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Space Institute
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**TECHNICAL PROGRESS REPORT
FOR
THE MAGNETOHYDRODYNAMICS
COAL-FIRED FLOW FACILITY**

**For The Period
October 1, 1990 - December 31, 1990**

July 1991

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**

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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 electrostatic precipitator), the environmental monitoring, and analyses of test data on the convective heat transfer components (superheater and air heater). For this quarter, additional data on these subjects, plans for materials testing in future western coal tests and environmental and diagnostic results from the final test in the 2000-hour long-duration proof-of-concept (POC) test series on eastern coal 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 summarizes the results of a multi-task research and development project directed toward the development of the technology for the commercialization of the steam bottoming plant for the MHD steam combined cycle power plant.

The report covers the final test in a 2000-hour proof-of-concept (POC) test series on eastern coal, the plans and progress for the facility modifications and the conduct of the POC tests to be conducted with western coal.

Results summarized in the report include chloride emissions from the particle removal (ESP/BH) processes, nitrogen and sulfur oxide emissions for various test conditions, measurements of particulate control efficiency and management of the facility holding ponds during testing.

Activities relating to corrosion and deposition probe measurements during testing and the fouling of heat transfer tubes and interaction with sootblowing cycles are summarized.

The performance of both UTSI and Mississippi State University (MSU) advanced diagnostic systems is reported. Significant administrative and contractual actions are included.

Significant findings and conclusions are highlighted by bold type in Section II of this report.

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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 (1) 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, include: a) Graphics Support Services, b) Engineering Services, c) Test Control and Support, Data Processing and Documentation, d) Analytical and Chemistry Laboratory Services, e) Environmental Monitoring, f) CFFF Mechanical Maintenance Operations, g) Instrumentation and Control, h) Quality Assurance, i) CFFF Preventive Maintenance and j) Safety.

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

Encompasses the testing of the CFFF equipment and designed components, test data collection, analyses and reporting. A total of 520 hours of testing on coal is planned during the period October 1, 1990 through September 30, 1991, 240 hours of which will be a long-duration proof of concept test on eastern coal and 280 hours of special tests which will encompass: a) using eastern coal to simulate the Scholz retrofit plant conditions; b) western coal system checkout; c) using western coal to simulate the Corette Plant conditions, and d) using western coal with iron oxide addition. 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 as the need arises.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

Provides for the testing of DOE supplied components. Efforts to integrate a TRW supplied combustor spool piece into the LMF test train to evaluate the material under CFFF testing conditions were completed. The integrating hardware was designed, fabricated, installed, and tested for 252 hours during the August 1990 test (LMF-U).

No activity is foreseen during FY91.

TASK 6 - MODIFICATIONS TO THE CFFF

Provides for major facility modifications which includes conversion to a western coal processing system and a molten ash handling system.

The Babcock & Wilcox Company (B&W) and UTSI are designing and specifying the necessary equipment/hardware that will 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 has coordinated with B&W in the planning and preparation of this modification and in design reviews. UTSI will complete the final design, procure and install/integrate this equipment into the CFFF.

B&W and UTSI also designed an automated seed/ash handling system during FY89-90 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 includes providing proper interfaces for all utilities (fuel oil, electrical, instrument air, cooling water, etc.) as well as any piping and structural modifications required.

The high temperature air heater (HTAH) program has been redirected toward determining the feasibility of recuperative air heater concepts rather than regenerative approaches. New ceramic materials available in the market place have made the former technology more viable. Currently, candidate materials are being installed in the primary and secondary furnace of the CFFF to study their ability to endure the MHD flue gas corrosion, erosion and temperature conditions.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

Provides for additional technology development services on a task order basis as approved by DOE.

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 reviews and in the MHD Technology Transfer Integration Review Committee sessions are examples.

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, and contract administration.

CFFF PROGRAM GOALS AND SCHEDULE

Figure 1 shows the major program tasks and scheduled activities for completion through September 1991.

*(IBC) - Integrated Bottoming Cycle

GL-2138
6-28-91

FIGURE 1. SCHEDULED TASKS

SECTION II

SUMMARY OF TECHNICAL PROGRESS

This section addresses the technical progress of work conducted during the period October 1 - December 31, 1990 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

Extensive superheater refractory repairs were accomplished. Fiberboard and mortar were installed at cooling section 3 and cooling section 4. The refractory on the ceiling, floor, and one wall of test section 1 was chipped out and replaced with a blown refractory. In addition, a new floor of castable refractory was installed in the 180° elbow.

Repairs to the ash removal system were completed. These repairs included replacement of broken sprockets and freeing jammed grinders. The screw conveyors were cleaned out and the entire system was reassembled. During reassembly, all joints in the screw conveyors were sealed with silicone rubber.

A high temperature air heater (HTAH) material test assembly was fabricated and installed. In addition, two Babcock & Wilcox (B&W) material test probes were installed in the furnace.

Additional maintenance and fabrication activities were completed as below:

- Fabricated and welded rings for the spare combustor.
- Fabricated a new ash seed hopper bottom.
- Fabricated and welded spare replacement duct rings.
- Fabricated and installed a new manway door on the cyclone tank.
- Fabricated two new superheater cooling modules for use as spares.
- Fabricated new sootblower and gas sample probes.
- Rebuilt the transmission for the Baker fork lift and rebuilt the Clark lift mast.

Coal-Fired Flow Facility Test Train

FIGURE 2. LMF Test Train Schematic

TEST CONTROL AND SUPPORT

Primary emphasis this quarter was on activities associated with facility system preparation, check out, and conduct of the November LMF4-V test. Prior to the 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. All input and output channels to the facility control computer were operationally checked-out. Flow calibrations were obtained for the two Coriolis meters used to measure pulverized coal flow and for the fuel oil system turbine meters. New sootblower computer control sequences and a sequence to control the automatic ash removal system were written.

The Alkon on-line coal moisture meter located at the bottom of the coal baghouse was interfaced with the data acquisition system. An objective during LMF4-V was to calibrate the moisture meter output versus coal moisture analysis from the chemistry laboratory. The results indicated that the meter output is dependent on the amount of coal covering the probe. The amount of coal covering the probe can be controlled by turning off the rotary valve at the bottom of the coal baghouse for the desired length of time. It appears that a consistent probe output can be obtained when coal accumulates for at least three minutes which allows about 300 pounds of coal to accumulate in the bottom of the coal baghouse. Additional data will be obtained during the next test to confirm these results, establish a standard procedure for obtaining coal moisture meter readings, and finalize the meter calibration.

The Smith Coriolis meter evaluation was completed and the meter was returned to the vendor. Previously, a meter with a one-half inch inside sensor was tested but it was not possible to achieve the desired flow with this half inch meter. The vendor then supplied a one-inch meter. An output signal from the larger meter was received, but it was unstable and also not suitable for measuring coal flow.

An on-line test condition computer program is under development. This program will allow calculation by the test engineer of proposed changes to either combustor performance parameters (vitiator heater temperature, thermal input, etc.) or process flow variables (vitiator heater oil flow, coal flow, etc.). The program will calculate process flows from performance parameter inputs and/or it will calculate performance parameters from process flow inputs.

DATA ACQUISITION SYSTEMS

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 voltage from the measurement sensors or transmitters. The sensors are also 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.

Documentation of new electrical systems and changes dictated by test requirements continued. Changes were documented by making new drawings, updating drawings, updating cable lists, and updating measurement tag numbers using a computer aided drafting (CAD) system.

Regular disk drive backups were performed on the data acquisition system computers. Modifications to the data acquisition system database, required to support new test requirements and hardware changes, were completed.

A significant improvement to on-line data analysis was added this quarter. A new plotting program was developed and put into operation. The new program provides plots containing more information than previously available. The plots are also more legible than previous plots and the format for specifying data to be plotted is less complex.

ANALYTICAL AND CHEMISTRY LABORATORY SERVICES

During this quarter, the lab completed all routine analyses on the June 90 (LMF4-T) and the August 90 (LMF4-U) test samples. The chemistry lab also furnished analytical support for the LMF4-V test, providing moisture, seed, and sulfur analyses on pulverizer and feedtank coal samples. In addition, water samples from six CFFF sampling sites were collected each month and analyzed for routine water/wastewater parameters.

