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QUARTERLY TECHNICAL PROGRESS REPORT

October-December 1982

October 1983
Date Submitted

Work Performed Under Contract No. AC02-79ET10815

The University of Tennessee Space Institute
Tullahoma, Tennessee

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PROGRESS REPORT

OCTOBER-DECEMBER 1982

Prepared by:

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

Date Submitted - October 1983

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Under Contract No. DE-AC02-79ET10815

ABSTRACT

In this quarterly technical progress report, UTSI reports on the continued design work for the low mass flow train superheater. The detailed design of this component continued and the overall arrangement drawing for the superheater and air heater was finalized. The air heater procurement reached the point of contract award, but the actual purchase order award was held up pending receipt of additional funding from the Department of Energy.

Testing activity reported includes two additional tests in the LMF1C series, which concludes this test series. Test data is presented, along with preliminary analyses for the combustor, nozzle, diagnostic channel, diffuser, radiant furnace/secondary combustor and Materials Test Module. In addition to the nitrogen oxide test measurements, corrosion and erosion rates for the boiler tube specimens and the materials test module are reported.

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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 systems operating under conditions simulating those of central power stations.

The specific objectives of the UTSI, using the DOE Coal Fired Flow Facility, are to resolve experimentally and analytically the key technical problems which have been identified or which may be found to occur in direct coal fired MHD systems with moderate to high ash carryover. The problem areas involve (1) combustor performance, (2) seed separation efficiency from the exhaust gas stream, (3) MHD generator performance and design requirements using slag deposition on the channel walls to protect the walls from the intense thermal environment, (4) effects of plugging, fouling and corrosion by solid slag particles during normal operation, (5) response of candidate materials to direct coal fired MHD environment and (6) operating procedures and equipment to meet pollution requirements.

The overall scope of work contains eight tasks summarized under each of the following task headings.

1. Task 2 - Design and Fabrication of the 8 lb/sec Total Gas Flow, High Slag Throughput Test Equipment

Design, procure, fabricate and install the 8 lb/sec (3.63 kg/sec) total mass flow test equipment in the Coal Fired Flow Facility, providing DOE with a schedule and cost estimate for each activity. The design goal for all components is the demonstration of predicted system characteristics required of an MHD system (e.g. life, performance, reliability, failure mode, etc.) and determining applicability of design for base level operations.

2. Task 3 - Base Operations for the CFFF and ECF

Perform all operations and maintenance required to maintain the CFFF and the ECF in a standby condition. Items included are a) materials and components handling equipment, b) required equipment for installation of components, coal/seed handlings, etc., c) emissions monitoring, and d) instrumentation and sampling devices for continuous monitoring of O_2 , CO_2 , NO_x , CO , SO_2 , H_2S , etc. This Task covers such major services as:

- 1) General Administration and support
- 2) Operations planning
- 3) Crew and staff maintenance
- 4) Grounds and building maintenance
- 5) DOE vendor occupancy
- 6) Facility design maintenance

3. Task 4 - 8 lb/sec Total Gas Flow High Slag Throughput Test

Operate the Coal Fired Flow Facility to progressively test and demonstrate that equipment and subsystem requirements for UTSI-designed components (Task 2) are met via Operation, Performance Demonstration and Acceptance Tests. Based on acceptance test results, engineering data are to be obtained toward the development of scaled-up MHD systems.

4. Task 5 - Testing of DOE Supplied Components

Utilize the Coal Fired Flow Facility for purposes beyond the demonstration of the 8 lb/sec flow train and superconducting magnet flow train. Specifically, UTSI is to be the initial operations contractor in performing feasibility studies for testing components in the CFFF, the components being supplied by other Department of Energy contractors via DOE.

5. Task 6 - Modifications to the CFFF

Provide modification to the CFFF as required to test and to provide development assistance for DOE-supplied components, equipment and subsystems.

6. Task 8 - Test Integration and Interface

Provide technical and management expertise to DOE upon request to attend meetings and conferences and serve on panels relating to MHD power generation. Also, at DOE request, UTSI is to perform MHD related studies for outside contractors, and to aid component vendors in their development of components to be tested in the Coal Fired Flow Facility.

7. Task 9 - Program Management

Provide for effective project management by utilizing and updating the presently available PERT and MIS system activities for the total program. These systems identify firmly established baselines for each task. Project management is to be effected by close alignment of the UTSI reporting systems with the DOE Uniform Contract Reporting System (DOE/CR-0001/1) and the proposed MHD Division Work Breakdown Structure (WBS).

SECTION II

SUMMARY OF TECHNICAL PROGRESS

A. TASK 2 - DESIGN AND FABRICATION OF THE EIGHT LB/SEC TEST EQUIPMENT

2.3 Downstream Components

Activity on this project was increased during the first quarter of FY83. A final arrangement of the Super Heater Test Module (SHTM) in the CFFF flow train was approved and is shown in Figure 2.3-1. This arrangement allows for installation of the preferred air heater design, use of the forced draft fans in their present location, and a minimum of connecting ducts. Work on fabrication drawings was continued and all drawings should be completed next quarter and ready for use in bid solicitation.

Several design changes were made during the quarter. Flow straighteners (turning vanes) were installed in the 180° transition section of the SHTM (see Figure 2.3-1) to maintain a uniform flow pattern. Three sootblower ports were added to the SHTM, one before each test module. One port will use a fixed sootblower originally intended for use on the secondary slag screen of the radiant furnace, a second port will be used to activate a mechanical or hand operated sootblower, and the third port will be used to insert a simple UTSI-fabricated sootblower. A monorail to support the sootblower in the first port has been eliminated as unnecessary. Control loops for the superheater steam and water cooling modules have been specified, as have been the locations of instrumentation. Most of the activity in the second quarter will be centered upon procurement of the components to be fabricated by outside vendors and materials for components to be fabricated at UTSI.

Energy Conversion Technology, Inc. (ECT) of Pittsburgh, PA was selected as the Air Heater (AH) vendor because they proposed the lowest cost which met the technical specifications. Two representatives from UTSI visited ECT to assess their capability to produce the unit. ECT and their fabricator, Thermal Transfer, were considered to be capable of supplying an acceptable AH. Since funds were not available to award the purchase of the AH in the first quarter, ECT agreed to extend the bid to March 1, 1983. Once funds are available, the purchase order will be awarded to ECT. A sketch of the ECT design is shown in Figure 2.3-2.

B. TASK 3 - BASE OPERATIONS FOR THE CFFF

3.1 Laboratory Operations

Tests LMF1C-5 and LMF1C-6, which were conducted this quarter, completed the remaining cases in the LMF1C test matrix. No further testing is scheduled until March 1983. The LMF1C-5 test on October 8 was specially configured to provide exhaust gas conditions favorable for Mississippi State University's (MSU) gas diagnostic equipment. One additional case in the

Figure 2.3-1. Superheater Test Module Components

Figure 2.3-2. Air Heater Design for the CFFF Low Mass Flow Train Proposed By Energy Conversion Technology, Inc.

LMF1C test matrix was conducted as the last case of the LMF1C-5 test. Following this test, an additional section of cylindrical combustor 0.32 m (12.5") in length, was installed to increase the primary combustion gas residence time for higher thermal input cases at high N/O ratios for the LMF1C-6 tests on November 16.

The facility continues to perform well. Problems with induced draft fan vibrations were resolved by removing the rotor and installing a new rotor shaft. The impeller was modified to provide the maximum draft possible with the 350 HP motor. The new shaft and modified impeller performed as expected with reduced vibrations and increased draft available.

Because further testing will not resume until March 1983, the facility was completely winterized near the end of the quarter and activities were concentrated on maintenance and preparations for installation of additional systems. The Cleaver-Brooks boiler was moved from the Energy Conversion Facility (ECF) and installed in the CFFF to support operation of the planned superheater. The diagnostic channel used on the LMF1 tests was removed from the magnet so it could be disassembled and an investigation carried out of the interelectrode shorting experienced during testing. Fabrication of a replacement duct was completed and installation was started in preparation for the LMF1D and LMF1E tests in March 1983. Reconfiguration of the coal preparation and feed control system was started. Implementation is underway of all suggestions made by the Hartford Fire Insurance Company pursuant to obtaining an ASME code stamp. An inspection by the State of Tennessee and the Hartford Fire Insurance Company is scheduled for January 1983 to complete this action. Operator training courses and training sessions are being prepared for facility operators to train them to carry out long duration testing of the CFFF. An uncertainty analysis of the facility data systems was started. All actions listed in the Environmental Protection Appraisal Agreement and Commitment, which were originated during the DOE Chicago Environmental Protection Appraisal in August, were completed. Numerous maintenance activities are in progress.

