operation and it is now being used during all testing.

A major development project during FY92 was the procurement and installation of a wet electrostatic precipitator (ESP) to replace the existing, worn-out wet venturi scrubber and rotary vacuum filter. A wet ESP has several advantages: 1) a seed regeneration system first dissolves the seed in water for processing, and will already be in this form exiting from the wet ESP, 2) this system, unlike a dry ESP, can collect K_2CO_3 and K_2SO_4 separately for further processing, and 3) a wet ESP will allow the CFFF to consistently meet State particulate emission limits not achievable with the wet venturi scrubber. The latter item is the main reason for this procurement.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

Provides for additional technology development services on a task order basis as approved by DOE. No specific activity was scheduled during FY93.

TASK 8 - TEST INTEGRATION AND INTERFACE

Provides for technical expertise and support to DOE in the form of meetings, conferences, and review panels relating to MHD systems. UTSI's involvement in the annual MHD contractors' program review session is an example.

TASK 9 - PROGRAM MANAGEMENT

Provides for the overall management of the program which entails the planning, scheduling, organizing, staffing, directing, coordinating and controlling of resources required in the performance of the contract. Specific support staff functions include project control, reporting, accounting and financial affairs, government property administration, contract administration, and quality management.

CFFF PROGRAM GOALS AND SCHEDULE

Figure 1 shows the major scheduled program tasks completed during the April through June 1993 period.

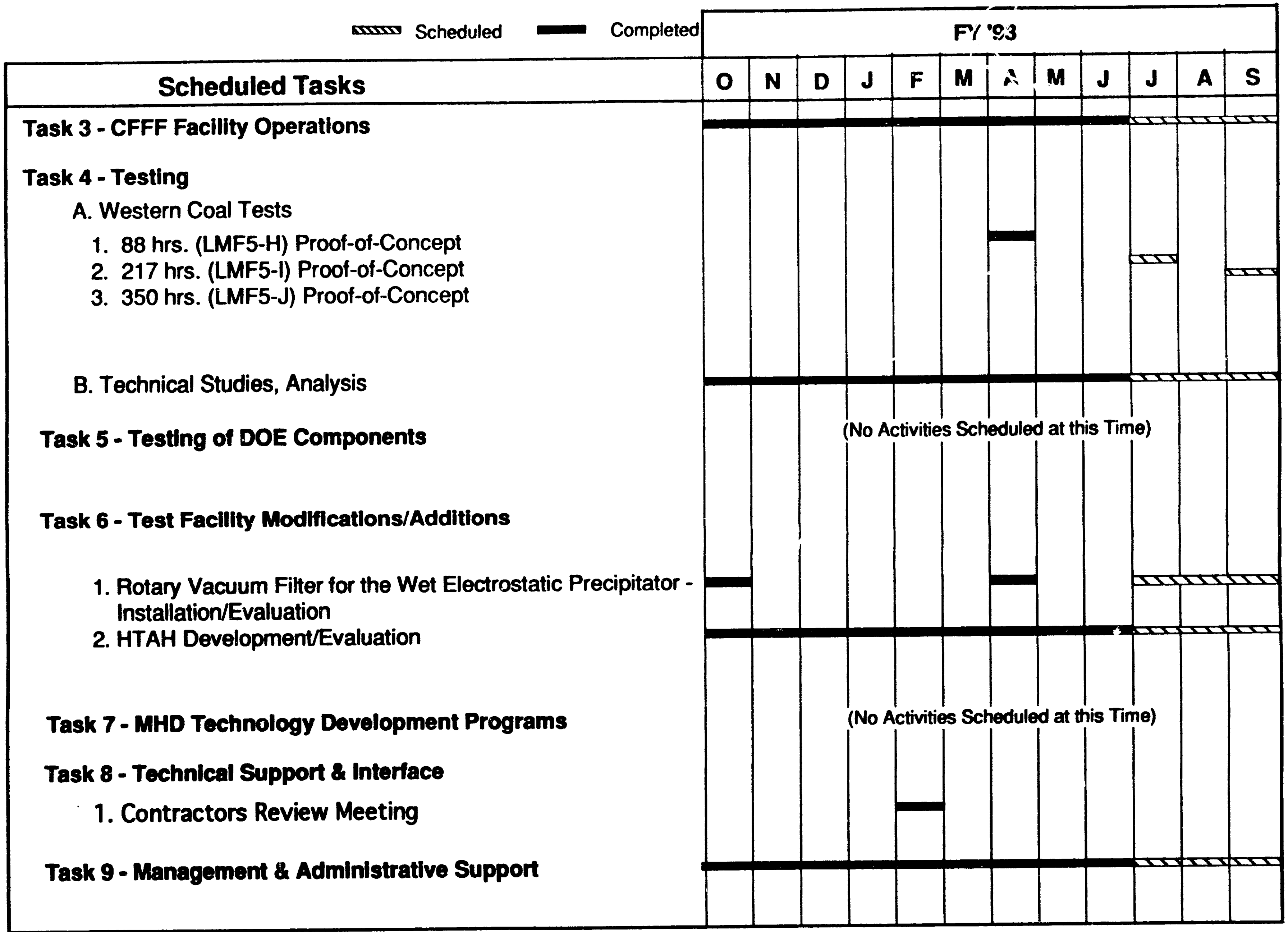

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FIGURE 1. SCHEDULED TASKS

SECTION II

SUMMARY OF TECHNICAL PROGRESS

This section addresses the technical progress of work conducted during the period April 1 through June 30, 1993, according to the objectives and scope of work tasks outlined in Section I. Tasks 1 and 2 are completed and no further effort is being expended in these areas. Figure 2 is a schematic of the current LMF test train.

TASK 3 - BASE OPERATIONS FOR THE CFFF

FACILITIES OPERATION, MAINTENANCE, AND REPAIR

During the LMF5-H test one of the balls in the coal pulverizer fractured (Figure 3) causing a main shaft failure (Figure 4). After the test, the pulverizer was disassembled and inspected. In addition to the failed shaft, the housing wear plates, the bearings and races, the yoke, and the main drive belt pulley were found to have been damaged. Required replacement parts were procured and the pulverizer reassembled and readied for the next CFFF test planned for early July 1993.

Repairs and modifications to the wet electrostatic precipitator (ESP) rotary drum filter were completed before the start of the LMF5-H test. Though the drum drive gearbox had been returned for warranty repair, the contractor determined that the gearbox should be replaced rather than repaired. A new unit was received and installed. Piping modifications also were completed. The rotary drum filter successfully operated during the LMF5-H test.

Before the start of the LMF5-H test, the following additional maintenance items were accomplished:

- The replacement of the 1/4" square and 5/6" diameter dry ESP discharge wires with 1/8" diameter wires was completed.
- All upstream cooling water orifices were reinstalled after completion of orifice calibration.
- Steam tubes and headers were installed in the superheater.
- Repairs to the ash transport system were completed.

TEST CONTROL AND SUPPORT

The major activities this quarter involved planning, preparation, and the conduct of the LMF5-H test in addition to planning and preparation for the LMF5-I test.

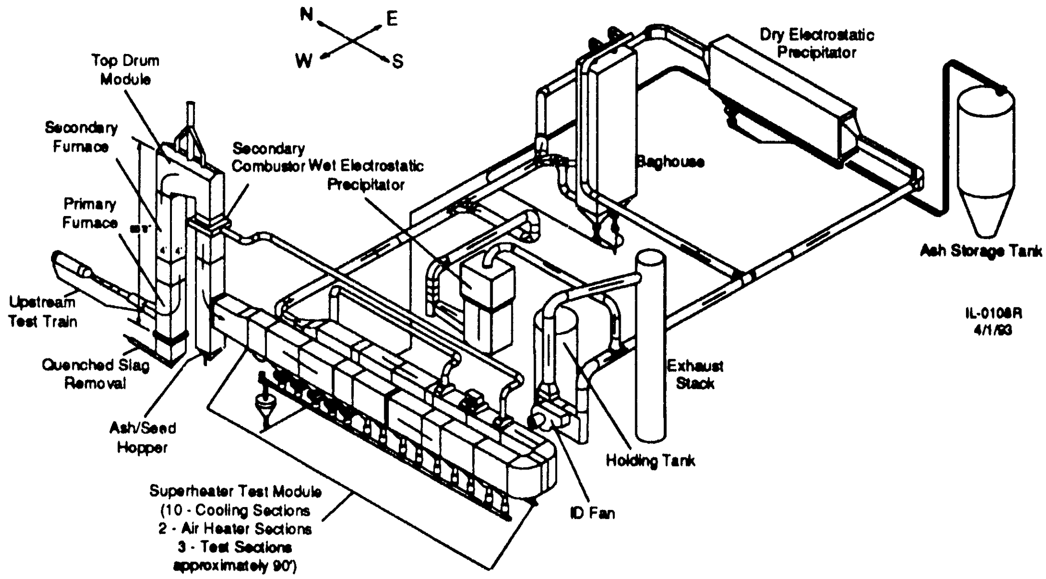


FIGURE 2. CFFF Integrated MHD Bottoming Cycle Schematic

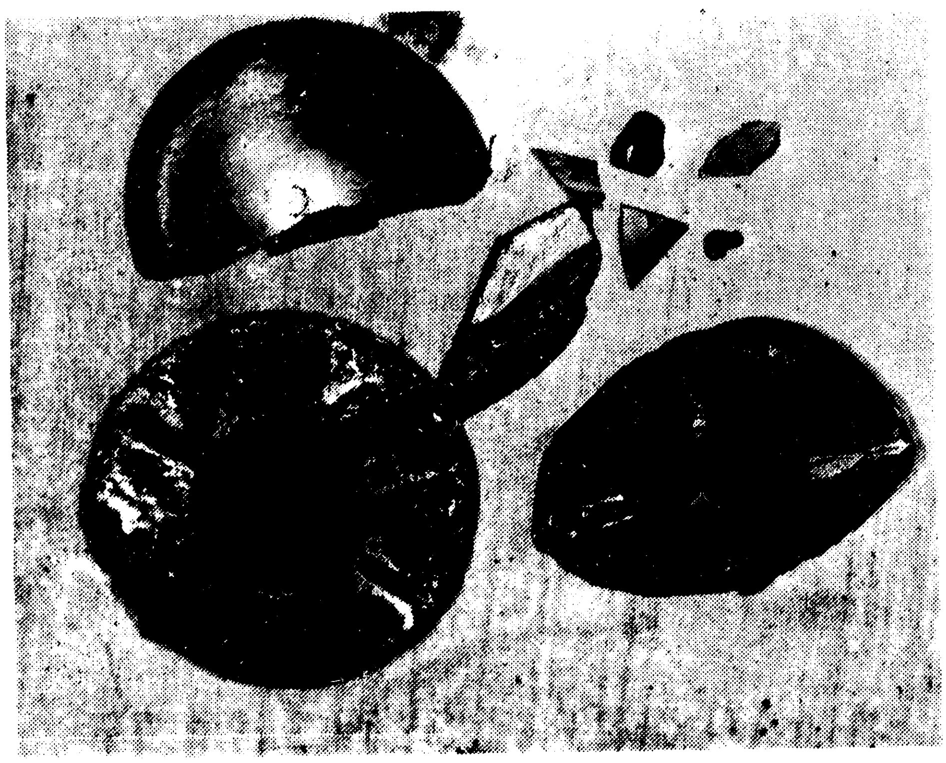


FIGURE 3. Fractured 9-Inch Pulverizer Ball

a. Pulverizer Shaft

b. Pulverizer Shaft Section Showing Break Surface

FIGURE 4. 3-1/2 Inch OD Pulverizer Shaft Failure

Prior to the LMF5-H test, individual facility systems and the Data Acquisition System were activated and checked for proper operation. To verify proper valve operation, all control valves were operated manually. Flow calibrations were obtained for two Coriolis meters used to measure coal mass flow and for two turbine meters that measure fuel oil flow. The facility control and burner management computers' input and output channels were verified and checked. New sootblower sequences were also written, and the calibration of facility cooling water orifices was completed.

After completion of the LMF5-H test, port opening times were compiled from port logs and official running time on oil and coal times were tabulated and published.

A draft topical report, "The Low Moisture Eastern Coal Processing System at the UTSI-DOE Coal Fired Flow Facility," was issued.

DATA ACQUISITION SYSTEMS

Activities this quarter included preparation for and support of the LMF5-H test and in preparation for the LMF5-I test.

Before the start of the LMF5-H test, pressure switches were installed in the wet ESP rotary vacuum filter water lines. One pressure switch was installed in the bearing cooling water line to the receiver pump. The second pressure switch was installed in the bearing cooling water/seal water line of the vacuum pump. The pressure switches were installed and set to turn the pumps off if water flow was lost to either of these systems. Indicator lights were installed in the control room to alert operators if one or both of these pumps shut down.

Calibrations of the data system continued this quarter. Periodic calibration of the data acquisition system is performed to insure that the system is reading correct volts from the measurement sensors or transmitters. The sensors are calibrated against a National Institute of Standards and Technology traceable source. The resulting data is entered into the data acquisition system database to convert volts to engineering units. In addition, regular disk drive backups were performed on the data acquisition system computers. Modifications to the data acquisition system database that were required to support new test requirements and hardware changes were accomplished.

An investigation into alternative methods of transferring CFFF test data to the ECP VAX computer in the main building was completed. At present, data is stored on magnetic tape on the Data General data acquisition computers and hand carried to the main building where it is then loaded on the VAX. Since the VAX and Data General computers are on the campus ethernet link, the data could be transferred directly over the network and eliminate the intermediate step of storage on tape. This requires a newer version of the Data General operating system, which is not in the current budget. Thus, the Ethernet data tranfer cannot be implemented at this time.

ENVIRONMENTAL AND ANALYTICAL SERVICES

During this quarter the chemistry laboratory provided analytical support for the LMF5-H test and completed all analyses of samples submitted to date. Also, environmental water samples collected each month from four lake/stream locations and from both holding ponds were analyzed for routine parameters.

For the upcoming LMF5-I test, the laboratory plans to collect and analyze solid, liquid, and gaseous effluent samples for organic constituents which will be compared with Illinois No. 6 coal data and conventional power plant effluent characteristics.

ENVIRONMENTAL MONITORING

Water Quality

Efforts continued in the routine monitoring and treatment of the holding ponds.

Terrestrial Ecology

No activity was planned or carried out for this area during the quarter.

Ambient Air Monitoring

A quarterly QA audit by the State of Tennessee Division of Laboratory Quality Assurance was completed on May 26, 1993. The results indicated all instrumentation to be operating within EPA operational guidelines.

Groundwater Monitoring

Contact was made with the State of Tennessee Division of Solid Waste Management who will provide information regarding the scope and intensity of further groundwater monitoring requirements. Two UTSI personnel attended a Resource Conservation and Recovery Act (RCRA) training class in Atlanta, GA. One of the objectives of the course was to define the RCRA and Comprehensive Environmental Response Compensation and Liability Act (CERCLA) involvement in future groundwater monitoring at the Coal-Fired Flow Facility.

TASK 4 - OPERATION AT 8 LB/SEC TOTAL GAS FLOW HIGH SLAG THROUGHPUT TEST

TESTING

The CFFF test, LMF5-H, a long-duration, proof-of-concept (POC) test on Montana Rosebud subbituminous coal was conducted during April 1993. This test was terminated after 88 hours on coal due to the failure

of the main shaft in the coal pulverizer. A replacement shaft was procured and installed in the pulverizer under the guidance of a representative from the Babcock & Wilcox Company.

The next test, LMF5-I, is scheduled for 217 hours on Montana Rosebud coal and is planned for early in July 93. The primary objective of this test is to operate with 1% potassium in the primary flow, with seed added into the primary combustor as a 47% solution of potassium carbonate. A nominal primary stoichiometry of 0.85 and a nominal secondary stoichiometry of 1.10 will be utilized.

An additional 200 hours of POC testing in the CFFF was authorized by DOE. A 350-hour long-duration test is tentatively scheduled for September 1993. This will increase total testing in FY93 to 655 hours for a grand total of 1350 hours on Montana Rosebud coal.

Table 1 shows the CFFF testing completed on eastern Illinois #6 coal, special tests and POC testing conducted on Montana Rosebud coal completed through March 1993, and Montana Rosebud coal POC testing projected through FY93.

UPSTREAM COMPONENT SYSTEMS

The upstream test train components operated without significant incidence during the LMF5-H test.

DOWNSTREAM COMPONENT SYSTEMS

The 57% alumina castable refractory installed in the steam cooled tube section headers seemed to work well during the LMF5-H test. A patch of this same material was installed on the primary furnace wall opposite the diffuser and was reduced in thickness from about 3 inches to about 1.5 inches, which may be near the equilibrium thickness of the refractory under test conditions. Tube corrosion and ash deposition studies were limited to the monitoring of real time test conditions during the LMF5-H test.

Superheater Test Module (SHTM) Gas-Side Tube Corrosion

A topical report entitled, "Superheater/ Intermediate Temperature Airheater Tube Corrosion Testing in the MHD Coal Fired Flow Facility," was nearing completion this quarter. A technical presentation of the same work entitled "Gas-Side Corrosion Performance of Superheater/ITAH Tube Alloys in MHD Tests with High Sulfur Coal" was presented at the Thirty-First Symposium on Engineering Aspects of Magnetohyrodynamics (SEAM), June 29-July 1, 1993.

TABLE 1. CFFF Test Series

TEST CONFIGURATION	DATE OF COMPLETION	HOURS ON COAL
Completed Eastern Coal Tests - LMF4	05-91	2358
Shakedown - LMF5-A (Western Coal)	08-91	75
Corette Plant Conditions - LMF5-B	08-91	60
$K_2CO_3/K_2SO_4/Fe_2O_3$ Addition - LMF5-C	09-91	50
Special test using all carbonate seed - LMF5-D	11-91	107
*POC-LMF5-E	04-92	91
POC-LMF5-F	08-92	290
POC-LMF5-G	10-92	314
POC-LMF5-H	04-93	88
		TOTAL 3345 **
Projected POC-LMF5-I	07-93	217
Projected POC-LMF5-J	09-93	350

* Proof-of-Concept

** Total test train operation time to date on coal is 3433 hours

(Total test train operation on eastern coal POC testing is 2005 hours.)