The new light-element detector which was installed on the AMRAY 1000 Scanning Electron Microscope (SEM) was calibrated and was used for nondestructive qualitative analysis. Methods for the line-scan generator were developed and the system was used to generate distribution maps and line profiles of elements in various MHD solid samples. The Finnigan gas chromatograph/mass spectrometer (GC/MS) was repaired and was used for analysis of samples collected from the LMF4-V test. The thermal desorption unit was installed on the GC/MS and methods were being developed to analyze volatile and semivolatile organics.

Samples of the MHD gas stream were collected at the electrostatic precipitator (ESP) outlet during the LMF4-V test in an attempt to quantify the volatile metals and organic compounds being emitted from the CFFF. Three different sampling devices were used to collect metals, volatile organics, and semivolatile organic compounds. These samples will be analyzed during the next quarter along with coal, ash and slag samples to determine the fate of organic and inorganic priority pollutants during MHD combustion.

ENVIRONMENTAL MONITORING

Efforts during this quarter were focused on the preparation for and participation in the LMF4-V test. Highlights included:

- Continued utilization and development of the new Impact 2 monitoring location.
- Participation in the annual Quality Assurance audit by Mountain States Energy (MSE).
- On-line treatment and management of the holding ponds during the LMF4-V test.
- A site inspection of the holding pond facilities by the State of Tennessee, Division of Water Management.

Water Quality

The holding ponds were monitored and treated as necessary throughout the quarter. Monitoring and treatment were intensified, as usual, during the LMF4-V test. Figure 3 illustrates the effect of 10 gallons of buffering agents added directly to holding pond #2 on 11/8/90. At the time of introduction the ponds were stirred for a period of 20-30 minutes. Figure 4 shows the effects of 5 gallons of buffering agent added directly to holding pond #2 on 11/10/90. Figure 5 shows the reduction in pH as a result of the addition of 10 gallons of buffering agent to holding pond #2 on 11/14/90. (The reduction of pH in holding pond #2 is also affected by the overflow of the effluent from holding pond #1 which was flowing at a rate of 33.6 gallons per minute.) **Pond conditions were maintained within permit limits throughout the test period.**

On 9/27/90 a representative of the State of Tennessee, Division of Water Management, made an on-site inspection of the holding pond systems. **At the time of the inspection the sampling and treatment routine and procedures were found to be satisfactory for controlling effluent parameters.** As a result of the inspection a formal letter of evaluation was forwarded to the ECP Program Manager which referenced the satisfactory findings of the inspection but also indicated the need to clean the accumulated sediments from both holding ponds #1 and #2 on a more frequent basis. Draining and cleaning both ponds will take place before the next scheduled test in the CFFF.

Terrestrial Ecology

No activity took place during this quarter.

Ambient Air Monitoring

Routine sampling carried out during the LMF4-V test indicated several ambient SO₂ concentration elevations. Typical concentration data are shown in Figure 6.

FIGURE 3. Holding Pond #2 Outlet pH, 11/08/90

FIGURE 4. Holding Pond #2 Outlet pH, 11/10/90

FIGURE 5. Holding Pond #2 Outlet pH, 11/14/90

FIGURE 6. Impact 1 Monitoring Site SO₂ Concentrations, 11/11/90

Additional data taken on 11/8/90 shows that the wind directions were variable and favored CFFF effluent dispersion towards the Impact 1 site (Figure 7) at several times during the day. Figure 8 shows the amount of variation in wind direction from true downwind conditions for the Impact 1 site. The two time periods with greatest potential for dispersion of the CFFF effluent coincide with increases in monitored SO₂ concentrations. Solar intensity data collected at the site indicated overcast conditions with a peak intensity of 68.3% (Figure 9). Additional data analyses will be completed and presented in more detail in the "Coal-Fired Flow Facility Site Environmental Report For Calendar Year 1990" scheduled for completion in April 1991.

During the week of October 15-18, 1990 personnel from MSE of Butte, Montana conducted an audit of the ambient air monitoring network. All operating instrumentation was subjected to audit evaluation using criteria set forth by the US EPA Quality Assurance Handbook for Air Pollution Measurement Systems: Vol. II and US EPA Quality Assurance Handbook for Air Pollution Measurement Systems: Vol IV, section 2.1. Audit results were good. In addition to the MSE audit of the ambient air network, an audit was performed by the State of Tennessee Division of Laboratory Quality Assurance on 11/14/90. Audit results indicated all instrumentation to be within EPA performance standards.

POLLUTION CONTROL

Efforts during this quarter concentrated on preparation for the LMF4-V test and post-test data reduction and analysis.

Moisture Analysis

The installation of a new technology water vapor analyzer was completed prior to the LMF4-V test. Moisture is calculated based on composition and flow rate of all mass inputs. Since excess oxygen is present in the gas stream at this point, hydrogen is assumed to be converted completely into water. This instrument uses the principle of infrared absorption spectroscopy to measure H₂O in the gas phase. Infrared energy from the source is passed through the gas where a portion of the energy is absorbed by the water. Relating this to a known standard containing zero moisture yields the concentration of water in the vapor phase. Interferences by such common gas components as CO and CO₂ are automatically factored. Figure 10 demonstrates the ability of the instrument to measure the moisture content of the gas at the secondary combustor outlet (SCO). The difference between the theoretical moisture calculated with no leaks and the experimental data from the instrument averaged approximately 0.6 %. The differences between calculated and theoretical values for moisture content in the gas stream are probably a combination of several factors. First, since the CFFF radiant furnace contains numerous instrumentation ports and is under a slight negative pressure, there are air leaks into the furnace. This additional unmeasured air input serves to dilute the concentration of moisture in the gas stream. Errors in

FIGURE 7. Impact 1 Air Monitoring Site Trailer

FIGURE 8. Impact 1 Monitoring Site Wind Direction, 11/11/90

FIGURE 9. Impact 1 Monitoring Site Solar Intensity, 11/11/90

FIGURE 10. Comparison of Moisture at SCO Theoretical Versus Experimental by IR - LMF4-V

measuring parameters such as coal flow and composition also contribute to the difference between calculated and measured moisture. Figure 11 gives the results of two "simulated" water leaks. An upstream water leak into diffuser section #6 was introduced during each test. Average response time of the instrument was less than 5 minutes. As shown, the average delta between experimental and theoretical remained essentially constant throughout the tests. **This indicates good instrument response to a water leak in the upstream components. Lower detection limits have not been well quantified, although it is believed that a leak as small as 0.5 gpm can be detected.** In Figure 11, note that there is a time delay for the measured moisture at the beginning and at the end of the water injection. There is an air purge in the sampling system which coincides with the end of the water injection which may appear to be a time advance. Closer inspection of Figure 11 shows a time delay, rather than a time advance.

N₂O Analysis

Measurements of N₂O concentrations continued during the quarter. N₂O, a potential "greenhouse" gas, is being studied to determine if concentration can be predicted by current models, such as the NASA SP273 thermodynamic code, and if so, the level of concern and/or control necessary for this component. Additional data collected during the LMF4-V test correlates well with past results which indicate that N₂O concentration is not sufficiently high to be of concern. An on-going study of the formation and reduction of N₂O along the CFFF test train will continue.

As previously reported, a calculation based on a technical paper [Ref. 1] pertaining to N₂O formation in a corona indicated that the ESP might generate 2-3 ppm N₂O. Apparently, that calculation does not apply to the CFFF-ESP. On November 13 and 16, 1990, samples were extracted from the air heater outlet (AHO) (upstream of the baghouse and ESP) and a port downstream of the ESP before mixing with baghouse effluent. All readings were very low (<1 ppm) but, if anything, the N₂O contents were lower downstream of the ESP than upstream.

Emissions Analysis

A series of tests to measure the NO_x and SO₂ concentration at different thermal inputs was completed during the LMF4-V test. Table 1 gives averaged data for the nine test periods monitored. (Note that the baghouse/electrostatic precipitator (BH/ESP) outlet readings are not shown for periods of thermal input around 24.5 MW_t, since the BH and ESP were both off-line during these periods.)