The Chemistry Laboratory completed analysis of all samples taken from the LMF1C-5 and LMF1C-6 tests. The Laboratory has assumed responsibility of samples taken from the ongoing environmental program and thus has a large backlog of work to be performed.

FACILITY MODIFICATIONS

- Installed Cleaver Brooks boiler (from ECF) in the CFFF on its own foundation (piers) just south of the stack. Boiler is sheltered by a roof only.
- Resolved vibration problems plaguing the induced draft fan in the CFFF.
- Excavated around coal storage area in CFFF to divert runoff to holding ponds.
- Installed drain line to divert effluent from cryogenic boiler to holding ponds.
- Proposed addition of another catch basin in CFFF to catch runoff and drainage south of test building and divert to holding ponds.

ENVIRONMENTAL AND BIOLOGICAL STUDIES

Revised operating procedures for lake and water sampling were completed and issued. The procedures had been prepared in draft form, but were expedited to respond to DOE Environmental Audit recommendation. All environmental permits were put into an ECP Critical Events system to assure timely renewal, and those needing revision or modification were dealt with appropriately.

A review of Woods Reservoir Studies - An Interim Report, was performed for the Arnold Engineering Development Center (AEDC), United States Air Force Base (USAF). Studies being conducted of the ecology of Woods Reservoir by UTSI, other agencies and other universities have illustrated the value of such environmental studies to complement the investigation of potential environmental effects of MHD technology.

A joint effort with AEDC personnel to develop recommendations for a joint Quality Assurance (QA) program continued, to assure valid results while performing a variety of chemical and biological analyses required to support a water quality monitoring program. Plans are to provide a draft of the program for AEDC and UTSI review next quarter with hopes of activating this program shortly thereafter.

During this quarter, a significant portion of the effort on ambient air quality measurement was devoted to continued maintenance of the trailers and instrumentation. It was reported earlier that equipment had deteriorated because of a lack of adequate, trained personnel, thus maintenance requirements were higher than normally required. Furthermore, because of failure of an electronic flow meter, we have been calibrating flows to six analyzers using a manual bubble flow meter. This procedure is very time consuming, although steps are now being taken to substantially reduce the time required for calibration and improve the accuracy. Other alternatives to the electronic meter are being evaluated, with the expectation of making a decision on the optimum approach next quarter.

A draft copy of the Ambient Air Quality Baseline report was completed and circulated for internal review at UTSI. A high turnover rate of personnel assigned to this project has created significant problems, for example, in locating records and other information required to complete the baseline report. Before the report is issued to DOE, plans are to revise windrose plots to provide a graph that is much easier to interpret.

A preliminary review of the ambient air data collected during LMF1C-6 indicates little or no effect from the CFFF effluent. The Impact I Site, which was downwind of the CFFF during much of the test, did not show any higher levels of NO_x, SO₂ or TSP than the Base Site. A summary of pertinent data is tabulated below.

Ambient Air Quality - LMF1C-6

	<u>Base Site</u>	<u>Impact I Site</u>
NO _x -ppb	4	0
SO ₂ -ppb	0	0
Particulate µg/m ³		
TSP	31	32
ISP	28	30

A more detailed review of the data is underway, and chemical analyses of the particulate will be made.

The Environmental Plan review was completed by DOE and the reviewers' comments forwarded to UTSI. The plan is being revised in accordance with the comments and it will be issued in final form next quarter.

Samples were collected from all of the terrestrial plots including a new plot 7B. The new plot 7B was created when construction for a new power transmission line destroyed our old plot B.

Also during this quarter it was learned that MERDI would not complete the chemical analyses of the terrestrial samples, thus they will have to be completed at UTSI. The resignation of the Chemical Services Supervisor has significantly slowed that effort at UTSI, since only one analyst is available for all chemical analyses required in this contract.

C. TASK 4 - EIGHT LB SEC HIGH SLAQ THROUGHPUT TEST

4.1 Primary Combustor

During this quarter work under this subtask primarily supported ongoing LMF1 testing. During the period tests LMF1C-5 and LMF1C-6 were conducted. A discussion of some of the data generated on combustor performance during these tests is given here. A detailed analysis for all LMF1 combustion data will be presented in a test report for the LMF1A and C series which will be prepared during the coming quarter.

The LMF combustor was designed so that the volume of the combustion chamber could be varied using two cylindrical sections of lengths 0.32 m (12.5") and 0.37 m (14.5"). These sections can be used separately or in combination to vary the overall length and thus residence time in the combustion chamber. The third section, that completes the combustor assembly, was designed with a converging cross section to accelerate the combustion products leaving the cylindrical combustion chamber. The combustor configuration used prior to test LMF1C-6 consisted of the longer cylindrical section (0.37 m (14.5") long) and the conical section (0.460 m (18.1") long).

The LMF1 test matrix¹ included a range of thermal inputs, stoichiometries and nitrogen-to-oxygen mass ratios. The tests reported last quarter were conducted primarily at low thermal inputs (nominally 23.2 MW) for total flows that ranged between 2.7 and 3.7 kg/sec (5.94 to 8.14 lb/sec). Of the sixteen test points planned in the parametric variation on the test condition parameters, ten were scheduled for the LMF1C-6 test. To be assured of adequate residence times for the primary combustion gases at conditions of higher thermal input and increased N/O ratios, the second cylindrical combustor section (0.32 m (12.5") long) was installed in the flow train to enlarge the combustor volume. Test results obtained with the long combustor are discussed with reference to previous results obtained using the short combustor configuration operating at similar conditions.

The function of the LMF primary combustor is to mix and burn the vitiated oxidizer and pulverized seeded coal/fuel oil mixtures substoichiometrically at high temperature to produce a partially ionized gas suitable for MHD power generation. The optimum combustor performance occurs when the plasma leaves the nozzle in a state of uniform pressure, temperature, velocity and chemical composition. How well the combustor performs this task can be evaluated to some extent by examining factors that impact global performance. Experimental data available for this evaluation include reactant flow rates, combustor pressure and the distribution of heat loss along the axial length of the combustion chamber. During the LMFIC test series, the combustor was operated over a wide range of input and output conditions, i.e. flow rates, nitrogen-to-oxygen ratios, pressures and temperatures. Variations in these operating parameters are expected to produce changes in the combustor performance.

COMBUSTOR PRESSURE DATA

Combustor pressure is a parameter which is determined experimentally and is functionally dependent upon the total flow of reactants and the chemical properties of the combustion gases. For each experimental test point considered, the mass flow rates of all reactants are measured and used in estimating the combustion gas properties through use of a chemical equilibrium computer code. Since the theory considers ideal combustion to be chemical equilibrium, differences between experimental pressure data and theoretical pressures can be viewed as an indication of combustor inefficiency.

The correlation of experimental combustor pressure data from the LMFIC test cases with theoretical predictions is shown in Figure 4.1-1, as a function of total mass flow. Since theoretical combustor pressure assumes adiabatic combustion, the experimental data differ from the perfect agreement line. However, for the cases shown, the differences range between 5 and 10% which can be considered as an indication of good mixing in the combustion chamber.

By taking into account the heat transferred from the primary combustor walls, a relative measure of combustion efficiency can be defined as follows:

$$\eta_{c^*} = c^*(\text{exp})/c^*(\text{theo})$$

This is referred to as the "c-star" efficiency where c^* is a characteristic velocity defined by

$$c^* = p_0 A^* / \dot{m}$$

in which p_0 is stagnation pressure, A^* is throat area, and $\dot{m}$ is the total mass flow rate. The ratio of the experimental [$c^*(\text{exp})$] to theoretical values [$c^*(\text{theo})$] can be found through the ratio of the theoretical mass flow to the experimental mass flow, $\dot{m}(\text{theo})/\dot{m}(\text{exp})$ at the same combustor pressure level. The theoretical mass flow will be less than the experimental mass flow, since combustion inefficiencies tend to lower the combustion flame temperature.

