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

**For The Period
October 1, 1992 - December 31, 1992**

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

**Prepared for:
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**Prepared by:
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PREFACE

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

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

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

ABSTRACT

In this Quarterly Technical Progress Report, UTSI reports progress on a multitask contract to develop the technology for the steam bottoming cycle of a Combined Cycle MHD Steam Power Plant.

The report describes a 314 hour proof-of-concept (POC) test that was completed during the quarter. Results from this test that are reported include secondary combustion and the effect of potassium on the light-off temperature, fouling of heat transfer surfaces, particulate clean-up device performance and advanced diagnostic system performance.

Test results on ceramic materials and tubes directed toward the development of a high temperature recuperative air heater are summarized.

Facility modifications, operations and maintenance for the DOE Coal Fired Flow Facility are discussed. The major facility modification was the installation of a rotary drum filter to filter the effluent from the wet electrostatic precipitator (ESP). Although this component replaces the facility wet scrubber it is considered as an excellent candidate for application to the MHD plant and will be tested as a flow train component.

Results of data analysis of previous tests that are reported include the continuing analysis of tube materials that were exposed to 1500 and 2000 hours of eastern coal fired operation during the previously completed 2000 hour POC test series on eastern, high sulfur coal.

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

- **A western coal long-duration, proof-of-concept (POC) test, LMF5-G, was completed on October 14, 1992, and achieved 314 hours on coal. All primary objectives were accomplished. The rotary vacuum filter for the wet ESP was installed during the later part of the test run and checked-out successfully.**
- **The CFFF baghouse was operated successfully during the LMF5-G test.**
- **New Gore-Tex bags were successfully tested during the LMF5-F and LMF5-G tests.**

TABLE OF CONTENTS

SECTIONS

I. OBJECTIVE AND SCOPE OF WORK	1
CFFF PROGRAM GOALS AND SCHEDULE	3
II. SUMMARY OF TECHNICAL PROGRESS.....	5
TASK 3 - BASE OPERATIONS FOR THE CFFF.....	5
FACILITIES OPERATION, MAINTENANCE, AND REPAIR	5
TEST CONTROL AND SUPPORT.....	5
DATA ACQUISITION SYSTEMS.....	7
ANALYTICAL AND CHEMISTRY LABORATORY SERVICES.....	8
ENVIRONMENTAL MONITORING.....	8
Water Quality	8
Groundwater Monitoring	8
Terrestrial Ecology	8
Ambient Air Monitoring.....	9
TASK 4 - OPERATION AT 8 LB/SEC TOTAL GAS FLOW HIGH SLAG THROUGHPUT TEST	9
TESTING.....	9
UPSTREAM COMPONENT SYSTEMS	9
DOWNSTREAM COMPONENT SYSTEMS.....	11
Superheater Test Module (SHTM) Corrosion	11
Superheater Test Module (SHTM) Ash Deposition	19
Ash/Seed Hopper Gas Bypass Line	20
Summary.....	22

PARTICULATE REMOVAL SYSTEMS	22
Dry Electrostatic Precipitator (ESP) Performance	22
Baghouse (BH) Performance	23
MASS BALANCE AND AUTOMATIC DATA SCREENING	25
Secondary Combustion	27
Ash Deposition Modeling.....	27
ADVANCED MEASUREMENT SYSTEMS	28
Particle Sampling and Dilution System	33
TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS	36
TASK 6 - MODIFICATIONS TO THE CFFF	36
TEST FACILITY MODIFICATIONS/ADDITIONS	36
High Temperature Air Heater Development.....	36
TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM	38
TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES	38
TASK 9 - CFFF PROGRAM MANAGEMENT	39
MANAGEMENT AND ADMINISTRATIVE SUPPORT	39
REFERENCES	40
GLOSSARY	41
MAILING LIST FOR FINAL DISTRIBUTION OF REPORTS.....	42

FIGURES

1. Scheduled Tasks	4
2. CFFF Integrated MHD Bottoming Cycle Schematic.....	6
3. Photograph of the LMF Coal Combustor Following the LMF5-G Test	12
4. Temperatures at the Leading Edge of TS1 Tubes at the Beginning of LMF5-G ...	14
5. SEM Micrographs and X-Ray Dot Maps for Fe, Cr, and S	17
6. Photo of Deposits and Refractory Slabs Above Ash Seed Tap After LMF5-G Test	21
7. Typical Dry ESP Operating Conditions During LMF5-G.....	24
8. Typical Baghouse Operating Conditions During LMF5-G	26
9. Line Reversal Evaluation at TS1 Inlet	29
10. Predicted Fraction of Potassium in Condensed Phase.....	30
11. Spectra for Low TS1 T_g Conditions, $K_2/S = 4.2$	31
12. TS1 Spectra for Different K_2/S Ratios, $T_g \sim 1535K$	32
13. Particle Number Count versus Size Bin versus Time	34
14. Change in Instrument Activity with Time	34
15. MSU SIDA Probe versus TS1 Line Reversal Measurements	35
16. Location of Test Materials During LMF5-G	37

TABLES

1. CFFF Test Series	10
2. Sample Sections Cut from Test Section Tubes after 639 Exposure Hours	11
3. Dry ESP Performance During LMF5-G	23

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

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

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

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

Provides for the testing of DOE supplied components.