Figure 12 is a summary of NO results obtained from the LMF4-V test, during stoichiometry and thermal input variations. NO concentrations in the upstream section (before the secondary combustor) decrease along the test train. The NO levels achieved at the secondary combustor inlet (SCI) tend to be higher at higher thermal inputs (also mass flow) because of the shorter retention time and a higher SCI

FIGURE 11. Results of Simulated Upstream Water Leak Tests - LMF4-V

TABLE 1

RESULTS OF THERMAL INPUT VARIATION TESTS (PRIMARY OBJECTIVE #5)
LMF4-V NOVEMBER 15, 1990
AVERAGED DATA

Step Number (Time Period)	Thermal Input (MWt)											
	14.95				18.90				24.35			
	33 (8.45-9.84)	34 (9.84-10.58)	35 (10.58-11.45)	36 (11.50-11.88)	37 (11.88-12.62)	38 (12.62-13.27)	40 (13.61-14.47)	42 (14.47-15.24)	41 (15.24-16.01)			
Stoichiometry (%)	83.9	89.3	80.3	84.0	88.9	80.7	84.3	90.2	81.0			
DFO-NO (ppm)	875.3	1663.1	591.0	1343.0	1566.3	838.3	1853.6	3268.0	1199.2			
RF1-NO (ppm)	396.3	885.6	279.4	376.8	623.3	204.2	241.8	604.2	364.6			
SCI-NO (ppm)	41.8	118.6	44.3	71.8	140.4	70.3	89.7	368.2	116.1			
SCO-NO _x (ppm)	130.3	175.8	117.8	156.6	190.4	125.2	156.2	392.2	154.5			
BHO-NO _x (ppm)	76.3	84.0	68.9	89.4	109.6	68.3	†	†	†			
SCI-CO (%)	7.40	5.51	10.67	9.86	6.69	8.07	0.94	0.57	1.07			
SCO-O ₂ (%)	4.50	3.93	3.55	2.48	3.45	1.67	1.24	2.95	1.64			
BHO-O ₂ (%)	8.59	8.74	8.03	7.72	8.59	7.16	†	†	†			
SCO-SO ₂ (ppm)	472.6	430.8	610.3	632.5	361.0	899.7	638.5	93.8	695.3			
BHO-SO ₂ (ppm)	221.4	199.0	310.6	279.4	114.6	577.7	†	†	†			
SCO-H ₂ O (%)	14.6	15.6	14.9	16.8	16.8	16.7	18.1	17.8	17.6			

† Not available due to shutdown of ESP and BH at 25 MWt thermal input.

Stoichiometry
 □ 80 %
 ● 85 %
 ▼ 90 %

FIGURE 12. Summary of NO_x Results - LMF4-V

temperature (see Figure 13). For the same reason, higher thermal inputs generally produced higher NO concentrations at all locations. Stoichiometry was varied between 80 and 90 percent with the expected result of higher NO_x emissions at the higher stoichiometry near 90 percent.

Measurement of SO₂ at the secondary combustor outlet (SCO) and the baghouse outlet (BHO) was also conducted during the test. Figure 13 gives a summary of the SO₂ concentration during the test along with changes in temperatures (at the inlet transition (IT) and secondary combustor inlet (SCI)) and primary stoichiometry. As shown the SO₂ levels vary directly with primary stoichiometry (or some other parameter affected by primary stoichiometry) and temperature. The inlet transition is the horizontal section of the flow train connecting the secondary leg of the furnace with the SHTM. This measurement can be considered to be the temperature at the inlet to the SHTM, although it is known to be somewhat low due to lack of correction for radiation effects. The gas temperatures are also higher at the bottom of the inlet section. Previous reports documented these conditions through temperature transverse measurements. Total mass flow is being considered, although the analysis is not complete. Mass flow along with temperature will affect residence time, and since this analysis is based on the assumption that the gas is at equilibrium, reductions in reaction time can result in less agreement.

Figure 14 shows the relationship between primary stoichiometry, inlet transition and secondary combustor inlet temperatures, and SO₂ concentration at the baghouse and secondary combustor outlets for the periods of 15 and 19 MW_t input. Generally, lower stoichiometries produced higher SO₂ levels. This could be explained as the effect of higher inlet transition temperatures (brought about by lower stoichiometries). However, as shown in Figure 14, during the period of approximately 80% stoichiometry, small changes in stoichiometry related to corresponding changes in the SO₂. At this same time, the inlet transition and the secondary combustor inlet temperatures did not change appreciably. This appears to indicate that the phenomenon of changing SO₂ values is related to stoichiometry through some other parameter not yet identified. Another explanation might be that the kinetics of the system at lower stoichiometries favors sulfur species (unknown) which are less reactive with the potassium ions present. These species would not combine as readily with the potassium to form potassium sulfate, but instead would form SO₂ upon oxidation in the secondary combustor. This would explain the higher levels of SO₂ at lower stoichiometries and also would explain the "tracking" of the baghouse outlet SO₂ analyzer with the secondary combustor outlet analyzer noted during the test. Therefore, in effect, excess SO₂ measured at the secondary combustor outlet is not likely to be reacted and removed due to the low temperatures in the superheater test module (SHTM). High primary stoichiometry is favored if only the resulting SO₂ concentrations are considered. However, when the stoichiometry is increased to the

FIGURE 13. Summary of SO₂ Data Taken During Thermal Input and Stoichiometry Variations - LMF4-V

FIGURE 14. Effect of Primary Stoichiometry and Temperature on SO₂ Concentration - LMF4-V

point of significant SO_2 decline, the NO_x values rise rapidly. More tests are needed to study this effect on SO_2 and NO_x . Results from NASA code equilibrium calculations generally show only SO , SO_2 , and SO_3 in the gas phase after the secondary combustor.

In an attempt to further demonstrate the effect of stoichiometry on SO_2 concentration, Figure 15 shows a series of test periods when the stoichiometry changed from 90 to 80 percent. As shown, SO_2 concentrations were lower at the higher stoichiometry indicating the same phenomenon as previously identified.

One other test segment was also plotted to show the effect of changing inlet transition temperature at constant stoichiometry on SO_2 concentrations (Figure 16). As in the previous plots, peaks in inlet transition temperature have corresponding peaks in the SO_2 concentration. The cause of the sudden increase in inlet transition temperature without significant changes in secondary combustor inlet gas temperature or primary stoichiometry is from decreasing the secondary air which was introduced into the flow train. At this time as the IT temperature increased, the air flow was reduced from approximately 2.05 lb/s to 1.30 lb/s. This, in effect, reduced the amount of cooler gas admitted into the furnace (since the secondary stoichiometry remained greater than 100 percent).

In conclusion, based on the data collected during the LMF4-V test, stoichiometry (or more likely, some other parameter affected by stoichiometry) and inlet transition temperature have both demonstrated an effect on SO_2 concentrations. The SO_2 concentrations are "permanently" shifted because there is no appreciable reduction of SO_2 in the SHTM (between the secondary combustor outlet and the baghouse outlet). Indications are that kinetics play a large role in determining the SO_2 concentrations. An in-depth study of past test data will be undertaken in order to correlate the recent findings and to determine what factors play a major role in affecting the SO_2 concentrations.

Condensed Phase Sulfur Analysis

As reported previously, an effort was made to collect condensed solids in the upstream of the secondary combustor. The purpose of this effort was to determine the relative concentrations and species of sulfur in the upstream components. Using gas analysis systems, particulates were collected from three upstream locations in addition to the secondary combustor outlet during the LMF4-U and -V tests. Elementary analysis of these results continues. As a parallel effort, modeling across the secondary combustor using the NASA SP273 code was undertaken. Parameters chosen in calculations include gas phase temperatures, stoichiometry, and potassium-to-sulfur (K_2/S) ratio. The model predicts the disposition of sulfur and potassium in both the gas and condensed phase in equilibrium. This also supports the SO_2 variations described above. Comparison of theoretical calculations with the analysis of samples collected indicated good agreement.