LMF COMBUSTOR PRESSURE BEHAVIOR

Figure 4.1-1. Combustor Pressure Behavior, Measured Versus Theoretical

The characteristic combustion c-star efficiencies (η_c^*) calculated for test points of LMF1C are plotted in Figure 4.1-2 as a function of total mass flow rate for the same cases considered in Figure 4.1-1. Efficiencies were determined relative to both adiabatic combustion and nonadiabatic with the experimental heat loss taken into account.

This characteristic combustion efficiency is relative in the sense that it is determined assuming that the pressure measurements are accurate. However, as previously reported, the pressure measurements in the combustion chamber are affected by slag accumulation which often plugs the instrument ports completely.

HEAT FLUX DATA

The heat flux distribution along the axial length of the combustor system is indicative of the heat release within the combustion chamber, and together with analysis of chamber pressure, is important in assessing the performance of the LMF combustor. The heat flux characteristics and the percentage of heat transferred or recovered, based on the total thermal input for the short combustor configuration tested in the early portion of the LMF1C test series, have been analyzed and the results are reported. Also, the comparison between the short and long combustor configurations will be discussed.

The LMF1C-6 test included approximately seven hours of coal combustion which completed the LMF1C test matrix. Both cylindrical combustor sections were installed to give an overall combustor length of 1.143 m (3.75 ft.). Ten distinct operating points were specified for LMF1C-6 through parametric variations involving N/O ratios between 0.40 and 1.50, stoichiometry between 0.83 and 0.92, and mass flow rate from 2.2 up to 4.5 kg/sec. The thermal input range covered by these conditions ranged from 23.2 to 27.9 MW. Three operating points were selected from this data set that are comparable to previously reported data from earlier tests to provide the basis by which comparisons of the two combustor configurations could be made. Table 4.1-1 lists the average test conditions for the test points considered.

The average heat fluxes for the two combustor configurations are compared in Figures 4.1-3, -4 and -5. As shown in Figure 4.1-3, at the inflection point 1, the heat flux from the longer combustor increases rapidly, and then levels off throughout the remainder of this section and at the entrance of the conical section. The heat flux distribution for the short combustor follows a more continuous pattern, that is, the heat release seems to increase more linearly throughout its overall length.

The variation of the heat flux, if viewed as a means to deduce the progress of combustion, would indicate that the combustion process in terms of rapid heat release is essentially completed in the middle section of the long combustor where the heat flux maximizes. Furthermore, since the heat transfer through the wall at the axial station of the combustor is indicative of the gas temperature at that section, the leveling of the distribution curve suggests that a near maximum mean gas temperature has been reached. Downstream of this point the gas temperature decreases as the gas accelerates through the conical section and the nozzle.

LMF1C TEST RESULTS

Figure 4.1-2. Characteristic Combustion Efficiency, η_c , Defined as the Ratio of Measured Characteristic Velocity to the Theoretical Characteristic Velocity for an Ideal, Adiabatic Combustion Process with Isentropic Expansion

TABLE 4.1-1

COMPARATIVE TEST CONDITIONS FOR THE TWO COMBUSTOR CONFIGURATIONS

	CASE 1		CASE 2		CASE 3	
Combustor Length, m	1.143	0.826	1.143	0.826	1.143	0.826
Test Point	LMF1C-6 Step 9	LMF1C-4 Step 8	LMF1C-6 Step 7	LMF1C-4 Step 7	LMF1C-6 Step 14	LMF1C-1 Step 5
Mass Flow Rate, kg/s						
Burner Oil	0.071	0.069	0.065	0.063	0.044	0.043
Combustor Oil	0.205	0.207	0.211	0.211	0.185	0.182
Coal + Seed	0.545	0.604	0.560	0.594	0.533	0.524
Oxygen	1.835	1.894	1.703	1.640	1.437	1.420
Nitrogen	1.369	1.354	1.183	1.256	0.619	0.572
Total	4.008	4.128	3.722	3.764	2.816	2.714
Stoichiometry	0.945	0.944	0.866	0.834	0.818	0.846
N/O Ratio	0.739	0.712	0.688	0.785	0.426	0.379
Combustor Pressure (MPa)	0.706	0.708	0.662	0.546	0.512	0.492
Vitiation Heater Pressure (MPa)	0.869	0.893	0.809	0.820	0.607	0.595
Total Heat Loss (MW)	2.98	2.53	3.18	2.29	2.47	2.06
Thermal Input (MW)	27.9	27.9	27.9	27.9	23.2	23.2
Adiabatic Flame Temperature (K)	3051	3050	3056	3028	3115	3131

Figure 4.1-3. Heat Flux and Cumulative Heat Loss Distributions
(Case 1)

Figure 4.1-4. Heat Flux and Cumulative Heat Loss Distributions (Case 2)

Figure 4.1-5. Heat Flux and Cumulative Heat Loss Distributions
(Case 3)

The general character of the heat flux distributions do not appear to be greatly affected by the range of stoichiometry used in these test operating points. The two cases at lower stoichiometries, Figures 4.1-4 and 5, again reflect rapid rise and then flattening of the heat flux distribution as previously discussed. However, the heat flux distributions seen for the long combustor in Cases 1 and 2 at a stoichiometry of 0.92 show the profile to increase linearly to a maximum at about 0.46 meters. In contrast to these cases, Case 3 which was at a lower stoichiometry of 0.83 illustrates a linear type profile that extends further downstream to about 0.58 meters. These observations may be indicative of combustion efficiency in terms of the length required for burn-out as a function of operating stoichiometry. Higher heat flux levels were also achieved in Cases 1 and 2 which yielded overall heat losses on the order of 10 percent greater than that of Case 3. The cumulative heat losses for the long and short combustors are also compared in the same figures.

The heat transfer characteristics exhibited by the long combustor operating at different N/O ratios are presented in Figure 4.1-6. As is expected, the heat flux level is lower with a higher N/O ratio and tends to maximize farther downstream.

The total cumulative heat losses for all test points of LMF1C-6, are summarized in Table 4.1-2. Throughout the range of combustor operating conditions the total experimental heat losses were between 2.31 and 3.62 MW for the higher thermal input, 27.9 MW. Heat losses for the low thermal input level of 23.2 MW were in the range of 1.97 to 2.47 MW. These levels translate to percentage losses within 8.27 to 13.0 and 8.49 to 10.65 percent of the thermal input respectively.

TABLE 4.1-2
COMBUSTOR SYSTEM HEAT TRANSFER

TEST POINT	STOICH.	N/O	TOT. HEAT LOSS (MW)	% OF TOTAL THERMAL INPUT
LMF1 Step 5	0.78	0.70	2.47	8.85
C6 Step 8	0.78	1.00	2.51	8.99
Step 4	0.85	0.50	3.23	11.57
Step 7	0.85	0.70	3.18	11.39
Step 10	0.85	1.00	2.61	9.35
Step 6	0.92	0.50	3.62	12.97
Step 9	0.92	0.70	2.98	10.68
Step 11	0.92	1.00	2.31	8.27
Step 14	0.83	0.40	2.47	10.65*
Step 12	0.85	1.50	1.97	8.49*

*Thermal Input 23.2 MW; other cases at 27.9 MW

Figure 4.1-6. Heat Flux Distribution Throughout 1.14 m Combustor.
Data from LMFIC-6.

Based on this preliminary survey of comparative data on the two combustor configurations, it is not possible to say whether the performance of the LMF combustor was improved by increasing its primary chamber volume. Based upon the three cases compared in the above discussions, it is concluded that better characteristics were observed with a stoichiometric ratio of 0.85 and 27.9 MW thermal input (Case 2) while no improvement was apparent for the Case of the lower thermal input (Case 3). The analyses of all test data continued to date and will be ultimately reported in the LMF1 test report.