(Total test train operation on western coal is 1077 hours to date of which 783 hours are POC.)

(Total test train operation time to date is 3778 hours (including operation of the vitiation heater).)

Superheater Test Module (SHTM) Ash Deposition

A FINAL Topical Report, "Ash Deposition During Illinois #6 Coal Proof of Concept Testing at the Coal Fired Flow Facility," was issued and incorporates pertinent comments relating to DOE's review of the draft issue.

Other work involved characterizing the thickness and width of superheater deposits during the LMF5-H test. These results are given in Table 2.

TABLE 2. Deposit Measurements from Rotatable 63.5 mm (2.5") O.D. Air-Cooled Probe Using Computerized Image Analysis of Captured (digitized) VCR Frames

Hours since soot-blowing	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	Precision, ±σ
Clock time & date	09:45 4/24/93	10:45 4/24/93	11:45 4/24/93	12:45 4/24/93	13:45 4/24/93	14:45 4/24/93	15:45 4/24/93	16:45 4/24/93	17:45 4/24/93	
Average front-edge deposit thickness, mm	NA	2.5 (0.10")	2.8 (0.11")	3.0 (0.12")	4.1 (0.16")	4.6 (0.18")	5.6 (0.22")	5.6 (0.22")	6.1 (0.24")	±0.5 (±0.02")
Average front-edge deposit linear width, mm	NA	46.2 (1.82")	43.2 (1.70")	43.2 (1.70")	44.2 (1.74")	50.3 (1.98")	53.8 (2.12")	56.6 (2.23")	NA	±3.3 (±0.13")

A technical presentation of the same work entitled "Ash Deposition in the Coal Fired Flow Facility While Burning Illinois #6 Coal," was presented at the 31st SEAM.

Pollution Control/Gas Analysis

Work on this project centered on evaluation of pollution control equipment during the LMF5-H test and work on an LMF4 topical report on performance of pollution control devices (baghouse and electrostatic precipitators).

PARTICULATE REMOVAL SYSTEMS

Dry Electrostatic Precipitator (ESP) Performance

Prior to the LMF5-H test, discharge electrodes in the dry ESP were replaced, as suggested by ADA, Inc., to increase the current density and collection efficiency. The original electrodes consisted of a mixture of 1/4 inch square and 5/16 inch round cross-section wires. The new electrodes are slightly smaller than 1/8 inch diameter round cross-section.

CFFF tests using high K_2/S ratios on Montana Rosebud western coal result in particulate with a mixture of potassium carbonate, potassium sulfate, and fly ash. Potassium carbonate is very hygroscopic and tends to be difficult to remove from the discharge electrodes and collection plates. The electric-powered vibrators supplied by the dry ESP manufacturer were sufficient when the ash was primarily potassium sulfate ($K_2/S = 1$). However, the presence of significant quantities of potassium carbonate in the spent seed requires more vibrating force to clean the electrodes. Therefore, pneumatic vibrators were mounted directly on the discharge wire frame. The LMF5-H test was the first test when the vibrators were controlled automatically by using the timer supplied by the vendor, which is normally used to control the electric-powered type vibrators.

Collection efficiency of the dry ESP during the LMF5-H test was higher than was previously measured during prior tests (see Table 3) and readily met NSPS standards. Three particulate samples were collected at the dry ESP outlet during the LMF5-H test. Due to the failure of the dry ESP recirculating electric preheat system, condensation on the walls and insulator housings occurred during its startup. The combination of condensation and hygroscopic dust resulted in lower collection efficiency during the initial portion of the test as verified by the sample collected on April 23, 1993 (Figure 5). Approximately 24 hours of dry ESP operation were required to reach peak performance.

TABLE 3. LMF5-H Dry ESP Collection Efficiency

Gas Flow acfm	Specific Collection Area (SCA) sq ft/kacfm	Emission Rate lb/MBTU***	Collection Efficiency %
6684	449	0.0092	99.97
9723	309	0.0142	99.78

Note: nominal design flow is 6300 cfm (SCA=475)
*** NSPS limit is 0.03 lb/MBTU

The smaller diameter electrodes increased the current density while maintaining sufficient voltage to prevent high rates of particle reentrainment. Measured currents increased 2-4 times those obtained using the larger electrodes in

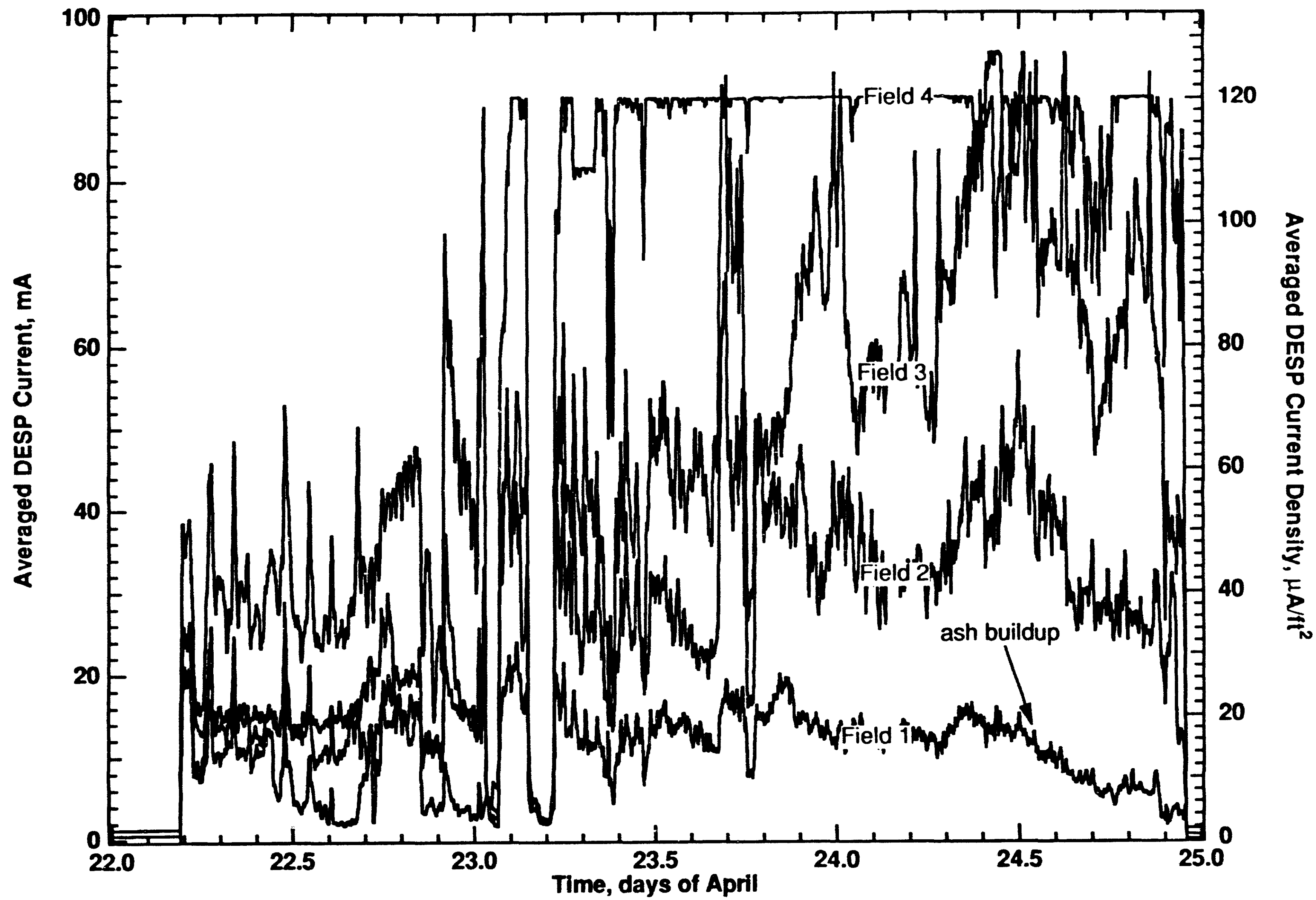


FIGURE 5. Dry ESP Current During LMF5-H

previous tests. Averaged current in Field 1 was as high as was typically measured in Field 4 prior to the electrode replacement. As was typical of CFFF operations, downstream fields have higher current levels due to fewer particles (see Figure 5). Field 4 current was limited by the transformer capacity at 90 mA for much of the test, while the applied voltages in each field were 55 - 60 kV (see Figure 6).

Because of the extremely high efficiency of the first 3 fields, Field 4 current levels did not appear to be affected by gas flow. Field 1 showed good correlation (see Figure 7) except during the last 12 hours of the test when Field 1 performance began to decline. Post-test inspection of the fields indicated that ash had not been sufficiently removed from Field 1 compared with the downstream fields (see Figure 8). With the increased performance of the dry ESP, Field 1 is probably removing a larger percentage of the incoming particulate load, making more frequent or more intense rapping necessary.

Baghouse (BH) Performance

Baghouse testing on Illinois #6 coal (LMF4 series) was conducted nominally at a K_2/S ratio of 1.0. Under these conditions, baghouse cleaning cycles were required approximately every 1.5 hours as the pressure-drop across the bags reached 10 inches water column (wc). Since low sulfur Montana Rosebud coal tests (LMF5 series) began with a K_2/S ratio of approximately 4.0, baghouse cleaning cycles were required at less than one-hour intervals. Based on suggestions from the W.L. Gore Co. and the Elkem Co., several experiments were attempted during the LMF5-H test.

As observed in past tests with high K_2/S, the time required prior to the first cleaning cycle was long (over 3 hours), but succeeding cycles were required at less than one-hour intervals (see Figure 9). This indicates that the bags were not blinded, but rather that the cleaning process was not efficient. The phenomenon of long cleaning cycles following a shutdown period in this test was not experienced as observed in prior testing. Possibly, in previous tests, several cleaning cycles were run through when the tests were down, which was not attempted during this test.

A reduction in the volume of reverse air flow during cleaning cycles was also attempted by reducing the pressure-drop across the tube sheet. This was only attempted once due to the premature ending of the LMF5-H test. It would appear that the lower reverse air flow did not improve bag cleaning and may have made it worse (see Figure 10). The reverse air flow was measured during a normal cleaning cycle based the manufacturer's fan curve (see Table 4). Gas flow was calculated both from fan static pressure and brake horsepower curves with fairly good agreement. Since the reverse air velocity is on the order of 2 ft/min, the fan appeared to be operating satisfactorily, although it may have been insufficient to effectively clean the bags at that flow rate.