FIGURE 15. Effect of Primary Stoichiometry and IT Temperature on SO₂ Concentration - LMF4-V

FIGURE 16. Effect of Temperature on SO₂ Concentration at Constant Stoichiometry - LMF4-V

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

TESTING

A long-duration proof-of-concept (POC) test (LMF4-V) was successfully conducted in the CFFF for 241 hours on coal during the period November 6-16, 1990. A continuous operation on coal of 191 hours was achieved. This is the longest continuous coal burning duration achieved to date by any MHD operation. All primary test objectives were met as listed below:

- Operate the coal fired flow facility on Illinois #6 coal for 240 hours minimum. (This completed the total planned 2,000 hours on eastern coal).
- Measure the efficiency and performance of the electrostatic precipitator (ESP) and baghouse (BH) while the K_2/S ratio is kept constant at 1.1.
- Evaluate the ability of the superheater test module to maintain proper test section and downstream temperatures with one module of cooling section #1 removed and with variations in the sootblower frequency.
- Evaluate mechanical operation of the automated ash handling system and determine post test bulk ash weights.
- Determine NO_x and SO_2 values while operating the CFFF at 15 MW_t , 20 MW_t , and 25 MW_t .

The next CFFF test is scheduled for April 1991 and will evaluate eastern coal at the Scholz plant operating conditions.

Table 2 shows the CFFF POC testing to date and the revised test schedule through FY91.

UPSTREAM COMPONENT SYSTEMS

All upstream test train component systems operated very satisfactorily during the LMF4-V test.

TABLE 2
CFFF Test Series

TEST CONFIGURATION	DATE OF COMPLETION	HOURS ON COAL
COMPLETED (Eastern Coal)	Prior test totals	267
POC*-LMF4-K	09-87	198
POC-LMF4-L	12-87	63
POC-LMF4-M	02-88	57
POC-LMF4-N	05-88	185
POC-LMF4-O	09-88	252
POC-LMF4-P	11-88	101
POC-LMF4-Q	05-89	41
POC-LMF4-R	08-89	263
POC-LMF4-S	12-89	135
POC-LMF4-T	06-90	217
POC-LMF4-U	08-90	252
POC-LMF4-V	11-90	241
		SUBTOTAL - 2,272**
PLANNED		
Scholz Plant Conditions Eastern Coal LMF4-W	05-91	80
Western Coal Mods Shakedown LMF5-A	07-91	80
Corette Plant Conditions Western Coal LMF5-B	08-91	60
Iron Oxide Addition Western Coal LMF5-C	09-91	60
Long-Duration POC Western Coal LMF5-D	10-91	250
		TOTAL - 2,802

* Proof-of-Concept

** Total test train operation time to date is 2572 hours (vitiation heater)

** Total test train operation time to date on coal is 2272 hours

** Total test train operation time to date on POC coal testing is 2005 hours

DOWNSTREAM COMPONENT SYSTEMS

The total duration of coal combustion during the November (LMF4-V) test was 241 hours in 6 segments with the longest continuous segment being 191 hours. The primary objectives of this test included the completion of the 2000 hour long-duration proof-of-concept evaluation of the downstream components.

Superheater Test Module (SHTM)

Convective Section Fouling

Progress was made towards getting gas temperatures in the SHTM closer to those required to provide retrofit plant simulation. This was achieved by the removal of the cooling section 1 (CS1) tube module. Measured average gas temperatures throughout the SHTM are shown in Figure 17 which shows that average temperatures were close to desired levels at each of the SHTM test sections. Measured temperatures were 2260°F at test section 1 (TS1) (adjusted to true gas temperature), 1676°F at TS2, and 1353°F at TS3, as compared to goal levels of 2250°F, 1700°F, and 1350°F, respectively. Gas temperatures throughout most of the upstream leg of the SHTM oscillated by about 200°F as a result of sootblowing. Except for the periods when low and high thermal input conditions were evaluated, the long term gas temperatures throughout the SHTM were reasonably stable, showing that there was little or no cumulative fouling.

Sootblowing of TS1 was on an 8 hour cycle, as were the other sections from CS1 through CS6. Little deposit was removed from TS1. The amount of deposit present after the LMF4-V test (see Figure 18) was much the same as after the prior (LMF4-U) test, for which a 1-hour TS1 sootblowing cycle was used. Since the gas temperature entering the single module of CS1 was above the potassium sulfate melting point, those deposits were also as much as 2-3 inches thick on the first pass. Liquid sulfate pools were present in both CS1 hoppers. TS2 tubes possessed friable deposits in the form of irregular "globs", 1-2 inches thick, on the leading sides of the first pass. All other tube sections were clean. The heat transfer coefficients for both TS2 and TS3, averaged over the sootblowing cycle, were constant throughout the test.

SHTM exit duct temperatures averaged 373°F, which was the desired value. This was achieved with a 4 hour sootblowing cycle for CS7 through CS10, with only an infrequent requirement to run a special 1-hour cycle to lower the temperature. Airheater inlet gas temperatures averaged 595°F, which resulted in an average secondary combustor air supply temperature of about 350°F, which was below the desired 600°F. This again demonstrated the need to move the airheater into a hotter gas regime. This is tentatively planned prior to the next test. In conjunction with the relocation of the airheater, tubes will be installed in the empty CS8 section in order to obtain requisite BH/ESP inlet temperatures with longer CS7-CS10 sootblowing intervals on the order of 8 hours.

FIGURE 17. Average Gas Temperatures Through the SHTM - LMF4-V

←
Gas
Flow

FIGURE 18. SHTM Tube Slag Deposition During LMF4-V

Water blowing was performed on an ash deposition probe located vertically in the SHTM inlet transition section. This probe consisted of a 6 inch long, 1.3 inch diameter air-cooled tubular section extending from a water-cooled holder. Deposits on the top half of the active probe section were removed by periodic momentary retraction into the holder. The near-surface metal temperature of the cleaned portion was maintained at 1200°F. Water at 150 psi was blown for about 1 second onto the probe deposit through a 0.5 inch venturi nozzle located 2.2 feet upstream of the probe. The frequency of water blowing was varied from 1 hour to 8 hours. For 1-4 hour intervals, most of the deposits spalled off after water blowing. For longer intervals, they normally did not. Blowing with 250 psi air immediately after the water blow was usually effective in removing the deposits. The duration of water blowing was limited to obtain a metal temperature change of no more than 200°F, as recommended in the literature [Ref. 2]. This was to limit the amount of thermal shock to the tube metal and the amount of thermal fatigue and corrosion fatigue cracking. The actual metal temperature change due to water blowing ranged from about 200°F to 600°F because control of the water blowing time was not precise and also due to temperature overshoot after the blow. Since the thermal fluctuations lasted only a few seconds, the rate of surface metal temperature change was very high. Automation of the water blowing and adjustment of probe temperature control parameters will allow better control of the thermal shock in the future.

Devices for water blowing of TS1 tubes are being considered. Since the amount of water that would be introduced into the flow train during the 54 second traverse of the TS1 sootblower would be prohibitive, water blowing must be limited to a small portion of the traverse, with air blowing during the remaining portion. If water is blown during a portion of the sootblower's initial or intrusive traverse, then the air blowing during the return traverse will remove deposits shocked by the water.

Superheater/Air Heater Tube Corrosion

The accumulated exposure times of the SHTM test section tubes were extended to 2000 and 1500 hours, for set A and set B respectively, during the LMF4-V test. As this completed the planned exposure times, the tubes were removed from the test train and prepared for corrosion evaluations.

Corrosion probe exposures at TS1 and at the secondary combustor outlet continued during the LMF4-V test. The total accumulated exposure time on each set of probe samples was 847 hours. The exposures were terminated at this point and corrosion analyses will be performed on the samples. No problems with TS1 probe temperature control occurred during the test.