4.2 Nozzle, Channel, and Diffuser Testing

Work reported under this subtask during the past quarter supported tests LMF1C-5 and LMF1C-6. The two tests provided data for twelve of the sixteen test points identified in the test matrix as contained in the LMF1 Test Plan. Operation of the nozzle, channel and diffuser was monitored for the tests. Data obtained throughout the entire LMF1 series to date are being analyzed and will be reported in the test report on the series.

Satisfactory operation for the nozzle, channel and diffuser was noted with the exception that plate two of the nozzle developed a water leak during the later portion of the LMF1C-6 test. It was determined that the burn-through of the plate occurred concurrently with a temporary loss of coal flow in the primary combustor which produced a highly oxidizing plasma condition. A modification of the nozzle is being considered to reduce the thermal stress to that component. Grooving part of the plates and filling the grooves with refractory may help promote development of a slag layer and thus reduce the heat flux to the component. This effort is in progress and will be reported next quarter.

The primary thrust of the analysis of the upstream components in supporting the LMF1 testing continues to be determination of the entrance conditions to the radiant furnace. This information is important for the subsequent heat recovery analysis of the downstream components as well as the NO_x thermal decomposition analysis. Heat recovery and gas dynamic data collected for all upstream components (the combustor as well as the nozzle channel and diffuser) form the data base for this continuing analysis effort. The modeling and analysis techniques used for the various components have been reported previously^{2,3}.

Plots of the heat loss to the various upstream components as a function of total mass flow rate and the corresponding prediction for adiabatic flame temperature in the previous quarterly report² are updated here to include the test points for LMF1C-5 and LMF1C-6. The figures (Figure 4.2-1 through 4.2-4) present heat loss data for the nozzle, the diagnostic channel and the diffuser as well as the total upstream heat loss. Table 4.2-1 lists the pertinent flow conditions for the data.

During the next quarter, the analysis effort will continue and will be reported in detail in the LMF1 test report.

4.3 Downstream Components

The primary objectives of the tests conducted during this quarter were achieved although some problems were encountered and resolved with

Figure 4.2-1. LMF1C Measured Nozzle Heat Loss
(See Table 4.2-1 for flow rates)

Figure 4.2-2. LMF1C Measured Channel Heat Loss
(See Table 4.2-1 for flow rates)

Figure 4.2-3. LMF1C Measured Diffuser Heat Loss
(See Table 4.2-1 for flow rates)

Figure 4.2-4. LMF1C Measured Total Upstream Heat Recovery
(See Table 4.2-1 for flow rates)

TABLE 4.2-1
TEST CONDITIONS FOR LMF1C

	Stoichiometry	(N/O)Wt	Total Flow (kg/s)
<u>LMF1C-2</u>			
Step 5	0.83	0.4	2.72
6	0.83	0.4	2.72*
<u>LMF1C-3</u>			
Step 5	0.83	0.4	2.72
6	0.94	0.4	2.88
7	0.92	0.7	3.41
8	0.83	1.0	3.58
9	0.83	0.7	3.16
<u>LMF1C-4</u>			
Step 5	0.83	1.0	3.58
6	0.90	1.0	3.79
7	0.85	0.7	3.85
8	0.92	0.7	4.09
<u>LMF1C-5</u>			
Step 5	0.85	0.4	1.67
6	0.85	0.4	1.88
7	0.94	0.7	3.29
8	0.92	0.4	2.94
<u>LMF1C-6</u>			
Step 4	0.85	0.5	3.48
5	0.78	0.7	3.58
6	0.92	0.5	3.69
7	0.85	0.7	3.82
8	0.70	1.0	4.05
9	0.92	0.7	4.06
10	0.92	1.0	4.19
11	0.92	1.0	4.62
12	0.83	1.33	4.24
14	0.83	0.4	2.20

*Vitiation Heater outlet temperature ~1255K, all other tests ~1144K

downstream equipment. The operation of a 152 mm (6 in.) diameter slag tap gas bypass line was degraded because of a water leak in the superheater access door and accumulated refractory pieces that entered the bypass line. Water from the access door flowing down the bypass line into the slag tap caused the flow of gas from the slag tap to be irregular, with occasional periods of no flow. The poor operation of the gas bypass made slag tapping difficult. Another factor which made slag tapping poor was varying the stoichiometry during the test, therefore the system did not remain at ideal slagging conditions for reasonable periods of time. It was observed that little or no molten slag was collected from the primary furnace when the stoichiometry was below 0.85, especially with the water leak. Rather, the slag solidifies in the cooler regions and eventually blocks the slag taps. When the stoichiometry was 0.85 and higher, molten slag was observed in the primary furnace, but conditions mentioned above resulted in poor slag tapping. The superheater access door was removed after the tests and rebuilt to stop water leakage.

The secondary test objective of demonstrating effective particulate removal by the venturi scrubber/cyclone was not achieved because the induced draft (ID) fan did not produce a sufficient pressure drop across the venturi scrubber and cyclone. Analysis indicates that to achieve satisfactory operation, these units require at least 38-51 cm (15-20 in.) of water pressure drop total maintained across both units. During all of the conditions of the test the maximum available pressure at the ID fan was approximately 51 cm (20 in.) with the venturi and cyclone experiencing essentially no pressure drops. Therefore, considering the conditions required for the components to operate properly, it appears that it will not be possible to achieve efficient particulate removal from the LMF test train, with the present ID fan system. It should be noted that the performance of the ID fan was improved by the modifications previously discussed.

Further attempts were made to use the DEMCO hydroclones to separate solids from the cyclone water. Smaller 51 mm (2.0 in.) cones for the unit were received and tested, but the amount of solids removed by the cones was not increased. It was then decided that hydroclones were not capable of the desired performance, so they were removed from the downstream equipment and placed in storage. Since funds are not available for investigating alternate methods of particulate removal, no further work is planned in this area. In conducting mass balances for future testing, the solids content of the cyclone water can be calculated from the total volume of the cyclone water and the solids content of a well-mixed sample of the cyclone water. Disposal of cyclone water solids will be reviewed and a procedure established.

Performance of the primary slag screen was unchanged this quarter. No leaks were evident in the metal tubes exposed by the degradation of the refractory coating, but ultrasonic measurements of the tubes revealed they are decreasing in thickness at a rate of 0.051 to 0.076 mm (0.002 to 0.003 in.) per hour of coal combustion. The tube wall thickness will continue to be monitored in future tests to determine if this deterioration continues. Water leaks were discovered in the entrance flange to the primary furnace and will be repaired prior to the resumption of testing. Another slag screen, called the alternate slag wall (ASW), is scheduled for installation before LMF1E. The ASW is shown in Figure 4.3-1 and is designed to protect the furnace wall during seed/slag interaction testing without the slag

Figure 4.3-1. Alternate Slag Wall

screen. All components of the unit have been received or are on order, but fabrication cannot be completed until certification to perform ASME code welding is received.

Particulate sampling this quarter was limited to determining the proper sampling procedures of the Flow Sensor Particle Sizing Sampler, a multi-stage inertial impactor, located in the crossover duct downstream of the Materials Test Module (MTM). Past experience has shown that low sample rates do not achieve acceptable particle separation and long sample times overload the filtering media. A sampling rate of 0.021 cubic meters (0.74 ft³) per minute for thirty seconds was found to be the optimum sampling rate, but this will be further evaluated in future testing.

REFRACTORY MATERIALS EVALUATION

An inspection of the CFFF refractory components was conducted on completion of LMF1C-6. Refractory components were generally in good condition, but several areas did experience excessive degradation. One of these areas was the upstream face of the primary slag screen which had a primary wear area of exposed metal tubes that was elliptically shaped, about 46 cm by 56 cm (18 by 22 in.) with its major axis parallel to the cooling tubes. The pattern of refractory studs was visible on about 90% of the upstream face of the membrane wall section and a few small areas of exposed metal were observed on the upper 30 cm (12 in.) of the tube screen. The stud pattern was also visible in this area. Walls of the furnace adjacent to the upstream face of the slag screen appeared to have a slag and refractory coating about 2.5 cm (1 in.) thick. Slag had also accumulated in the slag tap to the extent that the slag tap was blocked.