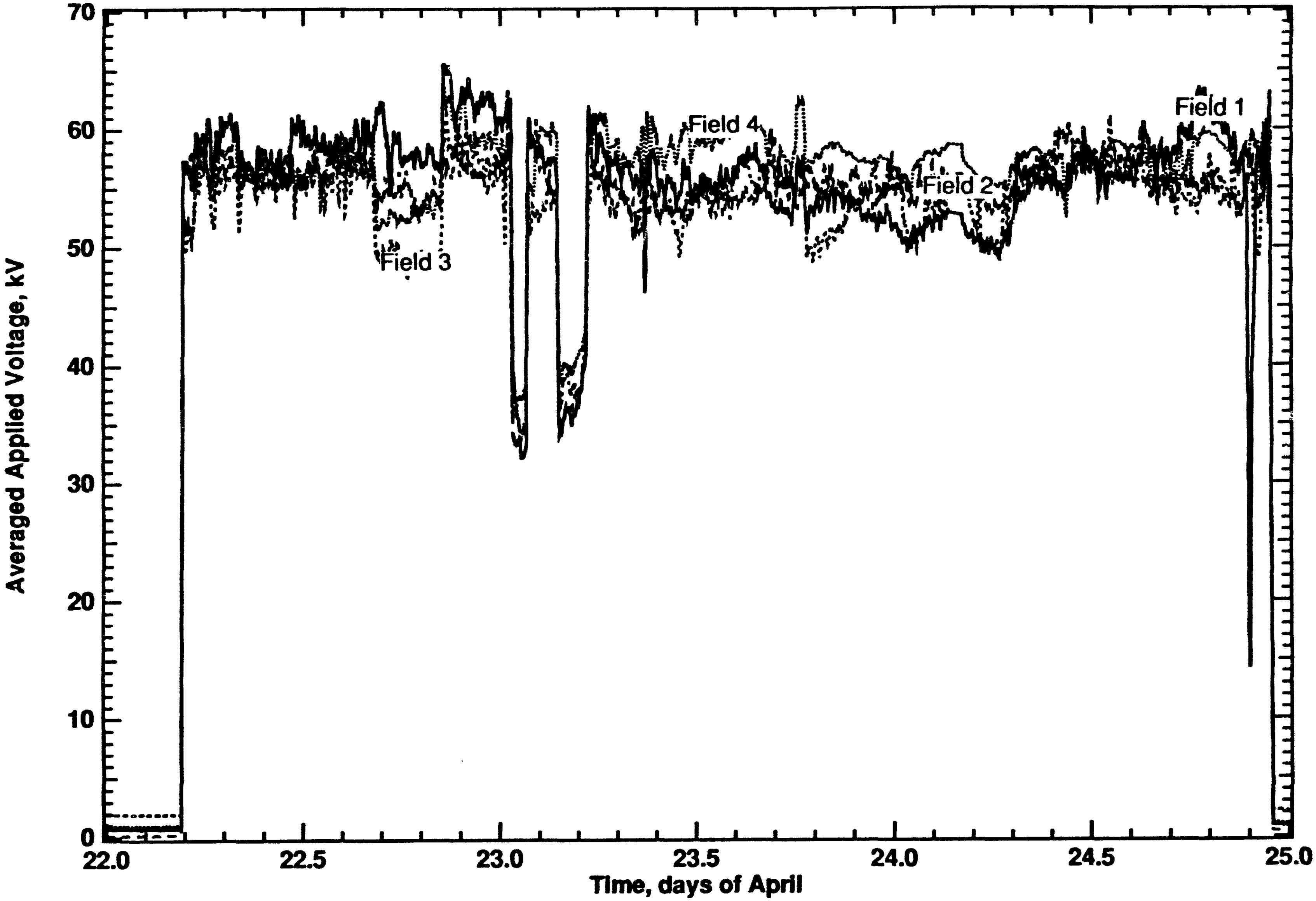


FIGURE 6. Dry ESP Voltage During LMF5-H

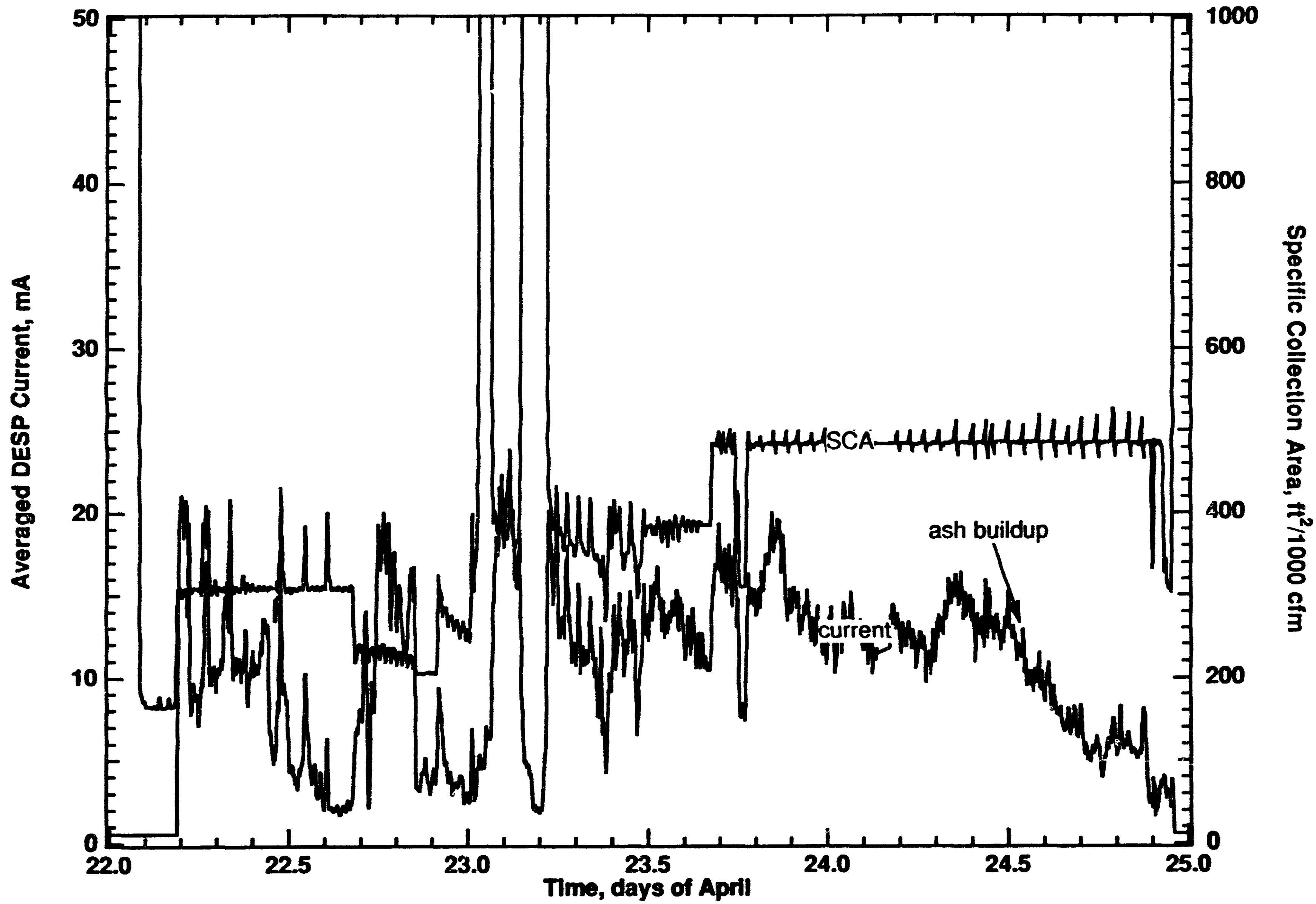


FIGURE 7. Effect of Flow on Dry ESP Field 1 Current During LMF5-H

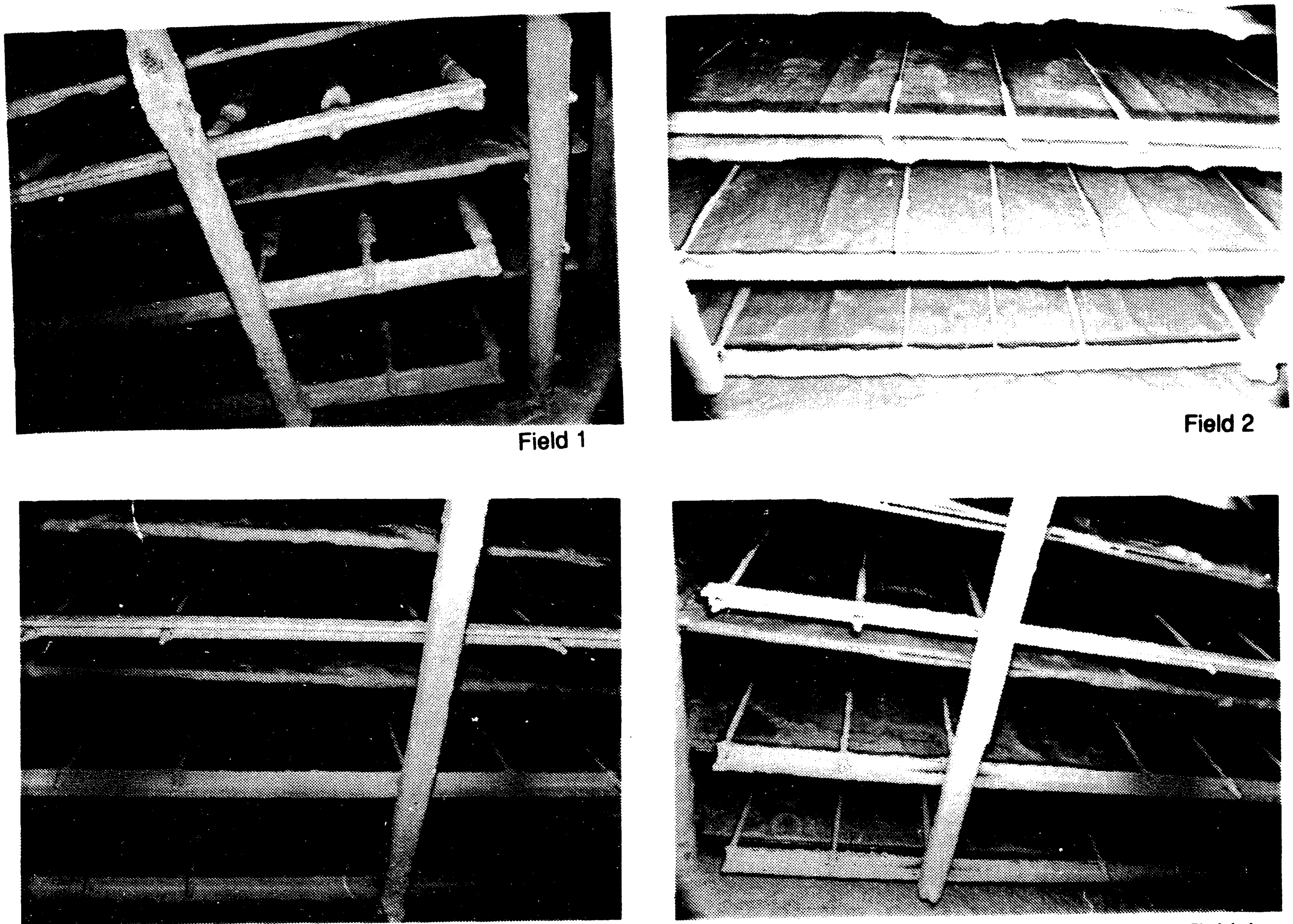


FIGURE 8. Dry ESP Wire Racks from LMF5-H (post test)

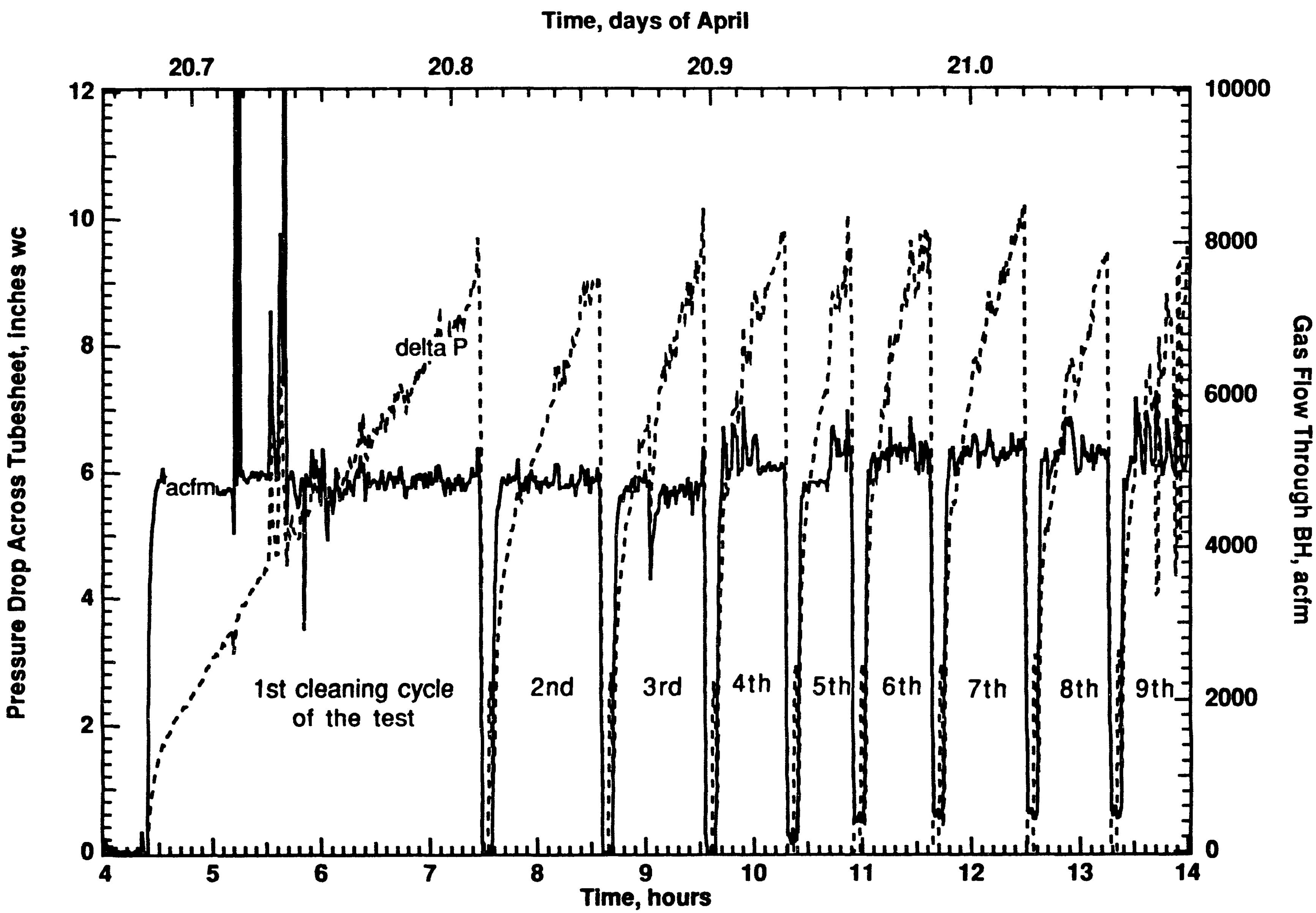


FIGURE 9. Ineffectiveness of Cleaning Cycles

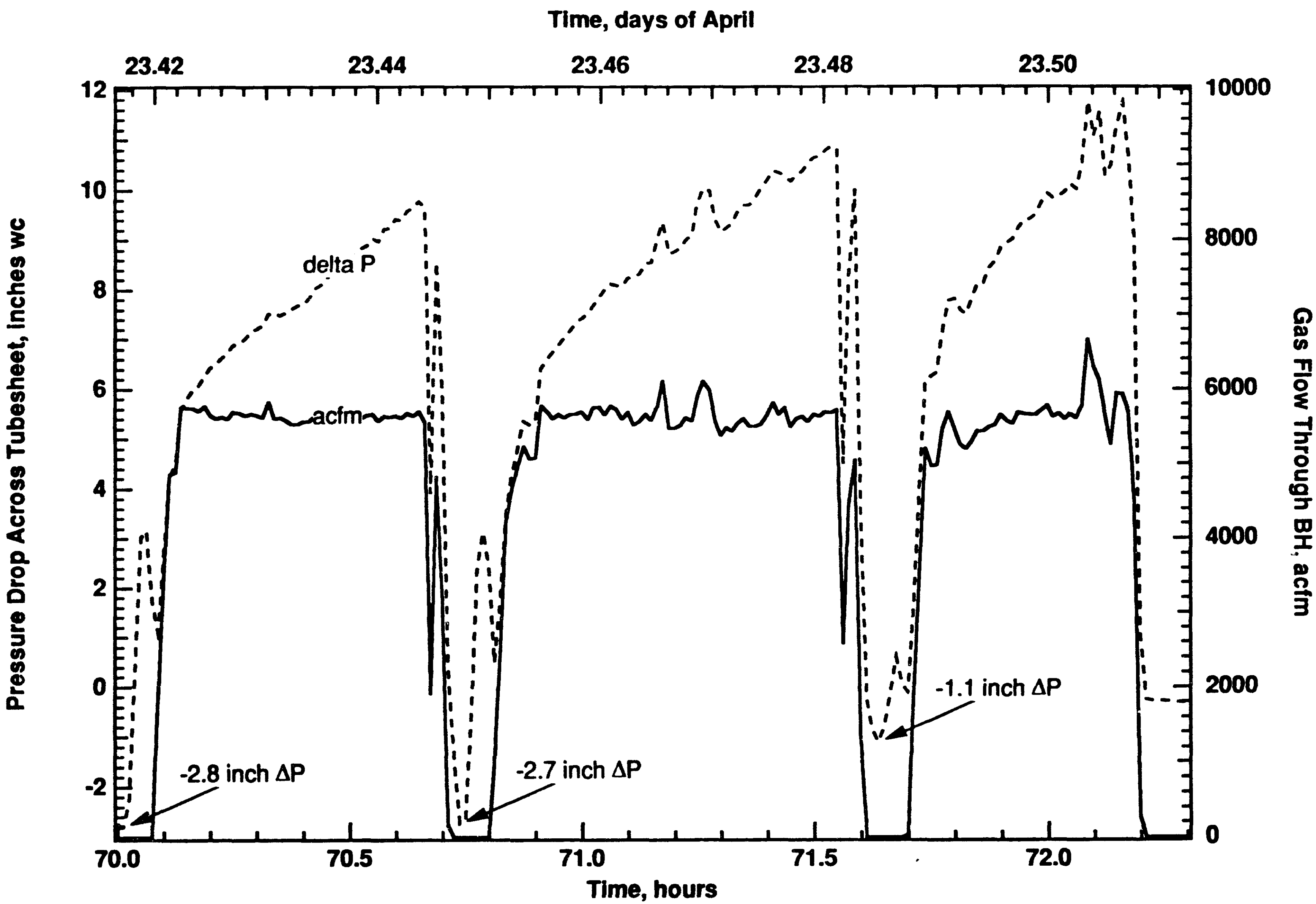


FIGURE 10. Effect of Reverse Air Pressure During Cleaning Cycles

TABLE 4. Baghouse Reverse Air Flow Rate on April 23, 1993

	Cleaning A	Cleaning B
ΔP inches wc	13.1	12.9
Temp °F	287	271
Amps	10.5	11.83
CFM (sp)	2330	2735
CFM (bhp)	2687	3150

The Elkem Co. representative recommended higher reverse air flow rates but shorter reverse air durations. Elkem actually operates reverse gas baghouses similar to a pulse-jet, and they clean every 10 minutes with high reverse air flow and extremely short reverse air times. Normally, the CFFF system utilized two minutes of reverse air on each compartment, but Elkem speculated that 15 seconds would probably remove as much dust as two minutes of reverse air flow. The next to last cleaning cycle of the test was conducted using only 30 seconds of reverse air flow and this did appear to be as effective as two minutes (see Figure 11). The last cleaning cycle was completed by cleaning only one compartment, followed by flowing 50% of the normal flow through the compartment which had been cleaned (2 minute cleaning). The test was terminated prior to reaching the 10 inch pressure differential limit, but this did not appear significantly different from the normal operation.

Wet Electrostatic Precipitator (ESP) Performance

The LMF5-H test was the first test since the complete wet ESP system was installed and utilized. Earlier attempts to operate the wet ESP were difficult due to the plugging of the spray nozzles. Even with the addition of the rotary drum vacuum filter to remove the undissolved solids, several nozzles were plugged with rust scale during the LMF5-H test. This scale is believed to have been deposited in the piping from prior tests run without the filter. This test should be considered the first true shakedown test for the wet ESP system.

Two particulate emission tests were conducted at the wet ESP outlet at substantially different inlet conditions. Because of the low inlet dust loading, due to the low seed flow on April 20, the outlet mass emission rate appears lower than normal. On April 23, the inlet loading quadrupled, so the effect of increasing specific collection area (SCA) was not apparent (see Table 5).

The wet ESP cools and humidifies the gases prior to the collection section. Correcting the volumetric flow to the inlet temperature and ignoring the addition of water vapor, the gas flows were 13,562 cfm and 5822 cfm. Operating currents and voltages are shown in Figure 12.