Exposure times on the low temperature sulfuric acid condensation probes at the airheater inlet were extended to 847 hours. However, similar to previous tests, the average #2 and #3 probe temperatures measured 187°F and 207°F, respectively, significantly lower than the planned temperatures of 200°F and 250°F. In prior tests, it was thought that the indicated temperatures must be erroneous. However, it has now

been concluded that the indicated temperatures of probes #2 and #3 were correct and that they were low as a result of the high liquid levels due to contacting in the bottom of the water-cooled condensers, except when the heat flux was abnormally high, such that sufficient fluid was in the vapor form and lowered the liquid level below the condenser. Therefore, proper corrosion evaluation was only possible on the 150°F probe.

PARTICULATE REMOVAL SYSTEMS

Electrostatic Precipitator (ESP)

Prior to the LMF4-V test, the wire to plate spacing in the ESP fields were checked and found in alignment. However, shortly after test start-up, field 1 wire-to-plate spacing changed and required manual correction. Efforts are underway to develop a system which can adjust to start-up conditions, but prevent the inadvertent shifting of the wire racks.

During the LMF4-V test, the ESP was operated during all major coal burning periods. The collection efficiencies for certain portions of the test were good. Collection efficiencies as high as 99.3% were observed with a specific collection area (SCA) for the ESP of 479 (see Table 3).

Table 3. ESP Performance Data During LMF4-V

Date	ESP outlet lb/MBTU	% Removal	Flow cfm	SCA ft ² /kacfm	Molar K ₂ /S	SCO SO ₂ , ppm	Rapper Setting
11-7	0.0854	98.4	6198	484	1.16	577	5
11-8	0.1455	97.3	6266	479	1.21	607	2
11-9	0.1821	96.5	6175	486	1.16	484	5
11-11	0.0449	99.2	5439	552	1.07	596	5
11-12	0.0482	99.3	6261	479	1.28	462	5
11-13	0.3764	94.3	5841	514	1.22	372	5
11-14	0.2193	96.4	6226	482	0.97	655	0
11-16	0.3405	91.2	6262	479	0.26	1255	5

ESP performance was inconsistent throughout the test, with periods of high performance, followed by only marginal performance. Unmeasured or undetermined changes in process conditions may have been the cause for the erratic performance. Another factor affecting the

performance could be ambient humidity, since the ESP insulator housings continuously pull in ambient air. Future tests will evaluate this parameter.

ESP performance at an SCA of 475 continues to be lower than values measured prior to the May 89 (LMF4-Q) test. Although some operational conditions were identified as detrimental to performance (i.e. high K_2/S ratios, misaligned wire racks), periods of testing when these conditions did not exist still resulted in higher emissions than were produced in prior tests. The effect of the K_2/S ratio on ESP performance was difficult to evaluate during the LMF4-V test. Mechanical problems such as wire-to-plate shifts and transformer failures also occurred during this test. Also, midway through the test a different coal was used. ESP performance is still believed to be a function of K_2/S , but test conditions did not allow for a parametric evaluation. Particulate samples were collected to determine particle size distribution at the inlet to the control devices. Three samples were collected using an extractive 5 stage series cyclone, followed by a final filter. The mass mean particle size appears to be approximately 1 micron or smaller which is typical of past measurements. K_2/S ratios of the samples varied from 1.2 to 1.3. Even periods of high secondary current in field 4 (> 60 ma) resulted in performance that did not achieve New Source Performance Standard (NSPS) levels at this SCA. Unless some currently unmeasured process parameter affected particulate collection efficiency, the ESP degradation must be related to the operation of the ESP itself. Major hardware changes in ash removal may be partially responsible, as currently all of the collected ash is directed to the field 1 hopper discharge point to accommodate the automated ash removal system, instead of each field having a separate discharge. A combination of either of the above hardware modifications could lead to increased particle reentrainment from the hopper. We are continuing to evaluate possible causes.

During the test, the ESP field 4 transformer-set experienced a failure which could not be repaired during the test. For the remainder of the test, the power to this field remained off and the ESP was operated with power to only 3 fields. The collection efficiency dropped to only 91% at an SCA of 479.

Due to damaged wiring sustained prior to the start of the test, the rapper and vibrator signals were unavailable for correlating with near real-time ESP emissions. Particulate samples taken during the more frequent rapper settings did show a lower performance similar to the previous test. Future tests are expected to have rapper and vibrator signals available for more detailed data reduction.

Although the results reported here cover only the LMF4-V test results, the overall suitability of the ESP will be evaluated upon the completion of all testing and the results collected and evaluated. The results to date indicate NSPS levels can be achieved with sufficiently high SCA's. The data collected to date does not indicate that a dry-type ESP is unacceptable for MHD. The ESP is still operating at a much lower SCA (higher flow) than is found in many operating ESPs in the pulp and paper industry. Our tests are designed to operate over a range of conditions to evaluate

performance and provide design data. It is expected that many of these conditions will result in lower performance efficiencies. Increasing the SCA would likely increase the performance to NSPS limits. The performance for the first few years was much better than we have at present. We are currently constructing a real-time particle sizing device which can identify many of the process changes which can affect ESP performance. In addition, a new vibrator system for the discharge electrodes will be tested to determine the effects of higher energy vibration. Immediately following an ESP shutdown, the performance increases for a short duration (< 1 hour) and gradually returns to the pre-shutdown performance level. Possibly, this is related to the ability of the vibrators and rappers to clean the wire and plate surfaces.

Baghouse (BH)

The BH was operated during all major coal burning periods of the LMF4-V test. During some of the short test segments, the BH was taken off-line due to the inlet gas temperatures exceeding 400°F. The flow rate through the BH was initially set at approximately 5300 cfm (2 ft/min filtration velocity) and later increased to 5850 cfm (2.2 ft/min) for the remainder of the test. The bags were cleaned when the pressure drop across the tube sheet exceeded 10 inches wc. The time between cleaning cycles averaged nearly 2 1/2 hours at 5300 cfm and nearly 2 hours at 5850 cfm. The time required between cleaning cycles was longer than on prior tests. **For the first time since the new bags were installed, and a sufficient level of particle coating established to form an efficient filtration barrier, all of the measured emissions were below the NSPS limit of 0.03 lb/MBTU (see Table 4).** Most of the collection efficiencies were 99.8 - 99.9 % which again is better than have been measured previously. BH performance did not appear to be affected by changes in the coal used. (Although the K₂/S ratio was held constant during this test, past experience indicates that baghouse performance is not affected by changes in this ratio within a range of 0.7-1.3 tested to date. Further evaluations of this aspect will be made in future tests.)

Table 4. Baghouse Performance Data During the LMF4-V Test

Date	BH lb/MBTU	% Removal	Flow cfm	Filtration Velocity ft/min
11-7	0.0075	99.9	5277	1.95
11-8	0.0180	99.7	5292	1.96
11-9	0.0070	99.9	5323	1.97
11-11	0.0098	99.8	5824	2.16
11-12	0.0098	99.9	5849	2.17
11-13	0.0093	99.9	5680	2.10
11-14	0.0082	99.9	5785	2.14

ADVANCED MEASUREMENT SYSTEMS

The advanced measurements efforts this quarter focused on supporting the LMF4-V test. Advanced measurements test objectives are listed in Table 5.

Table 5. Advanced Measurements Objectives for the LMF4-V Test

No.	Objective	Provider
1	Define relationship between plasma emission drop outs, system pressure fluctuations, furnace vibrations and aural "boom."	UTSI
2	Observe flow profiles at the baghouse outlet.	UTSI
3	Evaluate trace species means of detecting water leaks.	UTSI
4	Evaluate HTAH tube materials by measuring surface temperature and emission characteristics of a pressurized candidate tube.	MSU
5	Evaluate ash deposition on superheater deposition probe surface.	MSU
6	Measure ESP space charge between fields 1&2 and at the end of field 4 and relate to ESP performance and operational parameters.	MSU
7	Quantify particle size and loading characteristics at the ESP outlet.	MSU
8	Study coal feed system to identify possible control improvements.	UTSI

The aural "boom" study, objective 1, was primarily planned to correlate flow train vibrations with other "boom" signatures. Unfortunately, diffuser and furnace vibrations were not adequately measured because pre-test time was inadequate for evaluation of accelerometer performance. Success was achieved in installing additional helium-bleed dynamic pressure transducers, but one newly calibrated transducer experienced a cooling water blockage early in the test. Data, which was obtained from working transducers, supports previous conclusions concerning the phenomena reported last quarter. Efforts to further evaluate this test data will be completed during the next quarter.