Another of the areas of degradation was the primary furnace entrance flange. This area had been repaired with a chrome-alumina plastic refractory (Jade Pak 88P) and an alumina-silicon carbide plastic refractory (Narcarb ZP) prior to LMF1C-6. The area repaired with Narcarb ZP was degraded much more than the area repaired with Jade Pak 88P. This difference in performance could be due to the differences in binder, particle size, or aggregate chemistry of the two mixes. Jade Pak 88P will be used for all general lining repairs in the future, especially in this area of the furnace. The lining of the diffuser showed no additional degradation after LMF1C-6. Water was observed in the diffuser, but its source may have been the diffuser gas sampling probe, the optical port nearest the gas sampling probe, or the nozzle further upstream. Water leaks were also present in the primary furnace entrance flange and will be repaired.

A substantial amount of slag was seen downstream of the slag screen. Slag was present on the secondary furnace walls up to the bottom of the upper High Pressure Test (HPT) section. Refractory conditions on both HPT sections are good and further repairs are not expected for some time.

The drum module lining continues to be in marginal condition, but new spalling is not evident to any appreciable degree. A repair of this component should be completed prior to the next test. The secondary combustor is in good condition, but the lining has thinned in some spots and the tops of some studs are visible. The ash/seed hopper lining has cracked extensively in the lower portion and will be repaired prior to the next run. The superheater door refractory was also cracked extensively, and will be completely rebuilt before the next test.

METALS EVALUATION AND ASH/SEED DEPOSITION

The objective of this work is to investigate the extent and nature of ash/seed fouling of MHD superheater and intermediate temperature air heater tubes and the corrosion of tubes beneath these deposits. The corrosion of other metals is also being evaluated. This investigation has included testing in the CFFF by two means: 1) the MTM, which consists of a bank of air-cooled tubes located at the exit of the radiant furnace, and 2) air-cooled probes, having ring samples of various test alloys, which may be inserted in instrument ports in various regions of the flow train.

Partial loss of coolant air during LMF1C-2 caused general destruction of the MTM tubes as described in the previous quarter's report. The tubes were removed and were not replaced for the CFFF runs during this quarter. However, some tubes will be replaced for a resumption of testing in the next quarter.

Much of the information gained to date from MTM testing relates to the physical characteristics of deposited ash and seed with relatively little learned of its corrosion to tubing. Deposit appearance, structure, and strength was found to vary with deposit temperature. By comparing deposits found on the tubes with the results of placing similar materials in a temperature controlled laboratory furnace, the following observations can be made. Freshly deposited material was white and powdery with ash particles ranging from submicron to about 16 micron diameter and seed (K_2SO_4) particle diameters averaging 2-3 microns. The deposit remains white and unsintered at temperatures below approximately 922K (1200°F). In the 922-1033K (1200-1400°F) range, the deposit becomes light brown in color but is still completely powdery. At about 1089K (1500°F), the first hint of sintering is evident, resulting in slight crusting of tube deposits. This crusted material is of extremely low strength and falls apart at the least disturbance. In the 1089-1200K (1500-1700°F) range of deposit temperature, the degree of sintering increases rather slowly and the deposit color becomes darker brown. At 1200K (1700°F) the deposit strength is sufficient that crushing between the fingers is barely possible. In the 1200-1255K (1700-1800°F) range the degree of sintering and, consequently, the strength and hardness, begins to increase greatly. At 1311K (1900°F) the deposit is very hard and nearly black in color. Melting of the K_2SO_4 seed occurs at about 1339K (1950°F). But in the 1339-1394K (1950-2050°F) range, the fluidity of the seed/ash mixture appears to be too low to allow significant flow. However, the existence of a molten phase results in segregation of the seed and ash. By surface tension effects, the molten seed collects together and tends to reject the solid ash to its outer surface.

The deposit structure produced at high gas temperatures >1339 K (1950°F) consists of two layers. The inner layer is relatively very thin (~1 mm) and never reached the K_2SO_4 melting point, but is fairly well sintered, adherent, and contains elemental species diffused from the tube. In the outer layer the K_2SO_4 had fused. Adherence of the outer layer to the inner layer varies greatly, increasing with temperature and being much greater for the high alloy tubes than for the low alloy ones. Outer layer thickness increases with temperature in the 1339-1477K (1950-2200°F) range, perhaps due to increased surface "stickiness" which enhances particle capture. At the highest deposit temperatures, very irregular and fluted deposits were formed on MTM tubes with flutes as long as 25 mm. The outer

layer is composed of two portions, an inner portion that is fused K_2SO_4 with islands of sintered ash and an outer portion that is sintered ash with islands of K_2SO_4 , the two portions grading into each other and being of roughly equal thickness. The extent of segregation increases with temperature, being very pronounced at 1477K (2200°F). Overall chemical composition of the outer deposits was 35-57% K_2SO_4 , 3-5% K_2CO_3 and 40-60% fly ash.

It is expected that the hard, adherent deposits formed on the front sides of tubes at gas temperatures above 1366K (2000°F) and metal temperatures above about 1089K (1500°F) would be difficult to remove by "on-line" methods such as sootblowing. At lower metal temperatures, sootblowing should be feasible, despite the existence of dense, hard outer deposits, because of the poorer adherence of the thick outer layer to the thin inner layer. However, longer operating periods are required to evaluate the effect of time and other parameters on deposit characteristics.

In the MTM, deposits on the back sides of tubes were quite friable except during the last test when very high metal temperatures (~1366K) were obtained. Large amounts of ash and seed collected in the bottom of the unit as a result of repeated sloughing of the backside deposits. However, this sloughing characteristic should not be as pronounced for actual superheater and intermediate temperature air heaters. In the MTM the back sides of tubes were cooler than the front sides because of the presence of the water quench immediately downstream of the tubes so that there was very little radiant heat input to the back sides.

Hot corrosion of the MTM tubes was evidenced by loss rates far in excess of that attributable to simple oxidation. Scales produced were composed of oxides and sulfides, their thickness, composition and structure depending most critically on the alloy chromium content. Because the MTM operated in the past at much higher metal temperatures than would actual operating units, no truly applicable corrosion data were obtained, although screening data were obtained. However, future testing with the MTM, the "superheater", and the material probes will produce such corrosion data.

Two materials probes were included in tests LMF1C-5 and LMF1C-6 during this quarter. These were located at the drum module and at the exit of the secondary combustor. The top drum module probe was selected to investigate ash and seed deposition and corrosion of boiler tubes and other metallic components in the reducing zone of the radiant furnace. The test materials were carbon steel, carbon-moly, 1/2 to 5Cr-moly, and 304 stainless steel. Although the ring samples were intended to be maintained at 644K (700°F) to simulate boiler tubes, inadequate air flow resulted in higher fluctuating temperatures, with time averages between 700K (800°F) and 755K (900°F) and maxima between 839K (1050°F) and 894K (1150°F), depending on position, as shown in Figure 4.3-2. Average gas temperature was 1946K (2233°F). Total exposure time was 16.6 hours with 10.7 hours on seeded coal.

Figures 4.3-3a and 3b show the front and back sides, respectively, of the TDM probe after LMF1C-6. Deposits were canary yellow on the outer surface, irregular, hard and 1.5-2.0 mm (0.06 - 0.08 in.) thick on the front side and relatively smooth, hard and about 1.5 mm (0.06 in.) thick on the back side. Both front and back deposits consisted of two layers, the inner very thin and mostly white in color and the outer thicker and yellow.

Figure 4.3-2. Corrosion Losses and Metal Temperatures of TDM Probe Samples

a. Front

b. Back

Figure 4.3-3. Drum Module Probe After LMF1C-6

Adherence between the two layers varied, being very high for the stainless steel and the back sides of all the other samples and fairly low for the front side of all but the stainless steel. These characteristics were in contrast to the nature of the deposits on the same probe after LMF1C-5, which were uniformly light gray in color on the outside and had very little adherence between the outer and inner layers. The difference was due to the lower probe temperatures during LMF1C-5, signifying the temperature dependency of deposit strength and adherency.