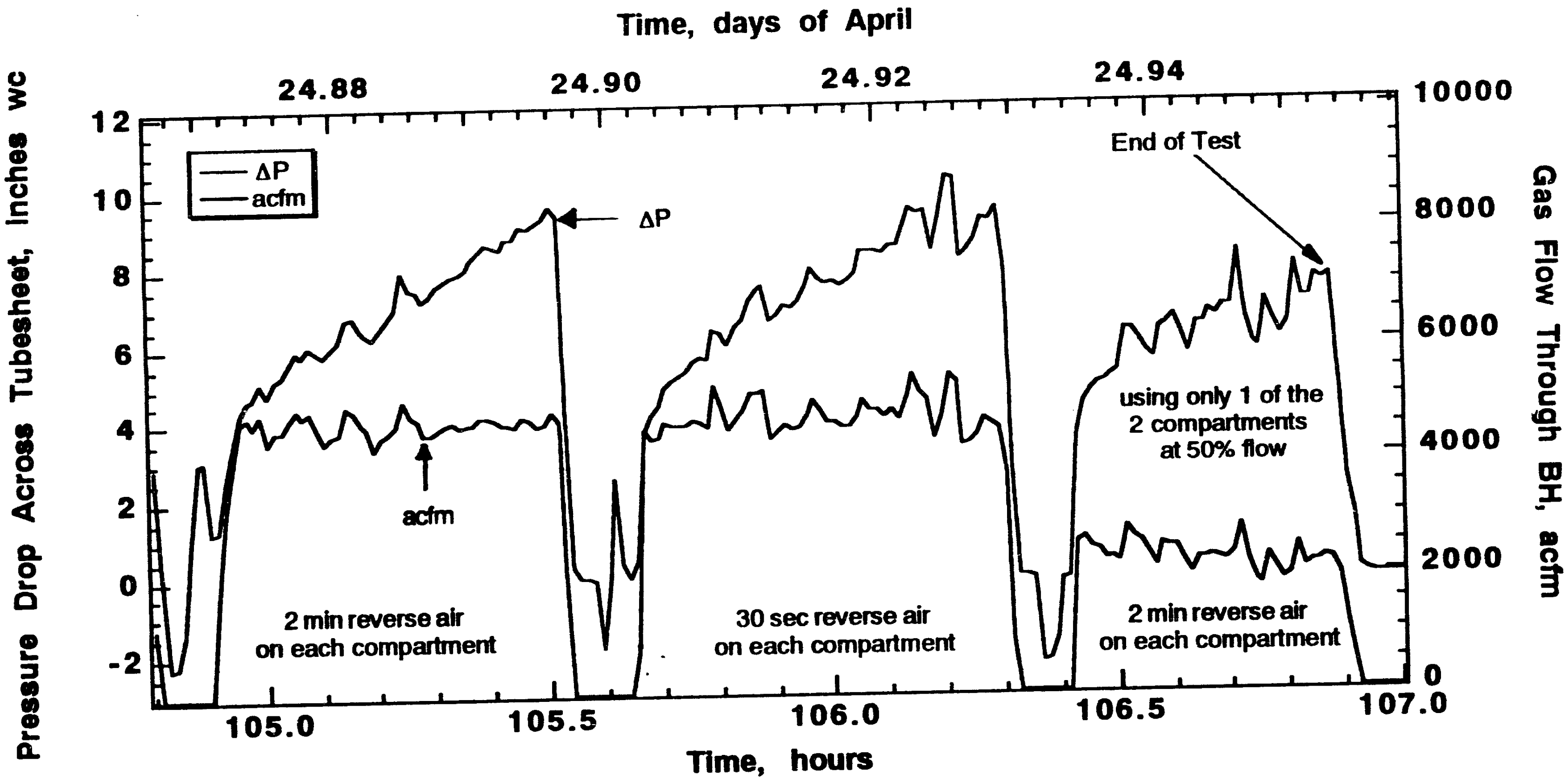


FIGURE 11. Effect of Varying Cleaning Cycle Parameters

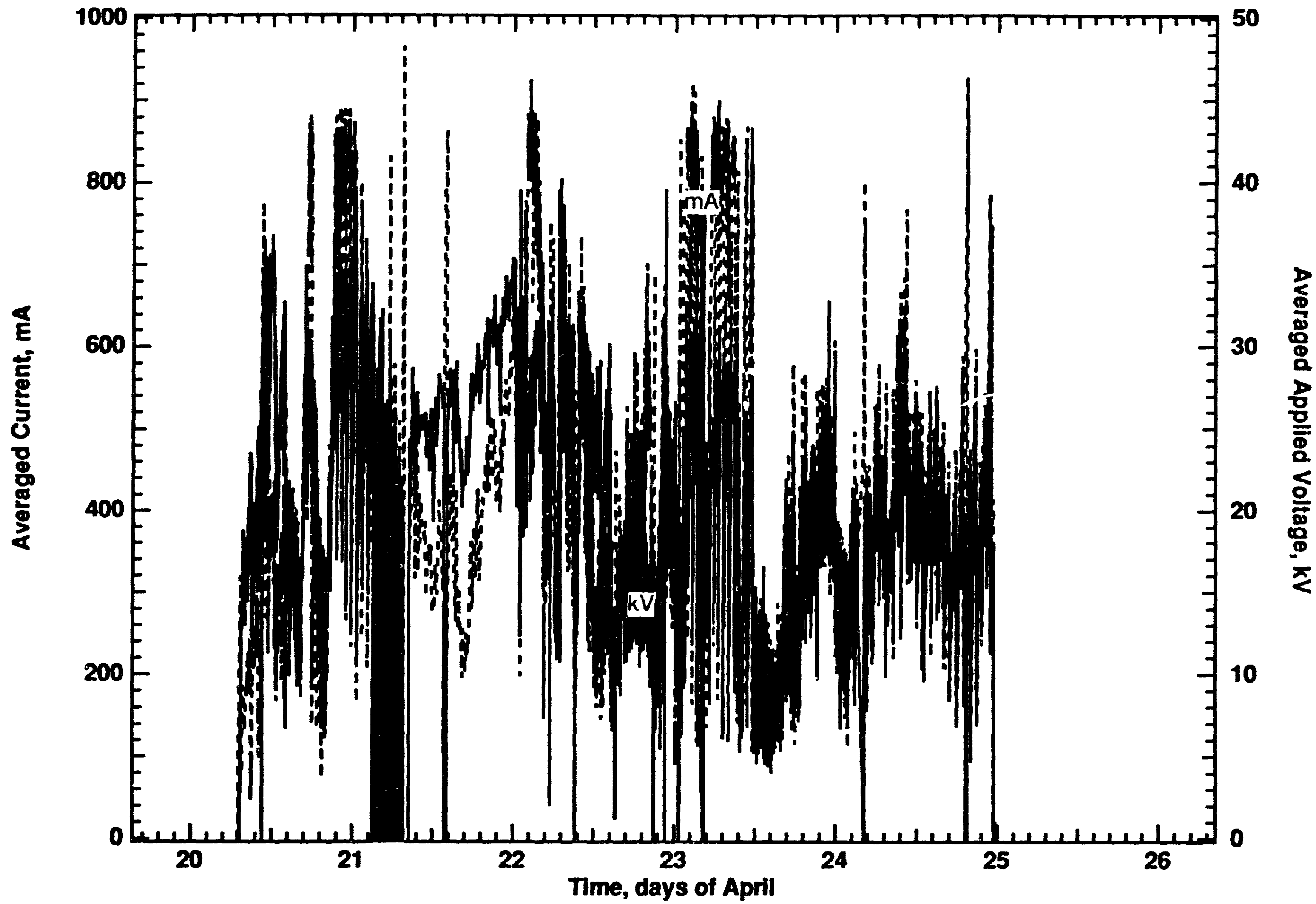


FIGURE 12. Wet ESP Operating Conditions

TABLE 5. Wet ESP Performance Results from LMF5-H

Date	Inlet gr/dscf	Wet ESP gr/dscf	Wet ESP lb/MBTU	Wet ESP cfm	SCA ft²/1000 acfm	Removal %
4-20	1.616	0.123	0.142	10729	186	9[illegible].3
4-23	6.404	0.088	0.046	4411	453	98.6

Although no significant operating problems were experienced, a post-test inspection of the wet ESP revealed a significant amount of K_2SO_4 deposition on the discharge electrodes (rods) and collection plates. This condition may have contributed to the lower than expected collection efficiency but primarily the lower efficiency was due to the plugged nozzles. During the first test with the wet ESP last year, when the water (pure) was first turned on with power, the stack became invisible for several minutes until the nozzles plugged with ash. The quantity of soluble species in the recirculated water may be contributing to the emission rate of particulate. **Nevertheless, the CFFF emissions permit limit of 0.19 lb/MBTU was met utilizing the wet ESP even at the high flow rate.**

Gas Analysis

An objective of the LMF5-H test was to investigate the effect of stoichiometry and thermal input on NO_x emissions at the secondary combustor outlet (SCO), for nominal thermal input at 80, 85, 90, and 95 percent stoichiometry, and at a lower thermal input at 85 percent stoichiometry. The effect of furnace draft was to be performed out at the last condition, and the stoichiometry tests were to be carried out after the furnace temperatures had achieved a steady-state at nominal thermal input and stoichiometry.

Although the shortened test did not allow completion of this objective, some significant observations were made. It was observed that the SCO NO_x level was significantly lowered by seed injection, as was the secondary combustor inlet (SCI) NO. The SCI CO level also appeared to be affected. The SCI probe was placed before the secondary combustor, hence, should not have been affected by secondary combustion ignition. The gas contents are shown in Figures 13, 14 and 15 together with seed flow. There is an anticipated delay between a combustor event and the gas analysis, about a minute for the SCO probe, and 3 minutes for the SCI probe, because of transit time from the probes to the analyzers. The effect of seed injection is dramatic. It is not clear if it is entirely due to chemistry, or may be partly related to the effect of seed injection on temperature levels. The spectroscopic temperature devices were not operating at the time of injection.

The SCI probe was shut down just before the end of the time segment shown in the figures. The NO decays to zero, but the CO does not decay. There was a decrease for several minutes in the SCO NO_x content just before the end of the time

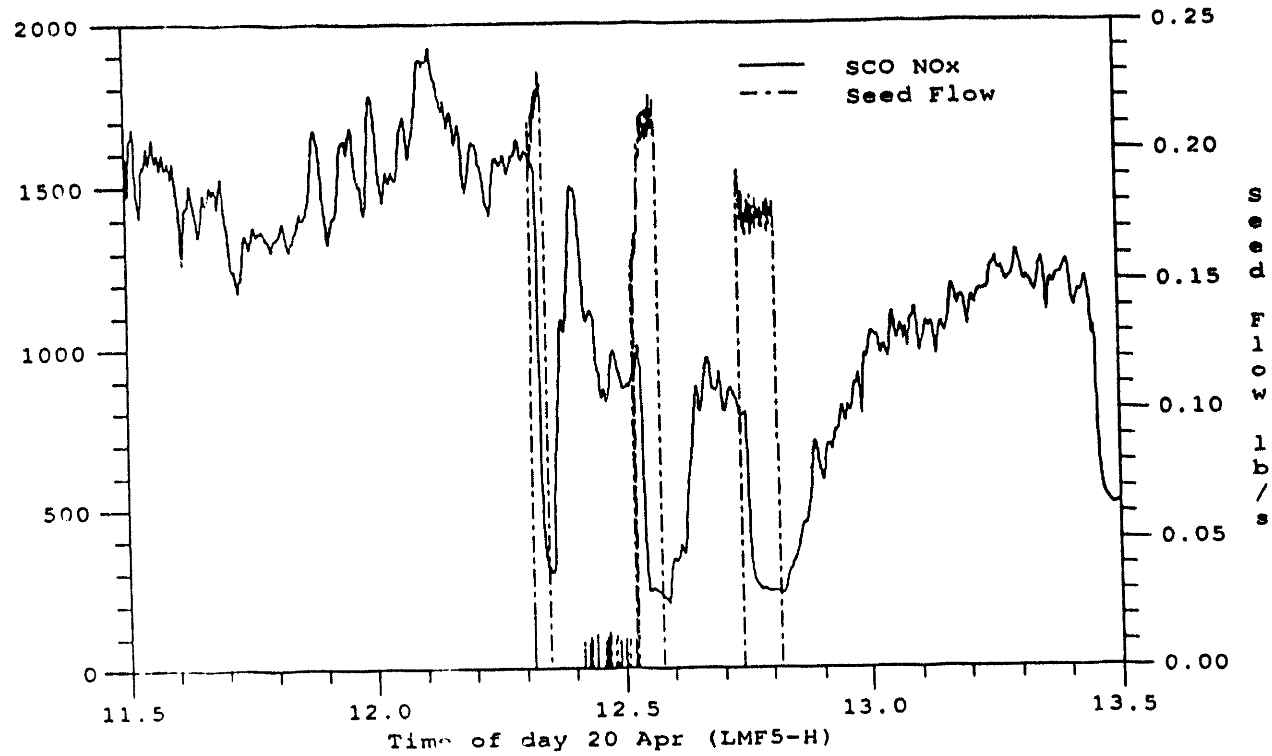


FIGURE 13. Effect of Seed on NO_x Emission

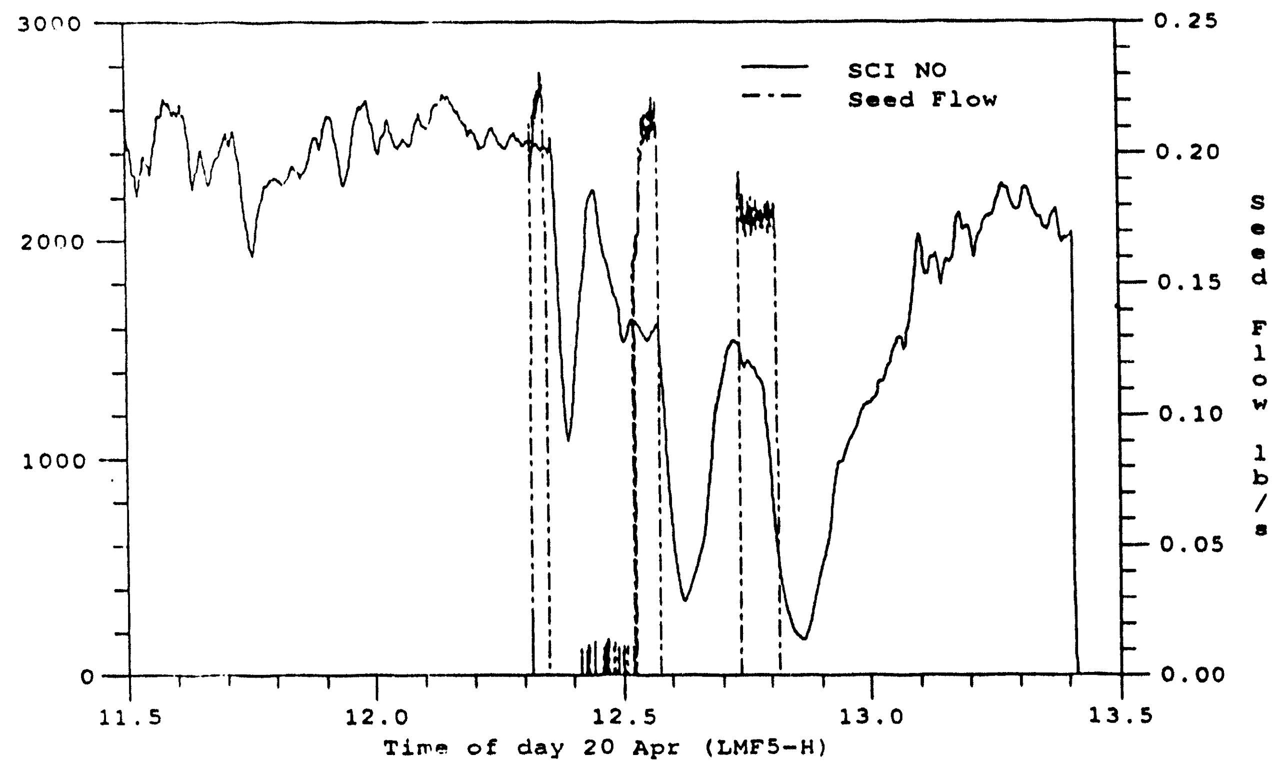


FIGURE 14. Effect of Seed on SCI NO

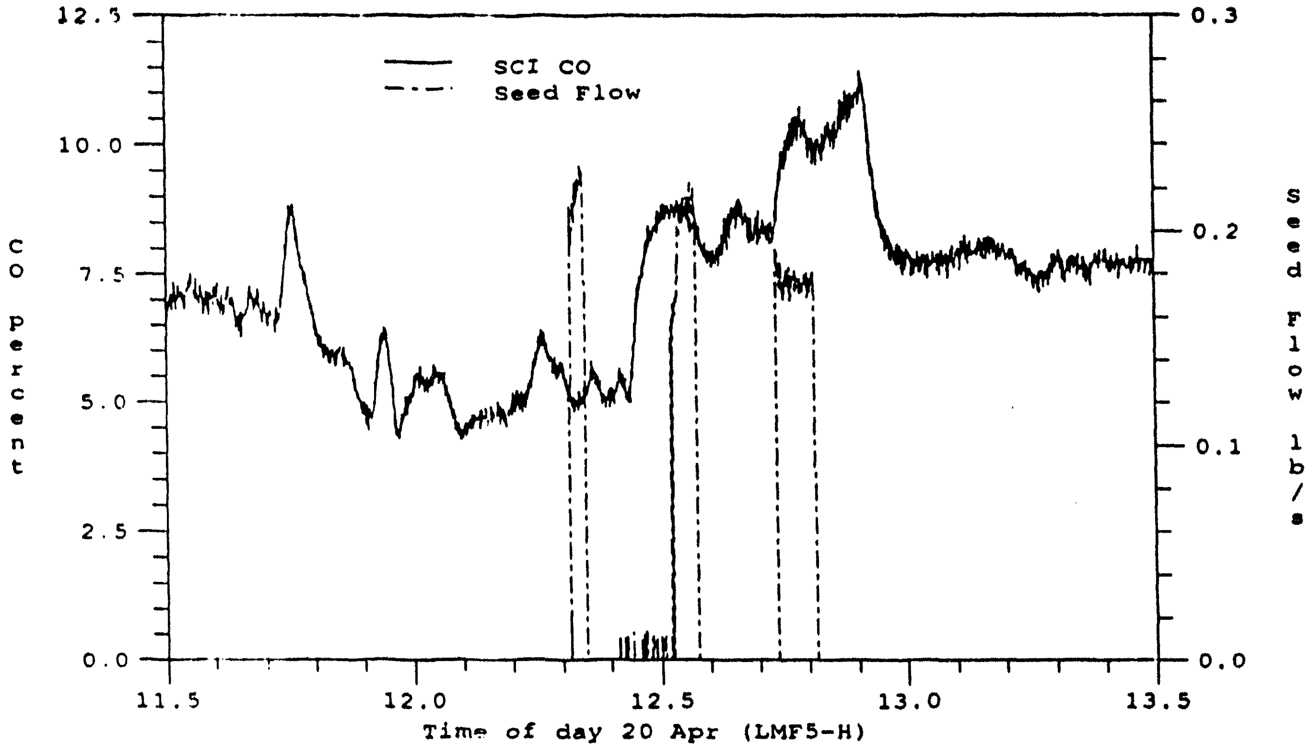


FIGURE 15. Effect of Seed on SCI CO

segment. No seed was injected, nor was there any other significant flow change noted in the data. Thermocouples upstream of the secondary combustor showed a modest increase in temperature, as if a port had been opened, but such an event usually causes an increase in NO_x, (however, there was no record of a port opening). A check of other parameters showed a decrease of about 2 psi in vitiation heater pressure, and also in the readings at some combustor pressure ports. These decreases occurred in the same time frame as the NO_x decrease. At about 14.0 hours into the test, seed injection started, and NO_x values came down to near normal values. This experiment will be repeated in the LMF5-I test.

MASS BALANCE AND AUTOMATIC DATA SCREENING

CFFF Mass Balances

A paper entitled "Analysis of Material Disposition for Illinois #6 Coal POC testing at the CFFF" was presented at the 31st SEAM. It includes the modification of the mass balance computer program to add balance and distribution outputs for alkali and non-alkali metals, which previously had not been part of the program. The analysis of the data from the mass balance program and covering the combined LMF4 POC testing series was completed.

CFFF Data Reduction and Filtration

Work was completed on modifying the FILTER and PULL computer programs to allow the selection of data channels by parameter name, and to allow portions of the test data to be pulled and filtered and the new results added to the existing output files. Work was in progress to make the coal-on periods identified by the reduction and the filtering programs more consistent. Work was also in progress to allow the mass balance program to account for carbonate in the solid product streams. With the LMF5 series tests and the use of low sulfur coal feedstocks, much higher concentrations of carbonate have appeared in the product streams, and it is no longer feasible to ignore this component.

Chemical Analysis Database

Enhancements continued to be added to the chemical analysis database to make it more user friendly. A listing of the chemical analyses needed to complete the LMF5-E to LMF5-H mass balances was generated.

Secondary Combustor Modeling

Two-dimensional calculations and work on the grid generating software were continued.

Optical Properties of Radiant Furnace

A study of the optical properties of the MHD furnace was completed. Equilibrium calculations were performed that indicated the significant drop in transmissivity that occurs as the furnace temperature drops from 2300K to 2100K and corresponds to an increase in condensed phase potassium salts (Figure 16). A Monte Carlo calculation of transmissivity was performed and was found to agree with the available experimental data (Figure 17). Additionally, a Monte Carlo heat transfer model was constructed and run. The model results showed that the increased scattering due to the particles increases the absorptivity of the gas by as much as 30% (Figure 18). These results were presented at the 31st SEAM in a paper entitled "Particle Effects on Gas Optical Properties and Radiation Heat Transfer in an MHD Furnace."

Potassium-Sulfur Kinetics Study

Construction of the flat-flame burner for these experiments was completed. The burner was found to produce a uniform flat-flame for a variety of mixtures. The nitrogen co-flowing sheath effectively isolated the post-flame region from the ambient atmosphere, making the flame well suited for spectrometric observation. A burner mount was constructed to allow three axis positioning of the burner relative to the optical table. Other hardware required for the experiment was received (e.g. flowmeters, gases, nebulizer), allowing the experimental setup to be completely installed. Flowmeters were calibrated and the nebulizer will be calibrated. The nebulizer will be used to produce a fine mist of a potassium salt solution, which is the source of potassium atoms in the flame. We are awaiting the delivery of the final pieces of the experimental equipment.