Equipment was installed to observe flow profiles at the BH outlet particle sampling station, objective 2, but timing of the lighting and injection of the smoke generating pellets was inadequate for the CFFF conditions. However, observations indicated that a primary concern about flow visualization in the CFFF ducting (i.e., overwhelming interference from flue gas suspended particles) was not a problem.

Fluorine was added as a tracer to water injected for this study, objective 3, but the resulting levels of fluorine in the gas stream were too low to permit definitive detection. This condition can be rectified with a higher capacity injection pump, but while the planned small amount of water was being injected, the new downstream exhaust gas moisture meter indicated an appropriate increase in the exhaust gas water content. **Since that instrument provided dependable moisture level measurements throughout the test, and was sufficiently sensitive to indicate even the small leak level injected for this test, it should be adequate for indication of the approximate magnitude of all significant water leaks in the future. Therefore, efforts to develop a non-intrusive leak monitor will be discontinued.**

Several instrument systems were requested from Mississippi State University (MSU) to measure thermal emissions from the high temperature air heater (HTAH) tube installed for materials evaluation during the LMF4-V test, objective 4. These systems included multicolor pyrometers (Figure 19) to measure surface temperature and emissivity, and a broad range infrared (2.0-4.8 μ m) spectrometer system to determine the radiation characteristics in a coal-fired MHD environment. Unfortunately, the candidate HTAH tube ruptured before any data could be acquired with either the spectrometer or the pyrometers. However, a study was conducted of the gas emissions so that the gas produced background radiation might be eliminated when tube-plus-gas radiation measurements are taken. The pyrometers were also used to measure surface temperature and emissivity of the HTAH tube mount and nearby furnace wall. This data indicates similar temperatures and emissivities as measured in prior test wall temperature data, except during the latter portions of the test when potassium seed was deleted from the coal. During this no-potassium period the emissivities gradually climbed from about 0.85 to essentially 1.0. Line reversal systems were also installed at locations bounding the HTAH tube. These were installed to verify that conditions had not significantly changed from earlier tests when the furnace gas temperature profile was measured. Gas temperatures were essentially the same as measured in prior tests, 2175K-2200K at the top of the primary furnace and 1875K-1900K near the top of the secondary furnace. These measurements are in good agreement with the UTSI line reversal gas temperature measurements of 2450K-2500K in diffuser no. 6 and 1875K-1900K near the top of the secondary furnace. Gas temperatures gradually increased as the test progressed, reaching typical values of 2550K at the diffuser during the later days of the test. The MSU Coherent anti-Stokes Raman spectroscopy (CARS) system measured core gas temperatures of 2550K-2600K at this time.

The MSU intrusive multi-probe system (IMPS) with the light pipe sensor (LPS) was installed in the inlet transition section of the superheater test module in order to monitor deposition probe surface temperatures as ash was deposited on and was blown off this probe, objective 5. A temperature history of the ash deposition probe was obtained for several days, and details of the temperature history during several sootblowing cycles were recorded. A total of 30 measurements were recorded from November 6-10. Fourteen were made specifically to record temperature changes

FIGURE 19. MSU Multicolor Pyrometer Installed for HTAH Studies

during sootblowing with water. A sootblowing measurement consists of 3 samples, one made before sootblowing with water, one before sootblowing with air and one after sootblowing with air. During sootblowing the outer surface of the deposition probe dropped between 22K and 54K, while thermocouples in the probe indicated a metal temperature swing of 57K to 167K. Observations of the probe indicated that immediately after sootblowing a fine deposit began to rapidly accumulate with a higher surface temperature than the probe itself. After sootblowing, the surface temperature was expected to rise rapidly at first, then to gradually rise as the deposit thickness changed from rapid growth to a more gradual growth. In several instances this did appear to occur, but in several instances only a minimal gradual temperature rise was measured. Correlation of the data with flowtrain conditions will hopefully explain this variation. Further evaluations could not be performed during the LMF4-V test because the LPS was damaged during an extraction. Additional LPS measurements are planned for future tests.

MSU installed electric field meters (EFM) between ESP fields 1 and 2 and downstream of field 4 to measure variations in the ESP space charges in order to help understand ESP performance, objective 6. Knowledge of variations of the space charge density in the ESP allows comparison with the design model of the ESP to help diagnose ESP performance changes. As in the August 90 (LMF4-U) test, the field 4 EFM performed as expected. However, apparently because the geometry of the ESP at the upstream EFM location was not properly accounted for, viable measurements were not obtained between fields 1 and 2. After appropriate facility parameter measurements are sent to MSU, modifications will be made to the EFM to compensate for the ESP internal geometry so that valid measurements can be obtained during the next test.

Data was acquired throughout the LMF4-V test using both the MSU two-color laser transmissometer (TCLT) and particle size distribution system (PSD) particle characterization instruments, objective 7. The TCLT again monitored changes with time in the Sauter mean diameter/particle loading at the ESP exhaust. Increases in Sauter mean diameter are consistently noted when the ESP wire rack vibrators are turned on, and cycling in the Sauter mean diameter corresponding to cycling of the ESP rappers was again observed. These data trends were confirmed with the PSD measurements at an adjacent ESP exhaust penetration. Also, the PSD consistently indicated significantly greater concentrations of 1-2 μm diameter particles than 3-5 μm particles, as indicated by all extractive sampling data. Since the TCLT and PSD can not, as currently configured, indicate the loadings and particle size distributions at the ESP inlet, an experiment was conducted with a fiber optic beam delivery system for the TCLT at the ESP inlet. The delivery system allowed determination of the TCLT signal level as a function of path length across the particle stream entering the ESP. The signal decreased, as expected, with increased effective optical path length, and the probe demonstrated that an interpretable signal could be obtained using the probe at the ESP inlet. Effective path lengths of 2-20 cm were examined and usable data was acquired when the path length was 14 cm or less.

As in prior tests, dynamic coal feed system data was obtained periodically during the LMF4-V test, objective 8. Two Coriolis effect mass flow meters, an Auburn volume fraction meter, 3 line pressure transducers, and feed hopper load cells were again installed for this purpose. Sufficient data was obtained for analysis, and further data will not be recorded in future tests, unless a need arises. Confirmation of the flow meter calibrations will continue to be done in future tests. On-line data analysis again confirmed agreement of the feed tank weight loss with the primary Coriolis meter indicating mass flow. The secondary meter again read slightly low.

No strong relationship has been found between coal line pressure and coal mass flow. The changes noted were not sufficient to use line pressure drop as a mass flow measurement.

WASTE MANAGEMENT STUDIES

Gas Phase Chloride Measurements

The EPA Method 17 flow train was modified to allow testing for gas phase HCl during all tests. In this flow train, gas phase HCl is absorbed by 0.1 N NaOH which is substituted for the deionized H₂O used in the impingers. Samples were taken at the BH/ESP inlet, ESP outlet, and at the BH outlet during LMF4-V.

The results of these tests indicated HCl levels to be higher at the BH and ESP outlets than at the BH/ESP inlet. The BH outlet had the highest concentration. In future tests attempts will be made to determine why gas phase HCl is lower at the BH/ESP inlet than at the BH or ESP outlets.

The LMF4-V test started with Illinois #6 (Herrin Seam) coal from the Old Ben #26 mine which was exhausted during the night of November 10, 1990. Coal from the Illinois #6 (Herrin Seam), Burning Star #2 mine was burned for the duration of the test. The Burning Star mine coal has a lower chloride content than the Old Ben mine coal which resulted in a lower gas phase chloride concentration in all tests made after November 10, 1990. The Old Ben mine and Burning Star mine coals had chloride concentrations of 2538 and 372, respectively. Average chloride concentrations decreased 9 percent at the BH/ESP inlet after changing to the Burning Star mine coal. Average chloride concentrations were 7 times lower at the BH outlet and 14 times lower at the ESP outlet when burning the Burning Star mine coal. Measured gas phase HCl concentrations at these three locations are shown in Figures 20 through 25 as functions of major parameters (gas phase temperature and K₂/S ratio).