Scanning Electron Microscope/Energy Dispersive X-Ray (SEM/EDX) examination of a sectioned carbon steel LMF1C-6 drum module probe sample showed an approximately 70 μm (0.00275 in.) thick oxide scale next to the metal with the remaining material being deposit (Figure 4.3-4). The deposit consisted of only salt in the inner portion grading to approximately equal amounts of salt and ash at the outer surface. The salt was mostly white K_2CO_3 in the innermost portion, grading to mostly colorless K_2SO_4 near the middle of the deposit, and changing again to mostly yellow K_2CO_3 on the outside. A possible reason for this is that the depositing salt is largely K_2CO_3 which is converted to K_2SO_4 in the center of the deposit by reaction with catalytically formed SO_3 , both the innermost and outermost portions having insufficient SO_3 for the reaction.

Figure 4.3-2 shows corrosion losses in mm per year of the drum module probe samples after removal of deposits by chipping and water washing (Fig. 4.3-5) and removal of scale in an acid solution (Clarke's Solution, ASTM G-1). The very high loss rate of 5.84-8.64 mm/year (0.23 - 0.34 in/yr) demonstrates the severity of the environment because of the higher than normal temperatures and reducing atmosphere. Operation of carbon or low chromium steels in the reducing part of the furnace will probably require refractory protection, which has been applied to the furnace walls in the low mass flow test train.

The probe at the secondary combustor outlet had the sample alloys shown in Figure 4.3-6 at gas temperatures which averaged about 1366K (2000°F) but which reached as high as 1604K (2427°F). Average metal temperatures varied from about 783K (950°F) at the far end to 916K (1190°F) at the near end with short excursions to as much as 954K (1258°F). This probe was designed to simulate superheater tube conditions.

Front and back views of the secondary combustor (SC) probe after LMF1C-6 are shown in Figures 4.3-7a and 7b, respectively. Only the inner deposit layer remained on the probe, most of the outer layer having fallen off during cooling and the remainder during removal from the flow train. The same was true for LMF1C-5 except that a few pieces of the outer non-adherent layer were salvaged. They were nominally about 2 mm thick or about 3 mm thick including the roughness height. Three portions were noted, the outer being shiny black, fused and very porous, the middle gray-white, crystalline and dense, and the inner partially sintered red-brown powder. The inner layer that remained on the probe was also the red-brown powder, about 0.5 mm thick.

Examination of a sectioned 316SS SC probe sample from LMF1C-6 by SEM/EDX showed an approximately 20 μm thick scale composed of three layers separated by gaps, the inner layer being adherent to the substrate. The

Figure 4.3-4. Drum Module Probe Deposit, LMF1C-6

Figure 4.3-5. Washed Drum Module Probe Samples, LMF1C-6

Figure 4.3-6. Corrosion Losses and Metal Temperatures of SC Probe Samples

a. Front

b. Back

Figure 4.3-7. Secondary Combustor Probe After LMFlC-6

scale was Fe, Cr and Ni oxides with small but detectable amounts of K and S in the inner layer and Al and Si in all three layers. After ultrasonic water washing and scrubbing, EDX spectra were taken of the exterior of the scale on all samples. These indicated oxides and no sulfides. All were Cr-rich relative to the substrate except for 5Cr-1/2Mo and 347SS, the degree of Cr-richness increasing with alloying content (Cr+Ni for the austenitics, Cr for the ferritics). Figure 4.3-8 shows the front side of the samples after water washing. The 5Cr-1/2Mo and the 18Cr-8Ni had considerable scale while the higher alloys maintained their original metallic luster.

Examination of the LMF1C-5 SC probe deposits showed the inner layer to be an unsintered mixture of K_2SO_4 (most abundant) and ash. The outer layer was a sintered mixture of K_2SO_4 and fly ash with the K_2SO_4 concentration decreasing and ash concentration increasing toward the outside. In addition to the amorphous K_2SO_4 mixed with the ash, isolated islands of crystalline K_2SO_4 were also present in the outer portion.

Figure 4.3-6 gives the corrosion losses for the SC probe samples from LMF1C-6 after descaling in 10% HNO_3 . The materials having 18Cr-8Ni had losses of 3.05-3.89 mm/year while all the higher alloys had less than 1.27 mm/year. These loss rates, while very high, are only 1/8-1/2 those of the MTM tubes which operated at higher temperatures. Lower loss rates are expected with better temperature control and lower temperature.

GAS ANALYSIS/POLLUTION CONTROL

The LMF1C-5 test was conducted in conjunction with MSU to evaluate temperature measurement and insitu NO analysis equipment, and included a step with a nominal 15 MW input while firing oil only at about 0.85 stoichiometry. The problems noted in earlier reports, i.e. filter pluggage and water carryover, continued although progress was made. The gas sampling and conditioning configuration currently used is shown on Figure 4.3-9. Steps were taken to improve resolution of the problems and improve data analysis techniques, primarily to decrease the time required to review, analyze and report the results.

Data for Steps 5 and 6 in LMF1C-5 and Steps 8, 10 and 11 for LMF1C-6 are shown on Figures 4.3-10 through -14, and the test conditions are summarized below. Data on those figures are plotted for NO upstream of the secondary combustor and NO_x downstream of that point. The data are not corrected for water vapor removed prior to the measurement thus actual values in the gas are 12-20% lower, depending on fuel inputs.

Test/Step	Thermal Input, MW	Fuel	N/O	Stoichiometry
LMF1C-5				
5	15.5	Oil	0.4	86
6	15.8	Oil & Coal	0.4	84
LMF1C-6				
8	27.9	Oil & Coal	1.0	82
10	27.9	Oil & Coal	1.0	88
11	27.9	Oil & Coal	1.9	93

Figure 4.3-8. Front Side of Secondary Combustor Probe
Sample After LMFlC-6

Figure 4.3-9. Gas Sampling, Conditioning and Analysis System

Figure 4.3-10. NO_x Through the LMF1 Radiant Furnace and Quench System

Figure 4.3-11. NO_x Through the LMF1 Radiant Furnace and Quench System

Figure 4.3-12. NO_x Through the LMF1 Radiant Furnace and Quench System

Figure 4.3-13. NO_x Through the LMF1 Radiant Furnace and Quench System

Figure 4.3-14. NO_x Through the LMF1 Radiant Furnace and Quench System

The data obtained during Steps 5 and 6 of LMF1C-5 indicate somewhat higher NO/NO_x values for oil only compared to oil and coal. Previous data indicated similar trends, although the differences were not quite as large as in the LMF1C-5 tests. The levels measured at the diffuser were 3330 ppm and 3270 ppm, for oil and oil plus coal, respectively. These values are within the analytical error for the instruments. However, the NO levels decayed more rapidly in the oil-coal tests. At least part of the differences are attributed to the higher stoichiometry in the oil only case. Tolerances in measuring coal flow and coal flow, coal/seed mixture, and coal composition variations may have also contributed. These cases and others are being analyzed by applying the Premixed One-Dimensional Flame (PROF) Kinetic Code to determine if the stoichiometry accounts for the differences, or if other factors are involved.

Data for Steps 8, 10 and 11 in LMF1C-6 show the strong dependence of NO/NO_x levels on the stoichiometry. As shown on Figures 4.3-12, -13 and -14, operation at stoichiometry of 93% results in NO_x levels at the secondary combustor outlet almost an order of magnitude higher than operating at 82% stoichiometry. Figure 4.3-15, indicates NO_x levels at the diffuser exit for different stoichiometries and the data show the strong dependence of NO on stoichiometry. Data analysis is continuing.

CFFF HEAT TRANSFER EVALUATION

Upstream and downstream component heat loss data from tests LMF1C-5 and -6 were analyzed during this quarter. As in the past, the data were time-averaged over two-minute intervals, and compared with numerical predictions from the downstream heat transfer code.