The CHEMKIN chemical kinetics computer program was run to support the experimental design. The program was run with several methane/oxidizer mixtures to generate a database of temperature profiles, species profiles, and flame speeds. These results were used for determining the flame temperature range that could be experimentally produced with various methane/oxidizer mixtures. Additionally, the data were used to generate the flow metering requirements for the experiment.

Ash Deposition Modeling

Work continued on the development of the overall analytical model, **AshEffects**, for evaluating and predicting the effects of fireside ash deposits on superheater tubes. When completed, this model will aid in predicting performance of specific commercial superheater and intermediate temperature air heater designs and for scale-up of CFFF test data. Both mass and heat transfer will be considered as a function of deposition time. The FuelCalc module of Ash Effects was expanded again. The data base of coal and coal-ash analyses includes MHD coals by test, typical U.S. bituminous coals by state, typical U.S. coals by rank, all coals tested at UTSI during other DOE contract work, a variety of special fuels such as chars and coal-water fuels, and selected foreign coals. The FuelCalc module also can obtain complete fuel and

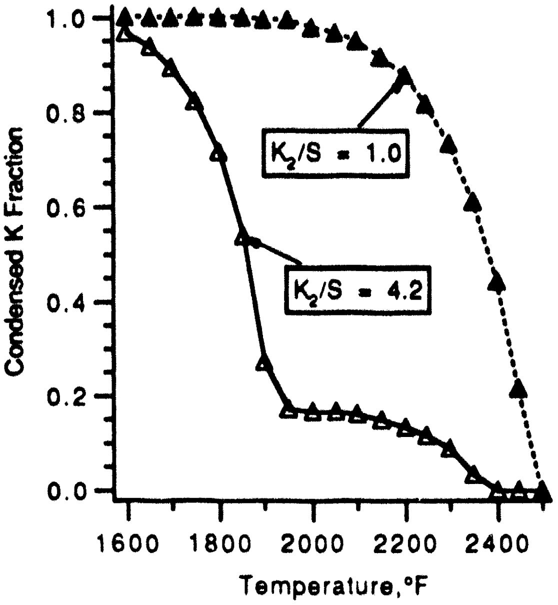


FIGURE 16. Predicted Fraction of Potassium in Condensed Phase

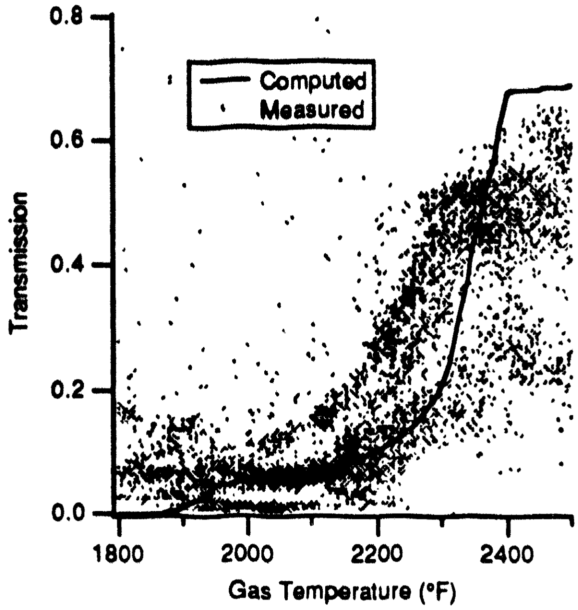


FIGURE 17. Comparison of Measured and Predicted Transmissivity at SHTM Entrance

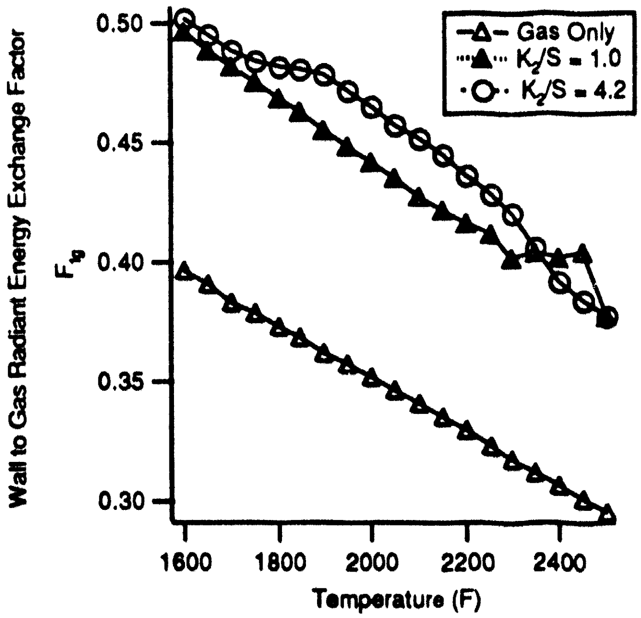


FIGURE 18. Wall to Gas Radiant Energy Exchange Factor (F_{1g}) versus Gas Temperature, Mie Scattering Results

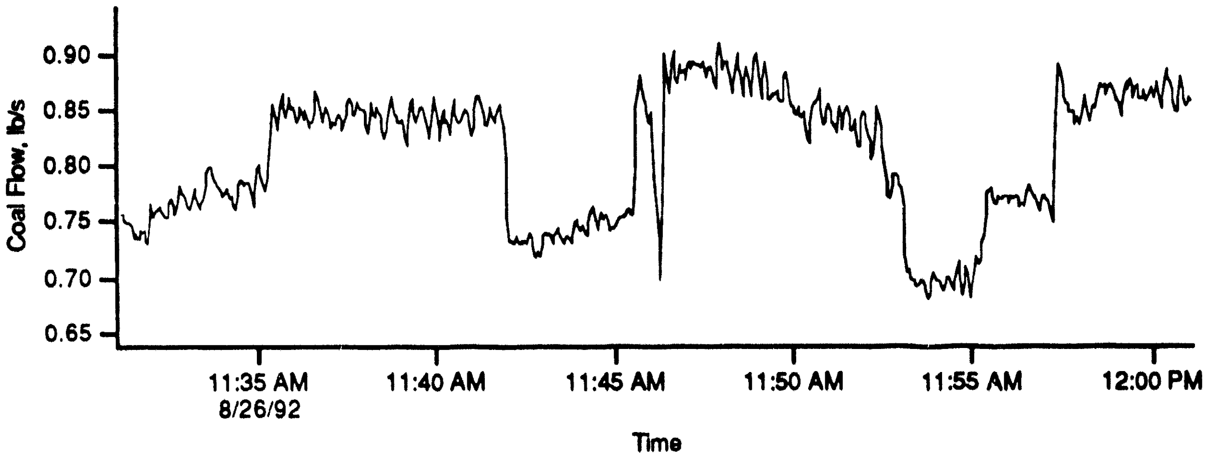
combustion calculations, including items such as flue-gas viscosity and coal-slag viscosity, both as a function of temperature.

Work continued on the calculation of mass transfer via the mass transfer mechanism of condensation on the fireside surface of a superheater tube and on the development of the finite-element control-volume mesh and on adding the calculation of heat transfer to the deposition model. A paper entitled "How Ash Impaction Changes Shape of Superheater Deposit Between Sootblowings" was presented at the Engineering Foundation Conference on the Impact of Ash Deposition on Coal Fired Plants, June 20-25, 1993 at Solihull, Birmingham, UK. (See Appendix A for a copy of this paper and the results of this effort).

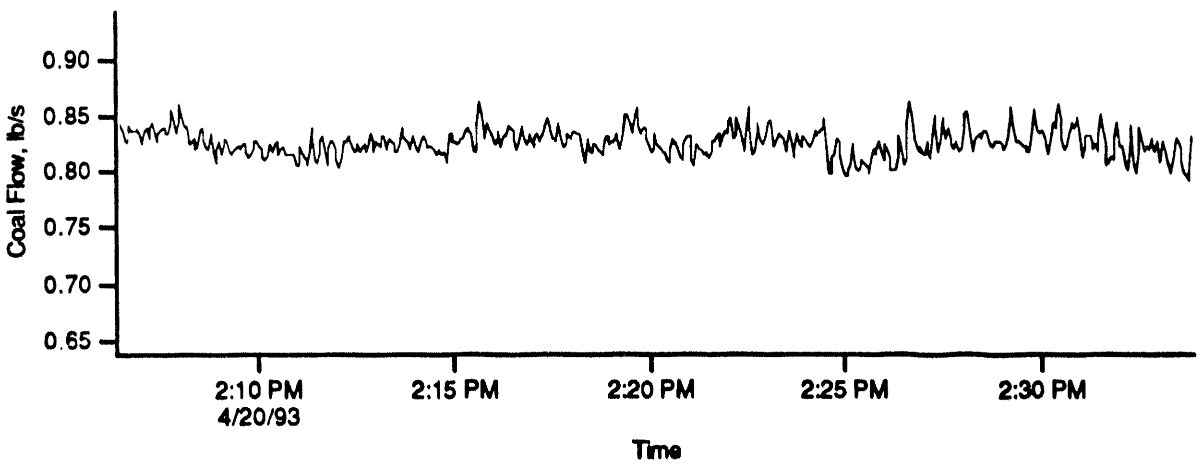
ADVANCED MEASUREMENT SYSTEMS

The LMF5-H test special diagnostics data was analyzed. As identified by the test section 1 (TS1) line reversal system during both the latter part of the LMF5-F test and all of the LMF5-G test, a steady coal flow could not be controlled because of abrasive wear of the coal flow Moulder valve. New Moulder valve components were installed for the LMF5-H test and this eliminated the coal flow jumps. The difference in flow stability is illustrated in Figure 19. Higher frequency variations in coal flow were also examined and up to 100 Hz a correlation above 0.8 was identified. Even higher frequency correlations appear to be random.

For the LMF5-H test the TS1 spectrometer line reversal system was calibrated for both sodium emissions (589/589.6 nm) and potassium emissions (766.5/769.9 nm). The operating wavelengths of 588.9 and 765.1 were selected from gas emission and transmission spectra to avoid the self reversal regions at line center created by absorption in the cooler boundary layers of the gas. During the start of the LMF5-H test the spectrometer was set to 765.1 nm to observe when potassium emissions could first be detected as the gas temperature was rising after ignition of the secondary combustor. Experiments to study the secondary combustion quenching effects of potassium were conducted during the first four hours of coal combustion. These experiments only introduced seed for short periods. As a result, potassium emissions were too weak or too short lived to allow line reversal measurements. During the conclusion of the secondary combustion experiments, once the secondary combustor inlet temperatures had attained sufficient temperature to maintain combustion with potassium, continuing seed flow was initiated. The TS1 potassium line reversal responded immediately, as shown in Figure 20. The high level potassium addition caused some quenching and cooling of the gas temperature at TS1, with the gas temperatures rising after the seed flow was adjusted down as planned to allow the secondary combustion temperatures to climb. As can be seen in Figure 20 the TS1 potassium line reversal provided gas temperature measurements for gas temperatures below 1700°F (1200K), which is expected to be near the lower limit where sufficient gas-phase potassium exists for line reversal measurements when the K2/S is about 4.2 (K flow of 0.25 lb/s in the LMF5 tests). Accurate sodium line reversal measurements were not possible below a gas temperature of about 2100°F (1420K) and the TS1 potassium measurements shown in Figure 20 are generally below this level. At 1700°F thermocouple radiation losses are much less than at the nominal



a. Coal Flow with Damaged Moulder Valve



b. Coal Flow with Repaired Moulder Valve

FIGURE 19. Moulder Valve Effects on Coal Flow

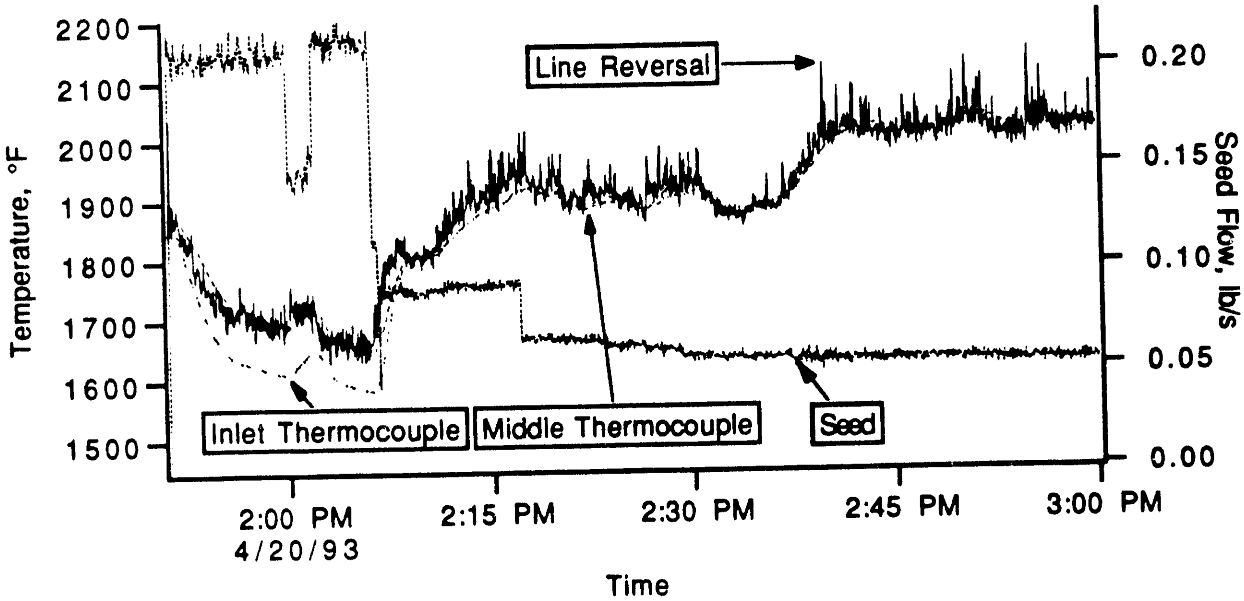


FIGURE 20. TS1 Potassium Line Reversal at Initiation of Seed Flow

2300°F TS1 temperature, and adjacent thermocouple measurements should essentially agree with the potassium line reversal, as was the case as shown in Figure 20. The middle thermocouple is located about 1 foot (.37m) above and about 3 feet (.98m) downstream of the line reversal penetration, while the inlet thermocouple is located about 5 ft. (1.51m) ahead of the line reversal penetration. The middle thermocouple lost its alumina sheath and responded with greater frequency response than the sheathed thermocouple during the LMF5-H test.

Previous comparisons of the Mississippi State University (MSU) SiDA probe and the TS1 line reversal showed good agreement, but these comparisons were limited because exact time correspondence was not established. During the latter portion of the LMF5-H test the SiDA system clock was set to the CFFF digital data acquisition system clock. Then data was taken from both systems at 20 samples/min for the line reversal and 30/min for the SiDA. Results are shown in Figure 21. The two systems show exceptional agreement in measured temperature levels and oscillations with the line reversal showing about a 20K (35°F) higher level. The line reversal gas temperatures were expected to be at a greater difference above the SiDA wall surface measurements and the small difference may have resulted from line reversal calibration shifts after superheater thermal expansion forced some optics realignment. It is also likely that some gas cooling has occurred over the 7 feet (2.12m) from the SiDA to the line reversal. However, enhanced radiant heat transfer from the condensing potassium compounds should also bring the SiDA temperatures closer to the gas temperatures[2]. These comparisons will be conducted again during the LMF5-I test to verify these results.

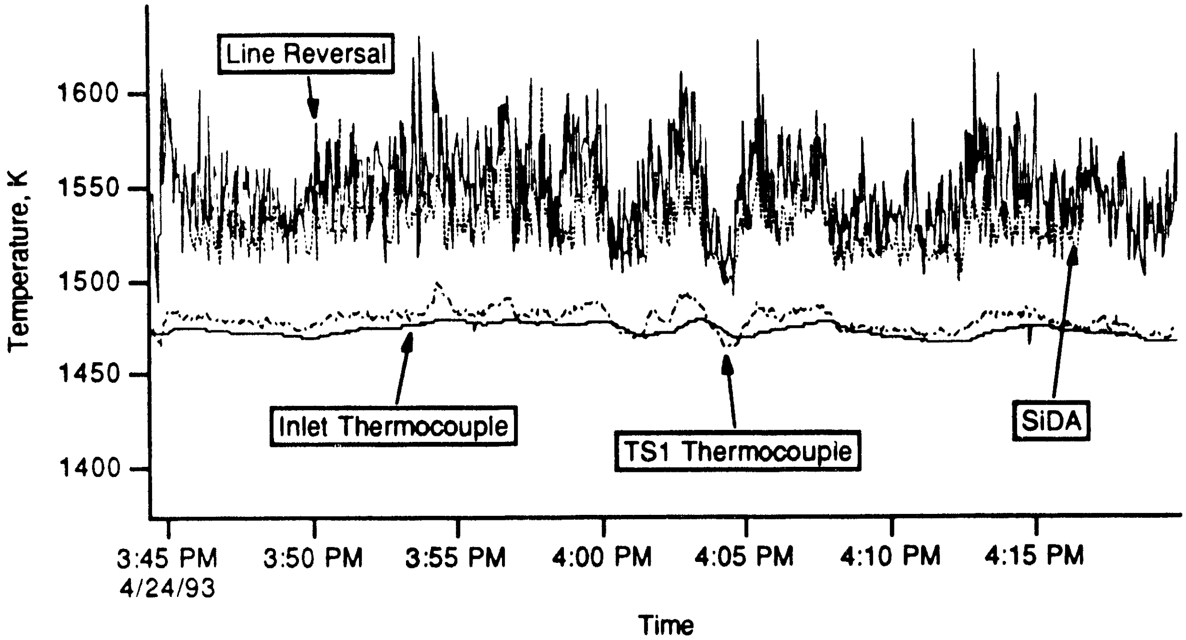


FIGURE 21. TS1 Temperature Measurement Comparisons

Preparations to perform a detailed study of the mixing and any induced velocity fluctuations in the secondary combustor were completed. These measurements are planned, using both the MSU and UTSI laser velocimetry equipment, for the LMF5-I test. Additional measurements planned for the LMF5-H test, but deferred to the LMF5-I test include the particle loading measurements at TS1 and on-line efficiencies for the particle removal equipment using Insitec, Inc. systems, as well as additional on-line sample extraction dilution particle size distribution (SEDS) measurements. Calibration efforts continued this quarter with the SEDS, but instrument problems prevented completion of these experiments. Training for calibration and repair/operation of these instruments is planned for early next quarter. The LMF5-I test also will use MSU support where funding permits.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

No activity was planned or carried out during the quarter.