FIGURE 20. Method 17 Particulate Chloride Concentrations, BH/ESP Inlet (Gas Temperature)

FIGURE 22. Method 17 Particulate Chloride Concentrations, BH Outlet
(Molar K₂/S Ratio)

FIGURE 23. Method 17 Particulate Chloride Concentrations, BH Outlet (Gas Temperature)

FIGURE 25. Method 17 Particulate Chloride Concentrations, ESP Outlet (Gas Temperature)

The gas phase measurements at the BH/ESP inlet are somewhat lower, but within the same order of magnitude as the NASA-predicted equilibrium values. However, from subsequent testing, we now believe that sampling with a stainless steel probe results in some reaction between the probe and the sampled gas. Use of an all-glass sampling system appears to be required for more accurate results. Chlorides in the collected dust are generally in the range of 1000 - 2500 ppm when burning the Old Ben #26 coal.

Due to the chloride concentration in the Burning Star #2 mine being 7 times lower than that found in the Old Ben #26, the gas phase chloride concentration has decreased significantly. With this low chloride concentration in the gas phase, our confidence in the actual measured values has also decreased. Since our measurements were nearing the detection limits of our equipment, no detailed evaluation of trends was attempted. However, during a short portion of a test chlorine gas was added downstream of the secondary combustor to simulate the chloride levels found in the higher chloride containing coal. Results from these measurements did show higher chloride at the inlet to the baghouse and ESP than was measured at the outlets. No explanation for this change is available at this time.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

No activity was planned during the quarter.

No activity is planned for next quarter.

TASK 6 - MODIFICATIONS TO THE CFFF

COMPONENT DEVELOPMENT AND TEST FACILITY MODIFICATIONS

Molten Ash Handling System

The design and drawings for this system to remove molten ash just prior to the superheater test module (SHTM) entrance were completed. Fabrication of the required parts was also completed. Installation will be completed prior to the next scheduled CFFF test in April 91.

Automatic Ash/Seed Handling System

During the LMF4-V test, only the BH and ESP portion of the automated ash handling system was activated. The SHTM portion of the system was inoperable due to control wiring problems. Also, electrical installation of the weighing system was not

completed prior to the test. Consequently, no attempt was made to weigh the ash from the BH and ESP portions of the system. The BH and ESP conveyors and the modified ash sampling system operated without incident during the entire LMF4-V test. The above problems will be corrected prior to the next scheduled CFFF test in April 91.

Separate Seed Injection System

Work on developing the design criteria for the separate seed injection system continued. Various emulsions of oil and K_2SO_4 were prepared for evaluation in possible alternative systems.

Superheater Test Module (SHTM) Tube Replacement

Specifications for the replacement steam-cooled, test section tubes for evaluation during western coal tests were completed and the procurement process initiated. This tube replacement will be completed prior to the first long-duration POC test on western coal scheduled for October 91.

Western Coal Processing System

The purchase order for the EL modification to the existing E-35 pulverizer was issued. Babcock & Wilcox (B&W) will complete the manufacture of the necessary parts and will ship these to UTSI by April 2, 1991. A B&W service engineer will oversee the installation and calibration of the pulverizer modification.

The first set of drawings was received from the Heil/Xerxes Company concerning the direct-contact water-cooled condenser system. These drawings were reviewed by UTSI and comments/questions were submitted to the Heil/Xerxes Company. The condenser system is scheduled to arrive during February, 1991.

The Stahl air heater arrived in December 1990, and efforts are underway to remove the existing Carl Mayer air heater and install the Stahl heater. Electrical and control hardware are being installed as well as some structural changes to the coal tower. The Lamson pressure blower was received in October 90. Both the blower and air heater will be installed and checked-out prior to the next test.

Details concerning operational procedures, control strategies, and safety concerns are being developed. Since the inerting of the recycled process gas is achieved by nitrogen addition, leakage from various pieces of equipment must be minimized to reduce operating costs. The existing coal tower baghouse is expected to be the major source of air leakage in the system, and mitigating efforts are underway. Miscellaneous control valves, gas monitors, thermocouples, pressure transducers, and ductwork are being sized and ordered.

Efforts to locate sources of tubing of various alloys for retubing the test sections for western coal testing were made during this quarter with only partial success, since some of the alloys sought are not readily available. Table 6 lists the alloys and Table 7, together with Figure 26, indicate their intended placement within the test sections. These efforts and procurement will continue during the next quarter.

HIGH TEMPERATURE AIR HEATER DEVELOPMENT

During the LMF4-V test, a bayonet style heat exchanger was positioned and tested in the radiant furnace as shown in Figure 27. The device consisted of a 43 inch long, 3.5 inch OD closed-end tube made from a silicon carbide/alumina/aluminum composite (see Figure 28). A 40 inch long, 0.75 inch OD silicon carbide tube was mounted inside the composite tube which was used to introduce preheated air into the outer tube. The bayonet assembly was mounted in a vertical water cooled support located 12 inches from the furnace wall in a zone with an estimated gas temperature of 1870°C (3400°F). Since furnace vibration could lead to excessive flexing of the tube, an additional water cooled support was used to stabilize the top (closed end) portion of the outer tube. The support consisted of a 2-inch high water cooled steel ring that encircled the top of the tube which allowed for expansion on heating. It was designed to provide a 0.06 inch clearance around the tube to permit the tube to expand both longitudinally and radially. Installation of the top support from inside the furnace was difficult and thus the support was difficult to level. Therefore, although the tube was still free to expand in the vertical direction, it was restricted from expanding radially. The outer tube broke after 100 seconds on-coal because the twisted ring was in contact with the tube at the top and (on the opposite side) at the bottom of the ring. The radial thermal expansion of the tube resulted in a catastrophic bending stress on the tube. Post test inspection of the supports and tube remnants supports this conclusion.

After the outer tube failed, the unsupported inner tube endured the vibration and gas flow for at least five hours. The stub that remained after the test exhibited the same tapered edges that were noted on previous tests with silicon carbide. The significance of the inner tube survival period without vibration protection indicates that the top support was not necessary. If the fragile 0.75 inch OD, 40-inch long ceramic outer tube could survive for hours while only supported at its base, then it is likely the larger diameter and thicker walled tube would not have been damaged by vibration if mounted differently.

In addition to the bayonet configuration, this test was the first time an attempt was made to pressurize the system. Two 0.075 inch orifices were used to maintain back-pressure in the tube, but the internal pressure was erratic and difficult to control. Although the mass flow was set at 15% of a maximum of 44 SCFM, the pressure ranged from 3 psig to 36.6 psig at which point the tube was broken due to thermal expansion. A post test inspection revealed that one of the orifices had clogged. A technique is also under study to provide an air pressure seal for this pressurized test.