A number of comparisons to various test points have been made. In Figures 4.3-16 and -17, predicted gas temperature distributions from test LMF1C-5 are plotted as a function of the axial distance from the primary furnace entrance to the centerline of the quench by-pass duct located in the ash/seed hopper. Conditions corresponding to the two test points are as follows:

	m TOT (Kg/s)	Pri N/O	Pri Stoich	Thermal Input (MW)
Step 6	2.14	0.38	0.81	17.4
Step 8	3.12	0.41	0.91	23.9

During Step 6, six platinum/platinum-10% rhodium thermocouples in alumina shields were operational. The data shown in Figure 4.3-16 represent two-minute time-averaged gas temperatures. Agreement is shown to be good, the maximum deviation being 5.5%.

At Step 8, only four thermocouples (indicated by circular data points) were functioning properly, two in the top drum module and two in the secondary combustor. In addition to these measurements, two optical temperature measurements were obtained. The first measurement was obtained using a modified potassium line reversal system (indicated by the square symbol)

Figure 4.3-15. NO_x Versus Primary Stoichiometry

Figure 4.3-16. Comparison of Calculated Gas Temperatures with Measurement

Figure 4.3-17. Comparison of Calculated Gas Temperatures with Measurement

located in the diffuser. This measurement basically confirms the initial gas temperature used as input to the code. This temperature is also determined independently by considering a heat balance on upstream components.³

The second optical measurement (indicated by the triangular symbol) was obtained using a luminosity temperature system located slightly above the slag screen. This measurement is relative as opposed to an absolute measurement. Based on the emissivity of the gas obtained by the line reversal system, an absolute value of the gas temperature was obtained as discussed in Section 4.6. Agreement again is shown to be very good.

Other items of interest indicated in Figure 4.3-17 are the following:

- a) At the slag screen location two step decreases in temperature are indicated. Physically a step decrease in the gas temperature does not occur. In this region of the calculation procedure, the energy extracted from the gas by the slag screen tubes and the furnace walls is lumped at two axial locations corresponding to the centerlines of the two sets of tubes. This basically accounts for the effect of the additional amount of energy that is removed from the gas as it passes over the screen.
- b) The effect of the various refractories that coat the walls of the components of the radiant furnace is also pronounced. This phenomenon is reflected by the changing slope of the gas temperature curve at three specific axial locations. Refractory change points are located at 5, 12.3 and 18.4 m.

In the top drum module (TDM) the refractory used (Green Cast 26L, a calcium-aluminate bonded insulating castable) has a very low thermal conductivity ~ 0.26 w/m-K, (0.15 Btu/hr-ft-°F). This effect is demonstrated by the slight temperature decrease in this component. In contrast, the refractory used in the primary furnace (Jade Pak 88P) has a thermal conductivity which is an order of magnitude greater. Therefore, the energy removed from the gas stream in this region is also much greater.

In Figure 4.3-18 the cumulative heat loss corresponding to test LMFIC-5, Step 8 is presented. For this particular step the predicted heat loss is 6 MW which represents 25% of the total thermal input into the combustor. An experimental value of heat loss is difficult to obtain. The major portion of the radiant furnace is cooled by water located in a jacket which surrounds the walls of the furnace. The water continually boils off, releasing steam to the atmosphere through vents located atop the top drum module. A water level indicator in the TDM senses a low limit and makeup water is fed into this component on an intermittent basis. In order to determine the amount of water that is fed into the system, a time-average over a long interval is needed. During this time period, flow conditions are changed in order to achieve the objectives of the test matrix. Therefore, this bulk heat loss is a "best estimate" from available instrumentation. This bulk loss coupled with the losses measured from the independently-cooled slag screen and various access ports and doors provides a total estimate. For this particular case, the experimental value obtained was about 7% lower than the predicted value.

Figure 4.3-18. Calculated Cumulative Heat Recovery

Figure 4.3-19. Calculated Heat Fluxes

The local heat flux distribution for Step 8 is shown in Figure 4.3-19. As can be seen, the heat flux in the top drum module is nearly constant and minimal ($\sim 2 \text{ W/cm}^2$). Figures 4.3-20 and -21 present the average gas velocity and cumulative residence time for this step. Average velocity is calculated from continuity and is a function of the gas density and flow cross-sectional area. The effect of the constrictions caused by the slag tubes is reflected in the two velocity spikes in this region. Thereafter, the flow area expands to a constant 1.49 m^2 (16 ft^2) square cross-section in the secondary furnace. Here a gradual velocity decrease occurs as energy is removed and the density increases. The flow area again expands in the initial part of the TDM and a further velocity decrease is observed. The last peak occurs at the throat of the secondary combustor. Flow velocity entering the MTM is approximately 9.8 m/sec (32 ft/sec).

The total residence time to the secondary combustor calculated for this step is approximately 2.2 seconds. Residence time coupled with the temperature distribution are then used as inputs for NO_x relaxation calculations.

Figures 4.3-22, -23 and -24 show temperature distributions for three steps in test LMF1C-3. Data comparison for these cases also appears to be good.

Finally, two predicted temperature distributions from test LMF1C-4 are presented in Figure 4.3-25. The purpose is to demonstrate the effect of primary N/O ratio on the level of the distribution. Step 8 has a slightly higher mass flow rate and an N/O ratio of 0.71, whereas Step 6 has an N/O ratio of unity. A "hotter" gas is produced at the lower N/O ratio and is reflected in the level of the temperature distribution.

During the next quarter the downstream heat transfer code will be modified to streamline the analysis procedure. At present two auxiliary codes (a radiation properties code and the NASA SP-273 combustion code) must be utilized prior to running the heat transfer code. These two codes created large data files which were accessed. The modification will incorporate the radiation properties code and an in-house combustion code into the heat transfer program. This will enable calculation of all the parameters necessary for a solution at each incremented step in the model.

4.6 Diagnostic Support

Diagnostic activities this quarter principally involved support of testing in the CFFF. Routine installation, set up and pre- and post-test calibrations of UTSI developed advanced instrument systems for the LMF1C-5 and 6 tests, as well as the CFFF wide band data recording system were performed. In addition, the LMF1C-5 test involved evaluation of a number of advanced instrument systems developed at Mississippi State University (MSU). Both UTSI and MSU instrumentation efforts continued to be concentrated on spectroscopic temperature measurements of the high temperature gas and walls upstream of the LMF1 top drum module. Table 4.6-1 lists the advanced instrumentation installed for the LMF1C-5 and LMF1C-6 tests.

As seen in Figure 4.6-1 the relative temperature distributions measured in the nozzle showed essentially the same temperature profile variations as

Figure 4.3-20. Calculated Gas Velocity

Figure 4.3-21. Calculated Residence Time

Figure 4.3-22. Comparison of Calculated Gas Temperatures with Measurements

Figure 4.3-23. Comparison of Calculated Gas Temperatures with Measurements

Figure 4.3-25. Comparison of Calculated Gas Temperatures for N/O Ratios

TABLE 4.6-1

ADVANCED INSTRUMENTATION EMPLOYED FOR LMFIC TESTING

<u>Location</u>	<u>Instrument</u>	<u>Measurement</u>	<u>LMFIC-5</u>	<u>LMFIC-6</u>
Throat	Luminosity Probes	Relative Gas Temperature Profiles	X	X
Diffuser				
entrance	Sodium Line Reversal (MSU)	Absolute Gas Temperature	X	
	Luminosity Probe	Relative Gas Temperature Fluctuations	X	X
exit	Potassium Line Reversal	Absolute Gas Temperatures/Spectral Emission	X	X
	Photodiode Line Reversal	Absolute Gas Temperatures	X	
	Luminosity Probe	Relative Gas Temperature Fluctuations	X	
Primary Furnace	Luminosity Probes	Relative Gas Temperature Profiles	X	
	Two Color Pyrometers (MSU)	Wall/Slag Temperature and Emissivity	X	
Secondary Furnace	Sodium Line Reversal (MSU)	Absolute Gas Temperature/Spectral Emissions	X	
	Two Color Pyrometer (MSU)	Wall/Slag Temperature and Emissivity	X	
	Laser Transmissometer	"Mean" Particle Size Variations	X	
Top Drum Module	Optical NO System	NO Concentrations	X

Figure 4.6-1. Temperature Measurements in the Plane of the LMF Nozzle Throat

observed in the earlier LMF1C tests reported last quarter. Such similarities were also observed in the radiant furnace luminosity measurements. Unfortunately, due to weather conditions the furnace luminosity probes failed during the LMF1C-6 test because of moisture accumulation and had to be removed. Modifications to the probes will be initiated next quarter to resolve this problem and to examine solutions for the probe slagging problem discussed last quarter.