No activity is currently planned for FY93.

TASK 6 - MODIFICATIONS TO THE CFFF

TEST FACILITY MODIFICATIONS/ADDITIONS

High Temperature Air Heater (HTAH) Development

Material Analysis

An investigation was begun using a laser to coat candidate HTAH materials with various protective coatings. A literature search was completed which will help guide this effort. A post-test analysis of Lanxide DIMOX materials used in the LMF5-H test was started, using an optical microscope.

Heat Transfer Enhancement

The lab setup for conducting heat transfer enhancing tests is complete and includes an automated data acquisition system, a preheater, a tube furnace, and temperature and pressure measuring instrumentation. A base condition of no-heat transfer augmentation was established. During the next quarter different heat transfer augmentation techniques will be tested and compared to the base case regarding heat transfer and pressure changes.

Sealing Techniques

A threaded Lanxide DIMOX tube was tested up to 25 psig during the LMF5-H test. Although the tube seal leaked, the threads held-up well mechanically. The same sealing configuration was tested on a lab scale and showed no leakage at room temperature at 125 psig. The lab scale test will be repeated at 1000°F. During the LMF5-I test, this sealing technique will be tested again, incorporating the improvements learned from the lab-scale tests. Other means of sealing will also be evaluated.

Materials Tests

Candidate HTAH materials from four different suppliers were planned to be tested during the LMF5-H test. The suppliers were Composite Ceramics Inc. (CCI), Hague International (HI), Babcock and Wilcox (B&W), and Lanxide. The CCI tubes did not arrive in time and were not tested. A mullite tube supplied by HI was tested using a new mounting technique developed by HI. The mount failed near the start of the test. B&W mounted several coupons made from their continuous fiber ceramic composite on a test probe along with a section of Lanxide DIMOX tube. These samples were exposed to exhaust gas at approximately 1593°C (2900°F). The Lanxide material appeared to have held up well. The other specimens were damaged by the slag. Portions from several of the B&W material fell off along with slag as the probe was removed from the furnace. The probe was returned to B&W for the analysis of the samples and results. A six-foot, two-inch OD Lanxide tube was tested which had one closed end and the other with threads machined into its outer surface. Video images showed the rate and type of slag buildup on the tubes. It also showed that the slag either drips off the tube or occasionally peels off in sheets. Good heat transfer data of the Dimox tube was also obtained. Figure 22 shows the Dimox tube temperatures measured during the LMF5-H test. This data will be used to determine heat transfer coefficients for the system.

Failure of the Dimox tube appeared to be due to thermal shock. A shutdown of the compressor supplying air to the electric preheater resulted in the loss of several heater elements. This led to the introduction of 149°C (300°F) air into the tube. The tube appeared to have suffered a thermal shock shortly after the third coal-off period due to this cooler air. The tube stayed in place seven minutes after the fourth coal-on cycle and then the center section fell away (44 hours on-coal). Samples from the tubes that were exposed for the entire 88 hours of the LMF5-H test showed no evidence of corrosion of the outer surface. One area was discovered on the inner surface which appeared to have eroded, but further analysis is underway.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

No activity was planned for this quarter and none is planned for next quarter.

TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES

The Thirty-First Symposium on Engineering Aspects of MHD (SEAM) at the Grouse Mountain Lodge in Whitefish, Montana, was attended by UTSI personnel from June 29 through July 1, 1993. The following papers were presented:

- "Particle Effects on Gas Optical Properties and Radiation Heat Transfer in an MHD Furnace"
- "Status of Proof-of-Concept Testing at the Coal-Fired Flow Facility - 1993"
- "Effect of Flow Variables on Temperature Levels and NO_x Emissions at the CFFF"
- "Analysis of Material Disposition for Illinois #6 Coal POC Testing at the CFFF"
- "Gas-Side Corrosion Performance on Superheater/ITAH Tube Alloys in MHD Tests with High Sulfur Coal"
- "Line Reversal Monitoring of Typical Superheater Inlet Temperatures"
- "Considerations for the Use of the Modified Line Reversal Technique for Gas Temperature Measurement"

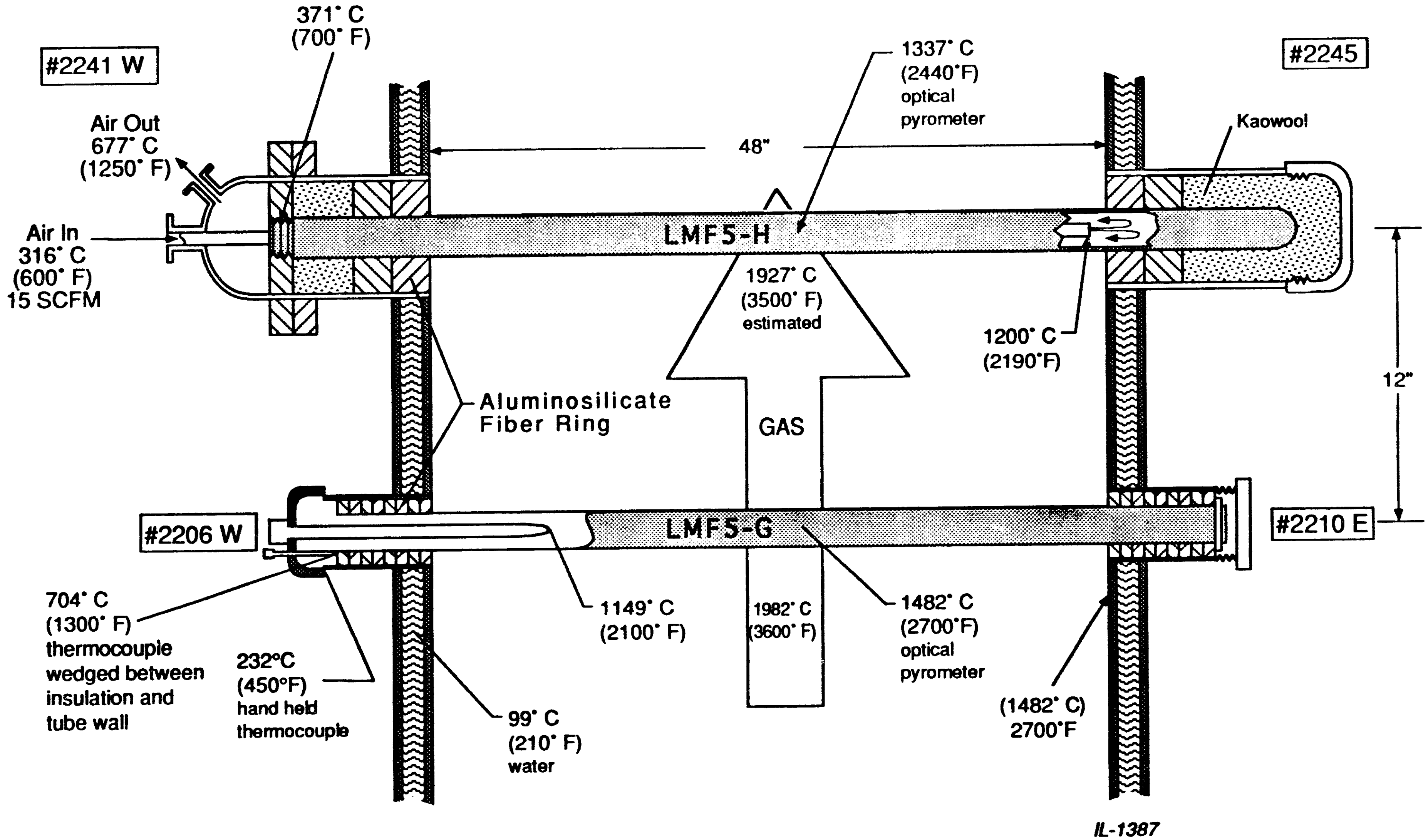


FIGURE 22. Temperature Data Relating to Tests of DIMOX™ Composite Tubes

- "Development of Particle Monitor for the CFFF" (Poster Presentation)
- "Ash Deposition in the Coal Fired Flow Facility While Burning Illinois #6 Coal" (Poster Presentation)
- "Evolution of Particles Size Distribution after the CFFF Secondary Combustor" (Poster Presentation)

TASK 9 - CFFF PROGRAM MANAGEMENT

MANAGEMENT AND ADMINISTRATIVE SUPPORT

The MHD contract renewal modification for the period of May 3, 1993 to March 31, 1994 was received, reviewed, signed and returned to DOE/CH.

The draft of the January-March 1993 Quarterly Technical Progress Report was issued to DOE/CH for review and comment.

Revision No. 1 to the Management Plan for FY93 was issued to include an additional 200 hours of CFFF testing on western coal as requested by DOE.

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GLOSSARY

AH	- Air Heater
ASTM	- American Society for Testing and Materials
BGC	- Bendix Gas Chromatograph
BH	- Baghouse, particulate capturing device using a fabric type filter bag
B&W	- Babcock & Wilcox
CARS	- Coherent anti-Stokes Raman spectroscopy
CERCLA	- Comprehensive Environmental Response Compensation and Liability Act
CFFF	- Coal Fired Flow Facility
CS(n)	- Cooling Section where n = number of section
CDIF	- Component Development Integration Facility
DCW	- Diagonal Conducting Wall
DDAS	- Digital Data Acquisition System
Diagnostic Channel	- A substitute channel in place of generator channel
DNCF	- Dry Normal (i.e. standard pressure and temperature) cubic foot
Downstream	- From exit of diffuser outlet to stack
DFO	- Diffuser outlet probe
DG	- Data General Computer
ε	- Emissivity or velocity fraction
ECF	- Energy Conversion Facility
EFM	- Electric Field Meters
EPRI	- Electrical Power Research Institute
ESP	- Electrostatic Precipitator
EDX	- Energy Dispersive X-ray
Flow Train	- Test facility including all components from the vitiation heater to the stack
GC	- Gas Chromatograph
GC/MS	- Gas Chromatograph/Mass Spectrometer
GIS	- Geographic Information System
HPT	- High Pressure Test
HR/SR	- Heat Recovery/Seed Recovery
HTAH	- High Temperature Air Heater
HVT	- High Velocity Thermocouple
ICAP	- Inductively Coupled Argon Plasma
IMPS	- Intrusive Multi-Probe System
IT	- Inlet Transition
ITAH	- Intermediate Temperature Air Heater
ITC	- Integrated Topping Cycle
LDV	- Laser Doppler Velocimeter
LMF(n)	- Low Mass Flow Test, where n = number of test
LPS	- Light Pipe Sensor
LV	- Laser Velocimeter
MCP	- Multicolor Pyrometer
MHD	- Magnetohydrodynamics
MPS	- Miscellaneous Process Sampling
MSE	- Mountain States Energy
MSU	- Mississippi State University
NPDES	- National Pollution Discharge Elimination System
NSPS	- New Source Performance Standard
ONR	- Office of Naval Research
PAD	- Pulsed Amperometric Detector
PE/AS	- Potassium Emission/Absorption System
PGC	- Perkin Elmer Gas Chromatograph
PMS	- Particle Measuring System
POC	- Proof-of-Concept
PSD	- Particle Size Distribution System
PTO	- Power Take-Off
RCRA	- Resource Conservation and Recovery Act
RF1	- Radiant Furnace #1 Position
SCA	- Specific Collection Area for ESP
SCI	- Secondary Combustor Inlet
SCO	- Secondary Combustor Outlet
SCR	- Silicon Controlled Rectifier
SEDS	- Sample Extraction/Dilution System
SER	- Site Environmental Report
SEM	- Scanning Electron Microscope
SHTM	- Superheater Test Module
SLR	- Sodium Line Reversal
Sootblower	- Device for removing particulate collection on heat transfer surface
T/C	- Thermocouple
TCLT	- Two Color Laser Transmissometer
TGA	- Thermogravimetric Analyzer
TS(n)	- Test Section, where n = number of section
TTIRC	- Technology Transfer Integration and Review Committee
Upstream	- That part of the Flow Train from the vitiation heater to the exit of the diffuser
UTSI	- The University of Tennessee Space Institute
VIES	- Visible/Infrared Emission Spectrometer
WBDAAS	- Wide Band Data Acquisition and Analysis System

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APPENDIX A

HOW ASH IMPACTION CHANGES SHAPE OF SUPERHEATER DEPOSIT BETWEEN SOOTBLOWINGS*

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1. ABSTRACT

This paper presents results of inertial impaction calculations using part of a comprehensive model being developed by the authors that considers the variations in target shape with time. 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 (or CCSEM) 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 near or downstream from the (pilot-scale-combustor-simulated or real) secondary-superheater location and elemental analyses of the stage-collected fly ash particles represent the major fuel-related input data. An alternative approach to direct measurement could use as input the fly ash data predicted from advanced coal analyses combined with appropriate computer models from other researchers when they are developed.

This paper presents calculated two-dimensional deposition results via the inertial impaction mechanism that show the influence of several variables including time, superheater tube diameter, flue gas velocity, fly-ash particle density, particle diameter distribution, and dust loadings. Fly-ash data from the +20MW$_t$ magnetohydrodynamic (MHD) facility at the University of Tennessee Space Institute (UTSI) are used for calculating deposition on superheater tubes during tests with coal+seed and coal alone. Additional data from the Pittsburgh Energy Technology Center (PETC) are examined for deposition of refractory Al_2O_3 particles injected into the flame zone to simulate fly-ash particles during 100% natural-gas firing in the Fuels Evaluation Facility (FEF).

2. INTRODUCTION

Typical calculations of trajectories of ash particles or molten drops that could contact a superheater tube via inertial impaction previously have been restricted to a target shape of a right circular cylinder, and often the predictions provide an integrated, one-dimensional view of deposition. This produced predictive results such as the average

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accurate extrapolations from the upper limit of viscosity measurement in a conventional rotational slag viscometer, 10^3 Pa.s (10^4 poises limit), to 10^{10} Pa.s (10^{11} poises) or greater are needed (>10^{14} Pa.s or >10^{15} poises for particles >1 μm with 8 hours exposure on an almost clean superheater tube) to describe a fairly common high-porosity deposit that is not sintered or perhaps one that is just slightly-sintered (Wagoner, 1989). A concept for calculating capture of non-sticky particles that impact non-sticky deposit surfaces has been developed (apparent impact viscosity of a dust layer transported to the tube surface and held in place by thermophoretic force, Wagoner and Yan, 1992) and will be included in the UTSI generic (or "unified") engineering model that has a goal of being almost universally-applicable. In equation (1) the penetration distance, s, for particle deceleration (Raask, 1985) will be calculated using values of η from state-of-the-art slag viscosity measurements/correlation-extrapolations, future "sintering viscosity" measurements/correlations (10^5 to 10^{11} Pa.s or 10^6 to 10^{12} poises), and apparent impact viscosity measurements (which are a function of the impacting particle diameter). The angle of impaction, θ, will be calculated in the UTSI model from the local trajectory of individual particles and the current local deposit surface shape/thickness resulting from multiple mass-transfer mechanisms.

$s = \frac{2 v_p R^2 \rho_p \sin\theta}{9\eta}$	(1) where s = depth of penetration, m, v_p = velocity of the impacting particle, m/s, R = radius of particle, m, ρ_p = density of the impacting particle, kg/m^3, θ = angle of impaction, rad., and η = viscosity of the surface layer, N.s/m^2.

For this paper, only single stagnation points were used to simplify the calculations. A MacIntosh Quadra 900 computer with a 68040 CPU and 28.7 MB of RAM was chosen for these calculations. Computer graphics were used extensively to produce the visual site-specific computer simulation results shown herein. For the deposition illustrations, flue gas flow is from the left to the right. The circle on the right represents a cross section of the exterior of a superheater tube, and the deposit contours to the left represent consecutive time intervals of deposition for periods as noted in the individual figures. The local layer thickness is derived from the calculated deposited mass, the measured density of the depositing particles, and the assumed porosity of the deposit. For all MHD computer simulations a deposit porosity of 0.0 was used, based on typical observations with actual deposits in appropriate temperature zones. The porosity used for dusty Al_2O_3 deposits in the PETC FEF tests was 0.65 which is the average of the range reported for dusty deposits by Wessel and Wagoner, 1986.

An illustration of the importance of the diameter of the superheater tube is shown in Figure 1. With inertial impaction of fly ash occurring on leading edge of the superheater tube, the shape and thickness and mass of the deposit changes significantly as tube diameter changes. Also fraction of the tube circumference covered by the deposit changes. As we shall see in more detail later, the average elemental composition of the deposit and the local gradients in composition also change with tube diameter. Therefore properties such as slag viscosity that are influenced by composition also will be affected. These local effects will be tracked in a future version of the UTSI engineering model using finite elements. The caption identifies the site-specific MHD conditions that were held constant for these calculations.

Although the tube was clean at the start of these calculations, if desired the current version of the inertial impaction module could start calculations at time zero with a non-circular shape to investigate the effect of partial cleaning by sootblowing with some deposit remaining, or perhaps to examine the concept of streamlined tubes.