TABLE 6. Typical Composition of Planned SHTM Test Section Alloys for Western Coal POC Testing (wt %)

	Cr	Ni	Fe	Mo	W	V	Nb	Ti	Mn	Si	P	S	Al	C	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	-
T91	9.00	-	Bal.	1.00	-	0.20	0.07	-	0.45	0.40	0.03	0.03	-	0.08	0.50
12Cr-1.5Mo-1W Stl	11.8	1.53	Bal.	1.51	0.95	0.16	0.05	-	0.60	0.26	0.01	0.01	0.01	0.07	0.04
316H	17.0	12.0	Bal.	2.50	-	-	-	-	2.00	1.00	0.05	0.03	-	0.07	-
347H	18.0	11.0	Bal.	-	-	-	0.70	-	2.00	1.00	0.05	0.03	-	0.07	-
RA85H	18.0	14.0	Bal.	-	-	-	-	-	0.50	3.50	-	-	1.00	-	-
304H	19.0	9.00	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	Bal.	-	-	-	-	0.38	0.80	0.50	-	-	0.38	0.08	-
253MA *	21.0	11.0	Bal.	-	-	-	-	-	0.80	1.70	0.04	0.03	-	0.10	0.17
556 **	22.0	20.0	Bal.	3.00	2.50	-	-	-	1.00	0.40	-	-	0.20	0.10	0.20
310	25.0	20.0	Bal.	-	-	-	-	-	2.00	1.50	0.05	0.03	-	0.25	-
310Nb	25.0	20.0	Bal.	-	-	-	***	-	2.00	1.50	0.05	0.03	-	0.08	0.10
314	25.0	20.0	Bal.	-	-	-	-	-	2.00	2.00	0.05	0.03	-	0.25	-
HR-160 #	28.0	Bal.	4.0	-	-	-	-	-	0.50	2.75	-	-	-	0.05	-
IN 690	29.0	Bal.	9.0	-	-	-	-	-	-	-	-	-	-	-	-
CR30A	30.5	Bal.	17.7	2.10	-	-	-	0.18	0.20	0.27	-	-	0.14	0.06	-
CR35A	35.0	Bal.	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

TABLE 7. Planned Placement of Test Section Tube Alloys for LMF Testing with Montana Rosebud Coal (letters in Parentheses Indicate Position on Tube in Figure 26)

	TS1	TS2	TS3
1	556 (AE)/ 316H (EF)	556 (AE)/ 316H (EF)	316H (AD)/ SA192 (DE)
2	RA85H (AB)/ HR-160 (BD)/ 253MA (DF)	RA85H (AB)/ HR-160 (BD)/ 253MA (DF)	347H (AB)/ T11 (CE)
3	310Nb (AE)/ 347H (EF)	310Nb (AE)/ 347H (EF)	T22 (AE)
4	CR30A (AE)/ 304H (EF)	CR30A (AE)/ 304H (EF)	T91 (AE)
5	IN 690 (AC)/ 310 (CF)	IN 690 (AC)/ 310 (CF)	12Cr-1.5Mo-1W (AE)
6	CR35A (AC)/ 314 (CF)	CR35A (AC)/ 314 (CF)	T22 (AE)
7	MA956 (AE)/ 12Cr-1.5Mo-1W (EF)	MA956 (AE)/ 12Cr-1.5Mo-1W (EF)	347H (AB)/ T11 (CE)
8	cr ¹ -800H (AE)/cr-T91 (EF)	cr-800H (AE)/cr-T91 (EF)	304H (AD)/ SA192 (DE)

¹ cr = chromized

Inlet Gas Temperatures (nominal)

TS1 2250 °F
 TS2 1650
 TS3 1350

Tube Metal Temperatures, °F

	Pass 1	Pass 2	Pass 3	Pass 4
TS1	950-1250	1250-1400	-	-
TS2	950-1250	1250-1400	-	-
TS3	620-850	850-950	950-1050	1050-1100

TS1 and TS2 Tube Section Lengths

AE	95.875 inches
EF	105.30
AB	48.875
BD	12.000
DF	140.30
AC	54.875

TS3 Tube Section Lengths

AD	297.05 inches
DE	105.30
AB	201.18
CE	201.18
AE	402.36

FIGURE 26. Planned SHTM Test Section Alloy Placement as Detailed in Table 7

FIGURE 27. Location of HTAH Test Materials During LMF4-V

FIGURE 28. Bayonet Style Heat Exchanger Tested During LMF4-V

A flange made from the same composite material as the tube was bonded to the tube during the manufacturing process. The flange was secured between two graphite gaskets within the water cooled bottom support as a pressure seal and a means to hold the tube. After the test the flange appeared to have held up well except for a slit which likely was propagated along the length of the tube from the initial fracture. Air introduced at 66°C (150°F) was initially heated to 230°C (446°F) before it exited. During the first 100 seconds of coal combustion the temperature of the air exiting increased to 327°C (621°F) at which time the tube broke.

This HTAH material sample test indicated that the bottom support design was adequate and that the top support was not needed. In addition, it was determined that the orifices need to be replaced with a pressure regulator at a point far enough downstream from the HTAH so that the 1093°C (2000°F) air can be cooled to permit use of the regulator. The flange concept appears to be adequate for securing the tube and sealing the pressurized air.

The LMF4-V test was also used to test several composite tube configurations provided by the Babcock and Wilcox Company (B&W). The composites consisted of different alumina based fibers in alumina and zirconia matrices. The materials were mounted in the zone of the furnace where the gas temperatures were approximately 2800 to 2900°F (see Figure 27). Sections of the exposed materials were returned to B&W for analyses.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

Activity under this task is entirely concerned with system analysis work performed under subcontract with the Westinghouse Electric Corporation, Advanced Energy Systems.

As noted in the prior quarterly report, funds budgeted for this quarter were almost completely expended prior to the beginning of the quarter. Westinghouse was able to complete the draft topical report documenting the first year's work. This report was reviewed by UTSI and forwarded to DOE/Chicago for review/approval.

The report covers the completion of the models of both the Corette and the Scholz plant retrofits. The primary emphasis was on analysis of the Topping Cycle Test Plans and the Bottoming Cycle Test Plans to resolve different test parameters, especially stoichiometry, potassium to sulfur ratio and additives. Recommendations for resolving differences were included in the report.

TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES

At DOE's request, UTSI participated in a facility readiness review meeting on the CDIF in Butte, Montana, in October 1990.

No activity was planned this quarter.

No activity is planned for next quarter.

TASK 9 - CFFF PROGRAM MANAGEMENT

MANAGEMENT AND ADMINISTRATIVE SUPPORT

A revised FY91 budget and management plan for the UTSI MHD project was submitted to DOE. It reflected a total FY91 program of \$8,600,000 which includes \$8,449,600 for contract operations and \$150,400 for electrical power.

The UT-DOE lease agreement renewal for the period January 1, 1991 to December 31, 1991 was signed by the University and sent to DOE/CH for final signature.

A transfer order was prepared and sent to DOE/CH to effect the transfer of accountability of the ash/seed handling equipment from the Babcock and Wilcox Company contract to the UTSI MHD contract.

The annual inventory of government property was completed satisfactorily with all property located.

Visitors to UTSI to observe LMF4-V testing and to discuss test plans and conditions for the CFFF during FY 1991 included: C. Thomas, DOE/PETC; N. Swift, DOE/CH; W. Swift, ANL; R. Cook, MSU; R. McIlroy, B&W; J. Lance, Westinghouse; D. Stopek, Illinois Power Company; and D. J. Farrell, Illinois Department of Energy and Natural Resources.

The following distinguished visitors visited UTSI on Sunday, November 18, 1990 to receive a tour of the CFFF and an overview of UTSI MHD project activities:

Marvin Singer - Deputy Assistant Secretary for Oil, Gas and Shale and Special Technologies, DOE, Washington, DC.

Bob Kripowicz - Staff Assistant for Energy, House Appropriations Subcommittee for Interior and Related Agencies.

Pam Pontillo - Controllers Office, DOE, Washington, DC.

Ann Shakety - Congressional Affairs Office, DOE, Washington, DC.

Chuck Roy - Financial Staff, DOE, Washington, DC.

Ralph Carabetta - Associate Director for Project Management, Pittsburgh Energy Technology Center, Pittsburgh, PA.

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GLOSSARY

AH	- Air Heater
ASTM	- American Society for Testing and Materials
BH	- Baghouse, particulate capturing device using a fabric type filter bag
B&W	- Babcock & Wilcox
CARS	- Coherent anti-Stokes Raman spectroscopy
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
DFI	- Diffuser inlet probe
DFO	- Diffuser outlet probe
DG	- Data General Computer
ϵ	- Emissivity
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 tes.
LPS	- Light Pipe Sensor
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
POC	- Proof-of-Concept
PSD	- Particle Size Distribution System
PTO	- Power Take-Off
RF1	- Radiant Furnace #1 Position
SCA	- Specific Collection Area for ESP
SCI	- Secondary Combustor Inlet
SCO	- Secondary Combustor Outlet
SCR	- Silicon Controlled Rectifier
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
TC	- 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
WBDAAS	- Wide Band Data Acquisition and Analysis System

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