The "absolute" gas temperature potassium line reversal systems employed at the sudden expansion diffuser exit operated well during both LMF1C-5 and LMF1C-6, providing gas temperature measurements which compared favorably with heat balance determinations of gas temperatures. A tabulation of mean diffuser exit temperatures measured with the spectrophotometer line reversal system is provided in Table 4.6-2. The new, compact photodiode line reversal system operating simultaneously with the spectrophotometer system at the diffuser exit measured gas temperatures which were in agreement well within the measurement uncertainties of the two instruments. A photograph of the diffuser exit line reversal systems is presented in Figure 4.6-2 to illustrate the greatly reduced size of the photodiode system. Both systems responded adequately to the high frequency temperature transients observed in all LMF1 potassium line reversal temperature measurements made to date, as evidenced by Figure 4.6-3. Because the photodiode system responded so well during this comparative evaluation, it will be used in future tests at a location separate from the spectrophotometer system, to provide additional data on the furnace gas cooling that is needed to evaluate thermal NO_x decomposition characteristics.

The MSU instruments evaluated during the LMF1C-5 test will be reported in detail by MSU. Data obtained with these instruments will also be reported in the LMF1A and C test report which will be prepared next quarter. The MSU two-color pyrometer systems continued to experience problems in measuring slag temperatures, apparently due to gas emissions interference from the extremely broadened 766.5/769.9 nm potassium doublet. Because the 1200 nm detected wavelength did not appear to be affected by gas emissions, one-color pyrometer measurements were obtained to establish a lower temperature limit for the furnace walls. Some measurements are shown in Table 4.6-3 for several LMF1C-5 condition steps.

Tests of the two-color pyrometer system were conducted during the LMF1C-5 test because of the uncertainty in the measured wall temperature resulting from possible potassium emission interference. These tests consisted of placing a blackbody, controlled at a known temperature level, at a line of sight port opposite a two-color pyrometer system. With the assumption that the gas emission/absorption characteristics cause no interference with the two-color system then the pyrometer should give a reading that corresponds to the blackbody setting. During oil-fired flow, both with and without addition of trace amounts of sodium and potassium compounds into the oil supply lines, temperature and emissivity measured by the two-color pyrometer agreed within experimental uncertainty with the blackbody temperature of 1255 K. However, during coal fired combustion the temperature measurement errors were 14%, 27% and 33% for coal-seed flows of 0.380, 0.346, and 0.513 kg/sec and total flows of 1.91, 3.27, and 2.91 kg/sec, respectively. Because of the errors introduced into the measurements

TABLE 4.6-2

MEAN DIFFUSER EXIT TEMPERATURES FOR VARIOUS TEST CONDITIONS

<u>TEST</u>	<u>STEP</u>	<u>OIL</u> (kg/sec)	<u>COAL</u> (kg/sec)	<u>O/C</u>	<u>STOICH</u>	<u>N/O</u>	<u>DIFFUSER</u> <u>TEMPERATURE (K)</u>	<u>TOTAL MASS FLOW</u> (kg/sec)
LMF1C-5	6	0.151	0.380	0.40	0.83	0.38	2468	1.91
	7	0.305	0.340	0.88	0.94	0.72	2482	3.27
	8	0.228	0.513	0.45	0.91	0.40	2460	2.91
LMF1C-6	4	0.274	0.558	0.49	0.87	0.52	2550	3.42
	5	0.275	0.562	0.49	0.79	0.72	2500	3.53
	6	0.274	0.571	0.48	0.93	0.52	2425	3.67
	7	0.276	0.558	0.49	0.87	0.69	2550	3.74
	8	0.275	0.522	0.53	0.82	1.00	2500	3.94
	9	0.276	0.544	0.51	0.95	0.74	2325	4.04
	10	0.274	0.517	0.53	0.92	0.97	2475	4.18
	11	0.271	0.540	0.50	0.96	1.64	2400	4.50
	12	0.269	0.549	0.49	0.83	1.33	2325	4.22
	14	0.228	0.530	0.43	0.82	0.43	2500	2.83
BASE		0.275	0.589	0.52	0.83	0.40		3.63

a. Source Configuration, with Chopper Installed for Spectrophotometer System

b. Detector Configurations

Figure 4.6-2. Potassium Line Reversal System Installed at the LMFl Diffuser Exit

4.6-3. Comparison of the Potassium Line Reversal Systems Installed at the LMFl Diffuser Exit

TABLE 4.6-3

MEASURED PYROMETER WALL TEMPERATURES DURING LMF1C-5

Step	Slag Screen * Surface Temperatures (K)	Mid-furnace * Wall Surface Temperatures (K)
4	>1476	>1385
5	>1338	-
6	>1444	>1326
7	>1605 to >1724	>1575 to >1725
8	>1699	>1698

*These one-color temperatures provide a lower limit to the actual surface temperatures.

made with the two-color pyrometer system when the potassium seed is injected during coal combustion, the system will be modified by replacing the wavelength band of 0.88 to 0.98 μm with a detector band of 3.0 to 3.8 μm for future potassium-seeded coal fired MHD testing.

The MSU modified sodium line reversal systems, incorporating wavelength scanning (to correct for hot particulate light emissions, absorption and scattering) and fiber optics (to allow operation in confined and/or harsh environments), were demonstrated to be operable for locations in the LMF1 radiant furnace. Unfortunately, the MSU processors had a data interface software problem that prevented data transfer to the CFFF data system for LMF1C-5. However, the measurements made at that time as recorded by the MSU system continue to indicate that particle emission, absorption and scattering result in single wavelength measurements that are approximately 60 K low.

The one-color transmissometer measurements made during test LMF1C-5 indicated, as expected, few particulates in the gas stream for oil-fired conditions. However, for coal fired conditions the transmission dropped to 0.0083 for a coal flow of 0.346 kg/sec and to 0.0065 for a coal flow of 0.513 kg/sec. Such high levels of attenuation because of scattering indicates a substantial particle loading in the secondary furnace with coal combustion. Unfortunately, because of a window purging problem the transmissometer measurements could only be made by opening the optical ports. Therefore, continuous monitoring of the transmission levels was not possible.

The tests of the optical nitric oxide detection system were performed near the entrance of the top drum module. In this region incipient condensation of the seed material is possible and thus a high concentration of submicron particles may exist. Submicron particles will substantially attenuate ultraviolet radiation, such as the 225 nm wavelength beam used in the system. During coal-seed combustion periods both the measurement and reference beams used for the optical NO measurement were completely attenuated, indicating a strong possibility of a high submicron particle concentration. Further tests will be necessary to determine feasibility of implementing the optical nitric oxide detection system and to define the possible interference from submicron particulates.

In addition to the LMFIC testing activities, the cold flow model studies in support of combustor development continued. Modifications were made to the data acquisition and reduction software to allow two component laser velocimeter data sets of over 3000 simultaneous samples. Although this significantly improved the statistical confidence tolerances in most of the highly turbulent primary combustor measurements, at some measurement locations the flow did not appear to be statistically stationary over the measurement time interval, and the resulting measured mean velocity vectors appear somewhat randomly oriented for these locations. Nevertheless, the base line testing with the water flow model of the primary combustor was completed, and detailed data evaluations will be completed this coming quarter. Further testing with configuration changes will follow.

D. TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

There is no activity to report.

E. TASK 6 - MODIFICATIONS TO THE CFFF

There is no activity to report.

F. TASK 7 - TECHNOLOGY DEVELOPMENT PROGRAM

There is no activity to report.

G. TASK 8 - TEST INTEGRATION AND INTERFACE

There is no activity to report.

H. TASK 9 - PROGRAM MANAGEMENT

There is no activity to report.

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3. Lineberry, J. T., et al., "Comparison of Experimental Results from the UTSI Coal Fired MHD Generator to Theoretical Predictions," Journal of Energy, Volume 6, No. 3, pp. 187-195, May-June 1982.