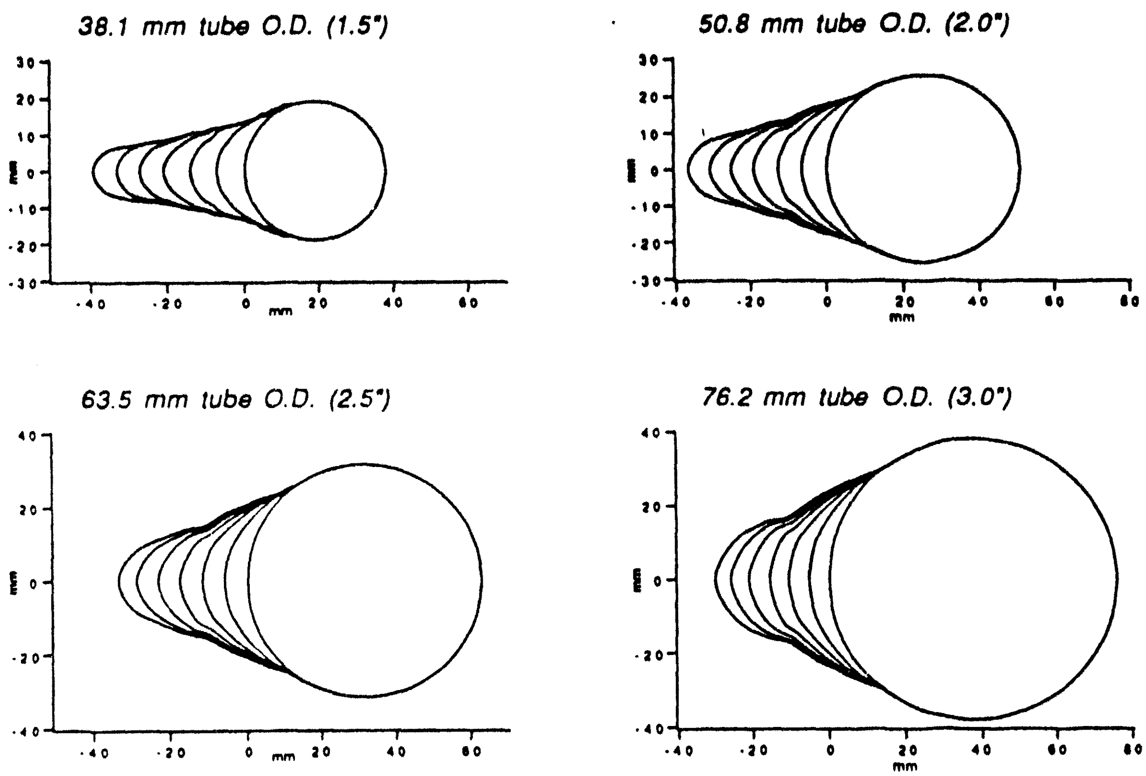

FIGURE 1. Effect of tube diameter during six-hour period. Calculated deposit growth on clean MHD superheater tube shown with one-hour time steps for fly ash particles from Montana Rosebud coal plus seed, 18.3 m/s (60 ft/s) flue gas velocity, 1478 K (2200°F) flue gas, and 866 K (1100°F) tube metal.

Velocity of the flue gas also is a very important consideration when inertial impaction is involved. In the next illustration we examine a range from 6.1 to 21.3 m/s with a constant tube diameter (63.5 mm) for an MHD visual site-specific computer simulation. The range in velocity might have been created by operational changes (boiler load) or design considerations, for example. Figure 2 shows that the deposit shape is extremely sensitive to changes in velocity. The shape and thickness and mass of the deposit changes significantly as velocity changes. Similar to what we saw with changes in tube diameter previously, the fraction of the tube circumference covered by the deposit changes significantly. Also as we shall see in more detail later, the average elemental composition of the deposit and the local gradients in composition also change with velocity.

Figure 3 illustrates the combined effect of tube diameter and flue gas velocity. The comparison of a 38.1 mm tube at 18.3 m/s (upper left) with a 63.5 mm tube at 6.1 m/s (lower right) vividly shows the powerful influence of the combined variables on the MHD visual site-specific computer simulations. These observations are especially significant when one considers that deposition probes with outside diameters in the range of 25.4 to 38.1 mm often are used by many investigators for "relative" deposition measurements and fuel evaluations in pilot-scale testing. If the small diameter tubes are placed in a test section with reduced cross-sectional area in an effort to produce desired flue-gas velocity, the risk is high that the walls of the constricting section ahead of the tube location will remove fly-ash particles selectively because of high target efficiency for specific particle diameters, and change particle size distribution and dust loading at the superheater tube site. Since the relative effect may be different for different ash particle-density/particle-size distributions, relative test results may not always be reliable.

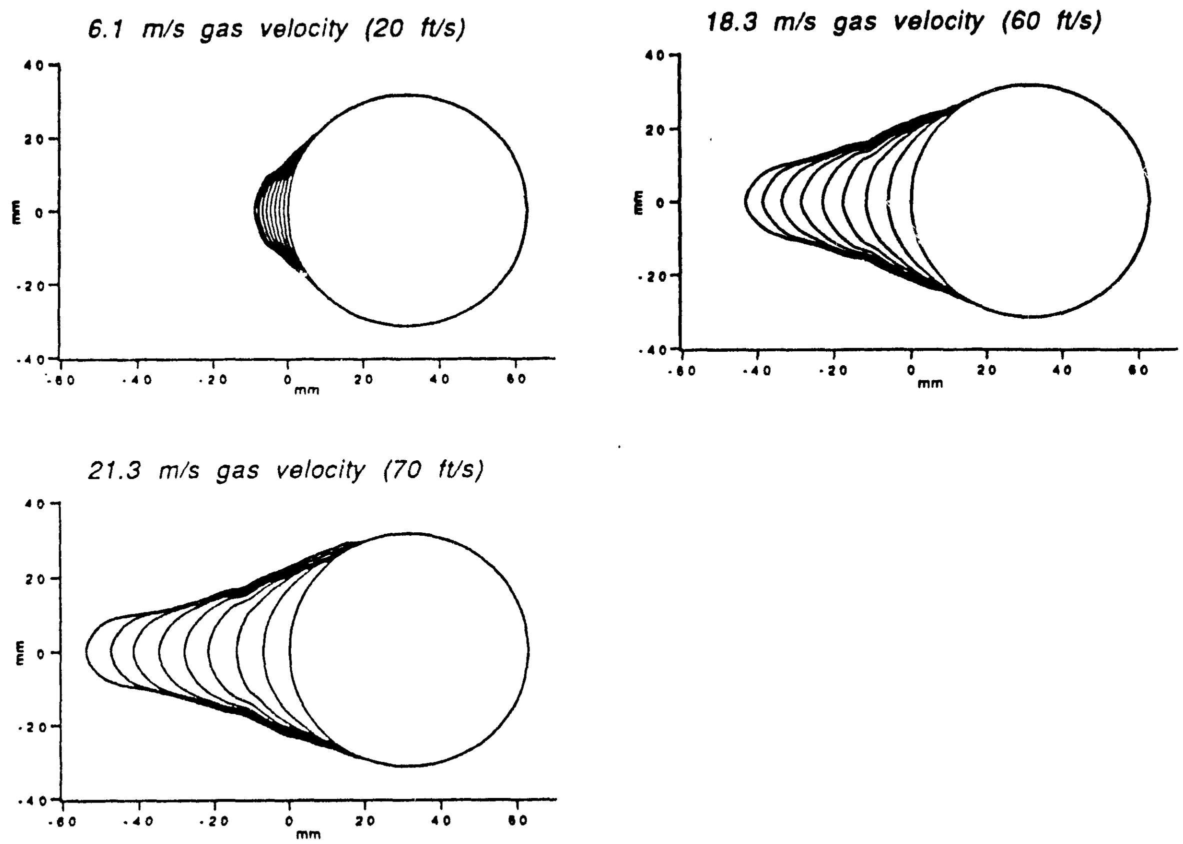

FIGURE 2. Effect of flue gas velocity during eight-hour period. Calculated deposit growth on clean MHD superheater tube shown with one-hour time steps for fly ash particles from Montana Rosebud coal plus seed, 63.5 mm tube O.D. (2.5"), 1478 K (2200°F) flue gas, and 866 K (1100°F) tube metal.

The effect of using MHD potassium-containing seed plus coal vs. firing only Montana Rosebud coal during an eight-hour period is shown in Figure 4. The fly ash produced while firing coal alone exhibits a much more massive deposit on the 63.5 mm O.D. tubes with 18.3 m/s gas velocity in the computer simulation. Also the deposit contacts far more of the tube circumference around the leading edge, and it has more of a blunt shape. These results are produced by the changes in particle size distribution of the fly ash and in the total dust loadings measured during MHD tests. More details will be presented later in this paper.

Two dust loadings were tested with the refractory Al_2O_3 particles that were injected into the combustion zone of the PETC FEF during 100% natural gas firing, Smouse and Wagoner 1992. The effect of dust loading on the two visual site-specific computer simulations is shown in Figure 5. Ten minute time steps are shown for the first hour of deposition in this figure. Calculated deposition rates are proportional to the dust loadings. As noted earlier in this paper, all particles that contacted the deposit surface were assumed to be captured in the deposit layer after penetrating and decelerating. An important question about these calculations comes to mind. How do the computer calculations compare with deposit observations reported previously by Smouse and Wagoner in 1992? The FEF observations were: • during a 4.25-hour total test period with lower dust loading the deposit approached 51 mm (2") in height several times during the test before partial shedding, and • during a 3.5-hour total test period with higher dust loading the deposit accumulated to approximately 51 mm (2") in height several times during the test before partial shedding. For comparison, Figure 5 shows ≈16 mm/h growth at the stagnation point for

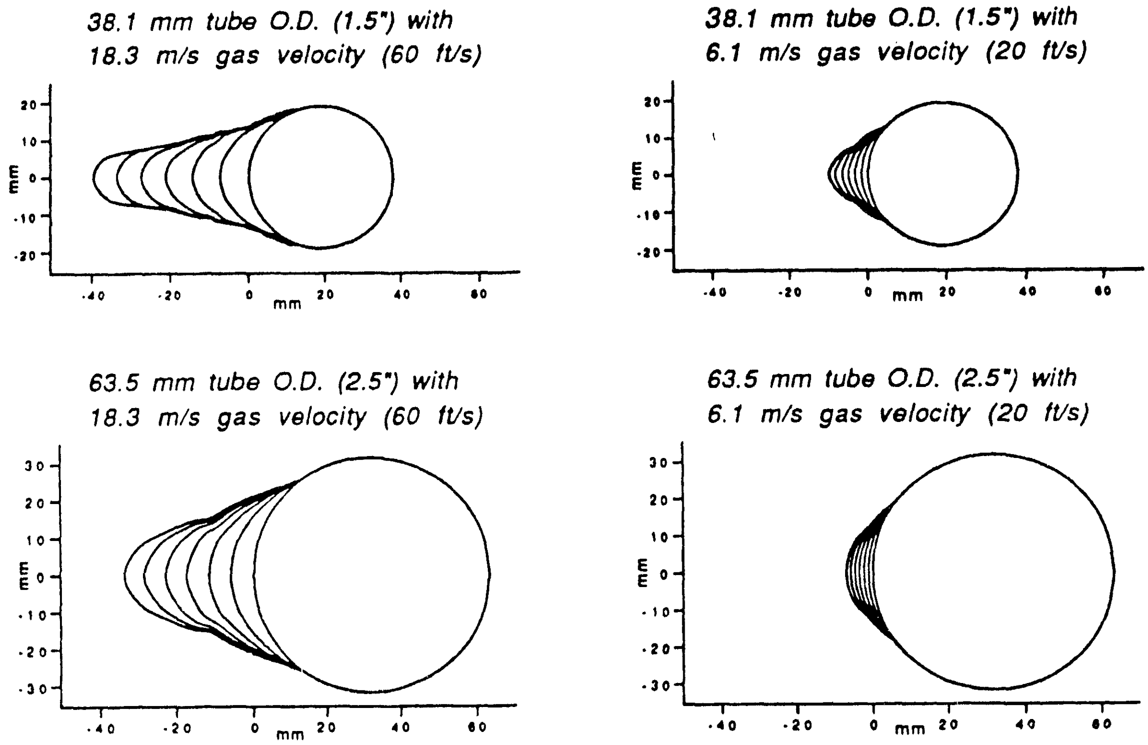

FIGURE 3. Combined effect of tube diameter and flue gas velocity during six-hour period. Calculated deposit growth on clean MHD superheater tube shown with one-hour time steps for fly ash particles from Montana Rosebud coal plus seed, 1478 K (2200°F) flue gas, and 866 K (1100°F) tube metal.

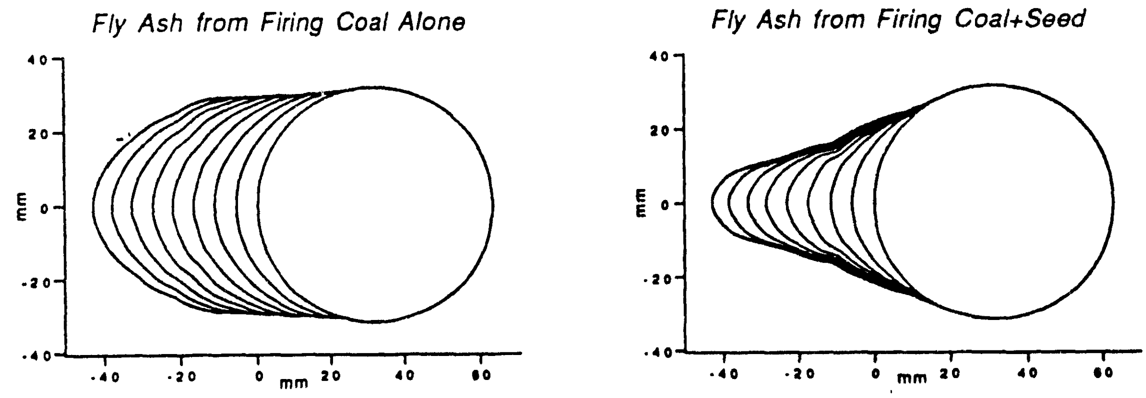

FIGURE 4. Effect of MHD seed vs. firing only coal during eight-hour period. Calculated deposit growth on clean MHD superheater tube shown with one-hour time steps for Montana Rosebud coal alone, or Montana Rosebud coal plus seed, 63.5 mm tube O.D. (2.5") with 18.3 m/s gas velocity (60 ft/s), 1478 K (2200°F) flue gas, and 866 K (1100°F) tube metal.

the lower dust loading and ≈ 31 mm/h at the higher dust loading. Therefore, we conclude Figure 5 is in reasonable agreement with FEF observations, and the local staying probability at the stagnation point was very high (approaching 1.0) during the PETC FEF tests.

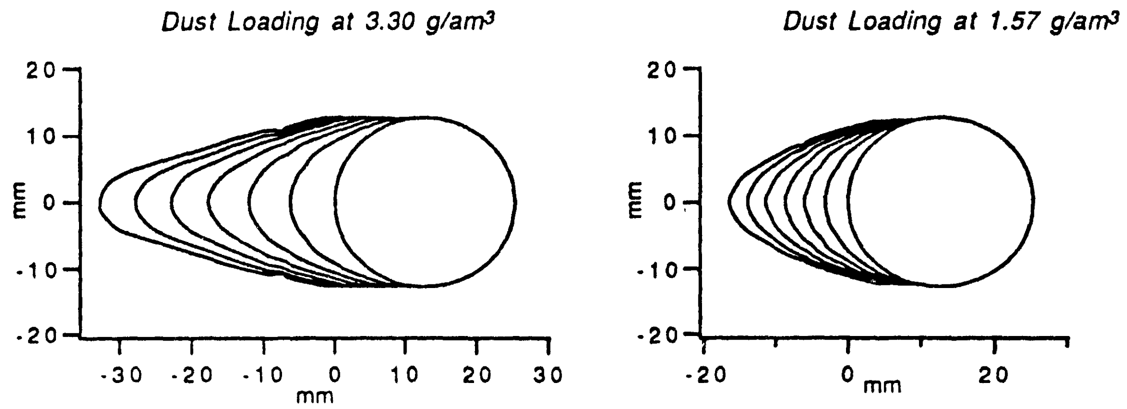

FIGURE 5. Effect of dust loading of refractory Al_2O_3 particles injected into the flue gas while burning natural-gas in the PETC Fuels Evaluation Facility showing a first-hour period. Calculated deposit growth on clean tube shown with ten-minute time steps for a 25.4 mm (1.0") O.D. simulated superheater tube with 18.8 m/s (61.8 ft/s) gas velocity, 1388 K (2038°F) flue gas, and 866 K (1100°F) tube metal.

The measured particle size distributions used for all calculations in this paper are shown in Figure 6. Note that although 87.9 weight % of the fly ash particles from the MHD coal-plus-seed test period (during LMF 5F) were smaller than 4.5 μm, there still is a significant amount of deposition produced by inertial impaction (Figures 1 through 4, and

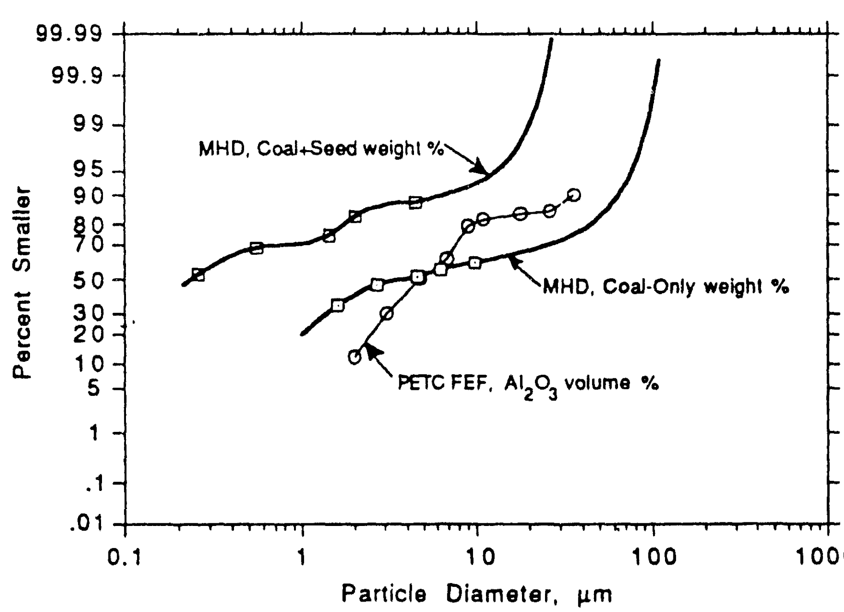

FIGURE 6. Particle size distributions of fly ash from five-stage cyclone data for MHD samples while burning Montana Rosebud, and from Leeds & Northrup MICROTRAC data for PETC Fuels Evaluation Facility with gas firing and Al_2O_3 particle injetion.

the appearance of actual MHD superheater deposits). Additional information is shown in Table 1 for total dust loadings in grams per actual cubic meter. The fraction of the total dust loading contained within specified particle size ranges are used as "bin" inputs for the deposition calculation.

Fly Ash Particles from:	Fly Ash Particle Density, g/cc	Total Dust Loading, g/am^3	Deposit Porosity Used in Calculations
MHD, Coal+Seed	2.66	12.77	0.0
MHD, Coal Only	2.66	2.01	0.0
PETC FEF, Al_2O_3	3.97	1.57 or 3.30 (2 separate tests)	0.65

TABLE 1. Additional data for the three fly-ash particle size distributions shown in Figure 6.

The MHD test period firing Montana Rosebud coal alone (without seed) during LMF 5F had significantly larger ash particles than the coal-plus-seed period (Figure 6), but also had a much lower total dust loading (Table 1). This should be considered when viewing Figure 4. Also variation in the MHD wet bottom slag tap removal selectivity could be a factor.

Compared to the ASTM coal ash data in Table 2, the ash elemental analysis values are quite different for the cyclone-sized data (by stage, S-1, S-2, etc.) from isokinetic sampling of MHD flue gas taken downstream from the superheater near the ESP inlet during LMF 5F periods firing coal alone or coal plus seed. Also significant differences in composition occur by ash particle size (impactor stage mid-points are shown as μm data). The UTSI deposition model uses combined input of "bin" particle size, particle density, particle elemental composition, and impacting-particle viscosity. Up to ten bins typically are input.

MHD Test Mode ------->		Coal Only	Coal Only	Coal Only	Coal Only	Coal Only	Coal + Seed	Coal + Seed	Coal + Seed	Coal + Seed	Coal + Seed
Wt. %	ASTM Coal Ash	S-1 9.87 μm	S-2 6.30 μm	S-3 4.63 μm	S-4 2.68 μm	S-5 1.60 μm	S-1 4.50 μm	S-2 2.03 μm	S-3 1.43 μm	S-4 0.55 μm	S-5 0.26 μm
SiO_2	37.26	19.93	21.60	22.39	23.50	24.24	7.45	0.24	4.94	3.80	3.85
Al_2O_3	15.37	11.78	12.15	12.82	13.55	14.07	4.01	2.99	1.60	0.67	0.38
Fe_2O_3	4.11	2.99	2.50	2.97	3.04	3.29	1.12	0.85	0.58	0.36	0.30
TiO_2	0.74	0.74	1.65	1.96	1.41	1.28	0.30	0.24	0.17	0.09	0.11
CaO	21.92	12.34	12.91	14.38	15.03	17.44	5.54	4.59	2.87	1.79	1.67
MgO	3.25	2.25	2.56	2.89	3.26	3.97	1.09	0.97	0.43	0.41	0.37
Na_2O	0.39	0.91	1.73	6.08	4.96	1.99	0.92	6.02	0.76	4.64	0.79
K_2O	1.01	29.97	30.12	24.91	21.74	18.56	49.75	47.40	50.27	51.12	53.37
SO_3	11.20	16.09	14.28	13.57	10.57	10.93	11.07	12.12	12.75	13.46	12.86
CO_2	N/A	N/A	N/A	N/A	N/A	N/A	13.57	15.15	14.45	N/A	16.14

TABLE 2. Elemental ash analyses comparing ASTM coal ash with cyclone stage samples with various mid-point particle sizes from MHD tests.

When considering inertial impaction, ash particles with different diameters contact the clean superheater tube at different locations. As the deposit grows with time, the locations for ash particle contact also change. This produces significant local variations in ash properties within the deposit that can be tracked and evaluated via computer. Although these details vary with time as deposit size and shape changes, Figure 7 illustrates how and why contact location varies with particle size. Only three particle diameters are shown, and this is just for time zero (clean tube) for simplicity. For a typical deposition calculation with ten particle-diameter bins and eight one-hour time steps there are eighty local collection efficiency curves calculated. Figures 7 and 8 show the effect of velocity on local collection efficiency, which can be considered as the probability for ash particles

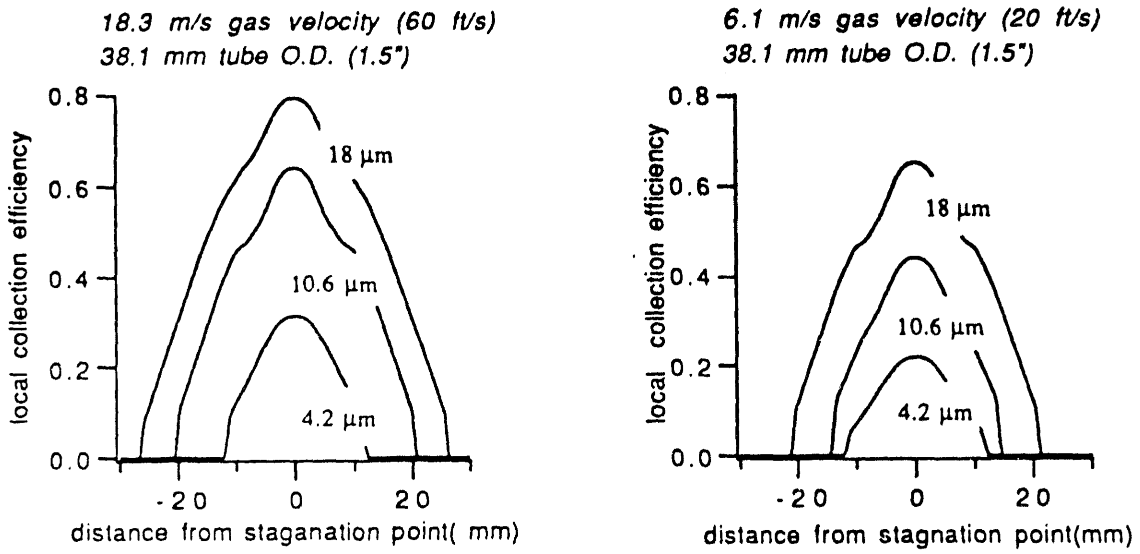

FIGURE 7. Effect of flue gas velocity at time zero with clean MHD superheater tube on local collection efficiency (ash particle contact probability) by location on tube surface for three impacting-particle diameters (18, 10.6 and 4.2 µm). Calculated for Montana Rosebud coal plus seed. Ash particle density is 2.66 g/cc with 1478 K (2200°F) flue gas and 866 K (1100°F) tube metal.

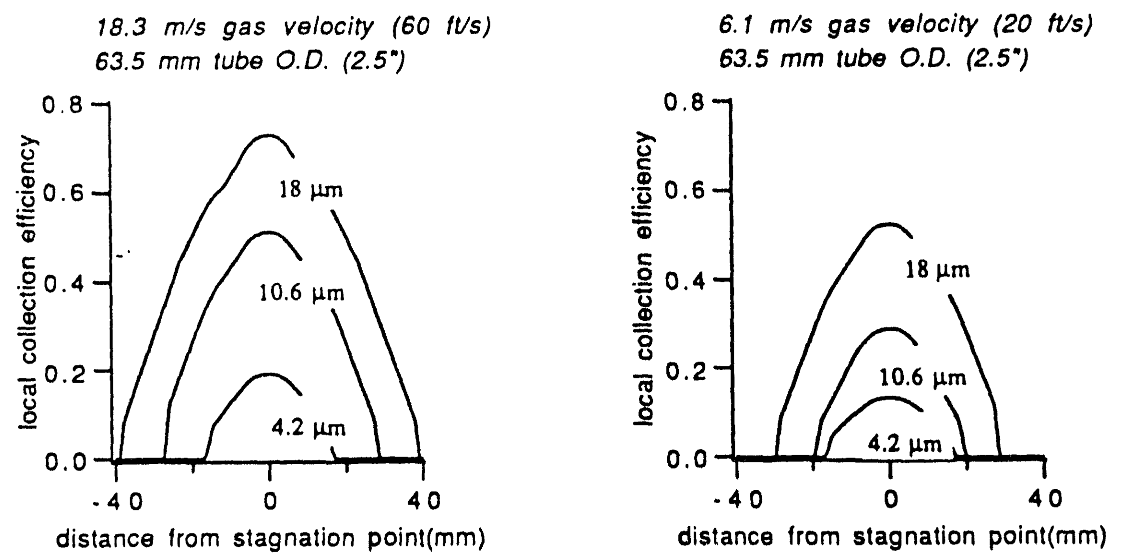

FIGURE 8. Effect of flue gas velocity at time zero with clean MHD superheater tube on local collection efficiency (ash particle contact probability) by location on tube surface for three impacting-particle diameters (18, 10.6 and 4.2 µm). Calculated for Montana Rosebud coal plus seed. Ash particle density is 2.66 g/cc with 1478 K (2200°F) flue gas and 866 K (1100°F) tube metal.

making local contact. Two tube diameters are considered (38.1 and 63.5 mm for Figures 7 and 8 respectively). Impactions of smaller diameter particles only occur near the stagnation point, and the smaller particles have much lower collection efficiencies. Collection efficiency decreases at lower velocity. Collection efficiency increases with smaller tube diameter. Larger particles impact more of the tube circumference (contact extends further around the tube from the center line stagnation point), especially with higher velocity and smaller tube diameter.

Figure 9 shows the effect of changes of the deposit shape with time on the cumulative target efficiency. The cumulative target efficiency indicates the weight fraction of all of the particles passing through a rectangular "window" of unit length with a height equal to the tube diameter projected upstream from the tube, accounted for by all of the particles that have contacted the surface of the tube per unit length via inertial impaction at the deposition time as shown. Comparisons are shown for two tube diameters and two velocities. The uppermost curve represents what would have happened if all fly ash from Montana Rosebud coal plus seed had been composed entirely of high density Fe_3O_4 particles (5.18 g/cc), such as would be produced from the oxidation of pyrite. For a comparison with the same tube diameter and flue-gas velocity, the third curve down was calculated for a density of 2.66 g /cc, taken from the actual MHD fly-ash density measurement.

All curves show a decrease in the cumulative target efficiency with increasing deposition time. This helps to identify the importance of considering the multiple effects of deposit shape changes.

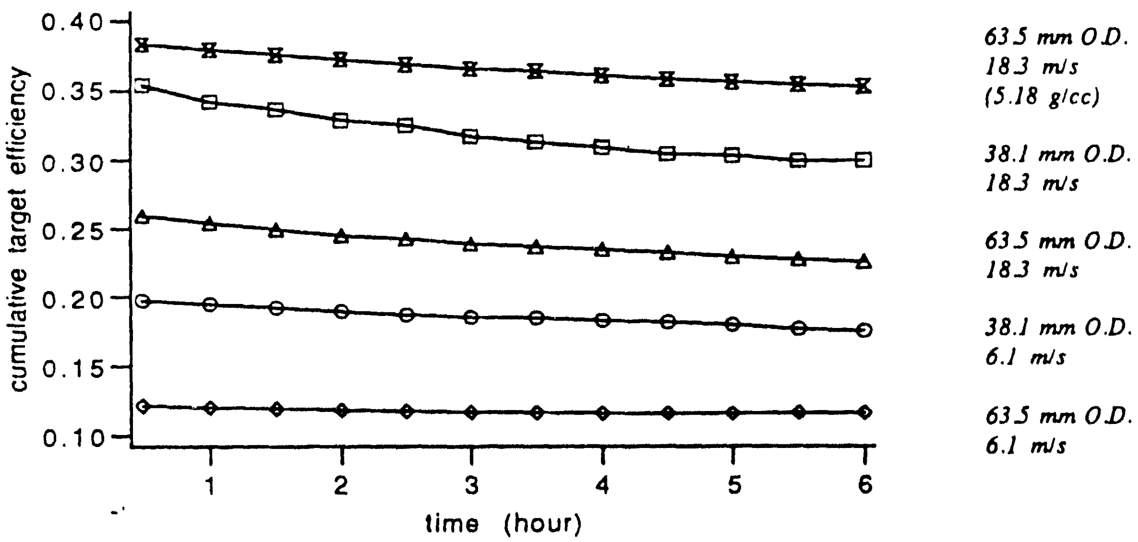

FIGURE 9. Effect of time, tube diameter, velocity and impacting ash particle density on cumulative target efficiency expressed as fraction of mass passing through swept frontal area actually contacting tube surface over a six-hour period of deposit growth after starting with a clean tube. Ash particle density is 2.66 g/cc except for high value on top line which represents Fe_3O_4. Temperatures are 1478 K (2200°F) flue gas and 866 K (1100°F) tube metal. Calculated for fly ash particles from Montana Rosebud coal plus seed.

Additional details of the effects of fly-ash particle density are shown in Figures 10 and 11 with the former displaying visual computer simulations for a six-hour deposition period, and the latter illustrating local collection efficiencies at time zero with a clean superheater tube. The higher density particles contact a wider portion of the circumference of the tube and have a higher probability of contacting the tube surface (Figure 11). However the thickness build up is less at the stagnation point with the higher density particles (Figure 10) because the deposit density also is higher (equal to the particle density because of the 0.0 porosity assumption for the MHD calculations. The net effect is a deposit with a more blunt shape for the Fe_3O_4 particles.

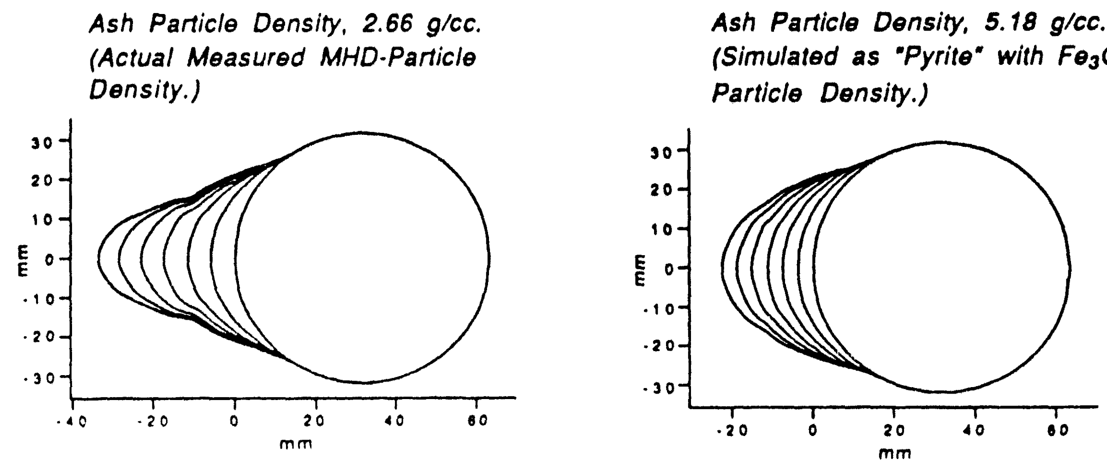

FIGURE 10. Effect of ash particle density during six-hour period. Calculated deposit growth on clean MHD superheater tube shown with one-hour time steps for fly ash particles from Montana Rosebud coal plus seed, 63.5 mm tube O.D. (2.5"), 18.3 m/s (60 ft/s) flue gas velocity, 1478 K (2200°F) flue gas, and 866 K (1100°F) tube metal.

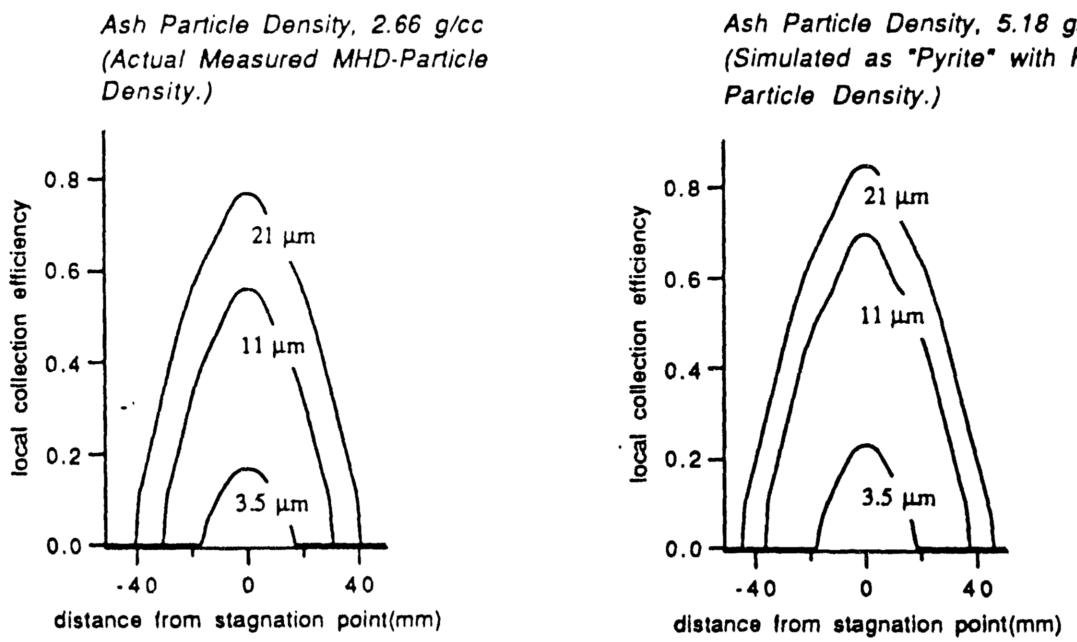

FIGURE 11. Effect of ash particle density at time zero with clean MHD superheater tube on local collection efficiency (particle contact probability) by location on tube surface for three impacting-particle diameters (21, 11 and 3.5 µm). Calculated for fly ash particles from Montana Rosebud coal plus seed, 63.5 mm tube O.D. (2.5"), 18.3 m/s (60 ft/s) flue gas velocity, 1478 K (2200°F) flue gas, and 866 K (1100°F) tube metal.

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