No specific activity was scheduled during FY92.

TASK 6 - MODIFICATIONS TO THE CFFF

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

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

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

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

A separate seed injection system to inject a 47% solution of K_2CO_3 directly into the combustor, as opposed to adding seed to the coal during pulverization, was developed and installed. The system will allow for a significant improvement in the control of the amount of seed added during combustion and of the molar

potassium-to-sulfur ratio. This system for separate seed injection has been upgraded and utilized for more automatic control during future CFFF testing.

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

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

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

Provides for additional technology development services on a task order basis as approved by DOE. No specific activity was scheduled during FY92.

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. UTSL's involvement in the annual MHD contractors' program review session is an example.

TASK 9 - PROGRAM MANAGEMENT

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

CFFF PROGRAM GOALS AND SCHEDULE

Figure 1 shows the major scheduled program tasks completed during the October through December 1992 period.

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FIGURE 1. SCHEDULED TASKS

SECTION II

SUMMARY OF TECHNICAL PROGRESS

This section addresses the technical progress of work conducted during the period October 1 through December 31, 1992, 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

At the start of the LMF5-G test, the rotary drum filter arrived on site. The rotary drum filter is used to remove solids from the wet electrostatic precipitator (ESP) effluent. Rotary drum filter installation and initial start-up was accomplished while the test was in progress. After completion of the test, a weather protection shelter was assembled around the new filter.

Facility winterization and freeze protection were completed. The feed and return lines to and from the rotary drum filter, and the coal condenser system were drained. The furnace, cryogenic system vats, and the water system were drained. Condensate trapped in steam valves was also drained. Buildings were checked to insure that they were sealed and that all heating systems were operating properly. The superheater circulating pump is now operating 24 hours a day to keep water flowing through the superheater.

Other significant maintenance items this quarter were as follows:

- All storage tanks in the test area were labeled to indicate chemical content.
- The steam tubes from all of the test sections were removed from the superheater.
- The process air compressor unloader control switch were repaired.
- All CARDOX fire system sensors on the coal system were replaced.
- The 600 HP boiler annual external inspection was accomplished.
- The mobile crane cable was unspooled and inspected. After inspection, it was respooled and lubricated.
- The coal system condenser pump seal was repaired.

TEST CONTROL AND SUPPORT

The major activities this quarter involved planning, preparation, and conduct of the LMF5-G test. In addition, coordination of installation, and development of operational procedures for the wet electrostatic precipitator system rotary vacuum filter were completed.

FIGURE 2. CFFF Integrated MHD Bottoming Cycle Schematic

A draft of a topical report that documents the history and performance of the coal system prior to the western coal modification was also completed and is being reviewed.

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

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

DATA ACQUISITION SYSTEMS

Activities for the Instrumentation and Controls Section this quarter included preparation for and support of the LMF5-G test and completion of electrical installations for the rotary drum vacuum filter.

Prior to the LMF5-G test, advanced preparation was made for the rotary drum vacuum filter. Wiring was completed to the cyclone drain pump and float switches were installed and wired. Wire and conduit were installed between the downstream motor control center and the concrete pad where the filter was to be located. When the filter arrived, filter controls and motors were wired to the filter control panel. Wiring and conduit that had been installed from the downstream motor control center to the vicinity of the filter were connected to the filter.

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

Other significant instrumentation and control system actions were as follows:

- Expanded the computer Ethernet system in the laboratory building.
- Repaired the dry ESP control system.
- Installed a new transformer in the former seed storage building.
- Replaced defective and noisy starters in the downstream motor control center.
- Repaired the cooling water pump house substation transformer.

ANALYTICAL AND CHEMISTRY LABORATORY SERVICES

During this quarter, the laboratory completed the analysis of all samples submitted to date from LMF5 testing. This data was entered into the Laboratory Information Management System (LIMS) and transferred to the VAX for inclusion in the mainframe database. Also, samples from the six surface water sampling sites were collected each month and analyzed for routine parameters.

A considerable amount of time was expended preparing for, participating in, and responding to the DOE Environmental Audit. As a result of the audit, laboratory procedures are being written or revised. Other actions are pending formulation and approval of an ECP action plan.

During the next quarter, laboratory personnel will participate in preparing an action plan as a result of the DOE audit.

ENVIRONMENTAL CONTROL

The primary focus this quarter for the Environmental Monitoring disciplines was participation in the DOE environmental audit. Much of the remainder of the quarter was spent assembling documentation and procedures in anticipation of corrective actions required as a result of the audit.

Water Quality

The holding ponds were monitored and treated as necessary during the quarter to maintain effluent conditions within permit limits. During this quarter effluent conditions exceeded permit limits for pH on November 3, 1992. The ponds were treated and effluent conditions brought within permit limits. Flow during the noncompliance was .0041 Million Gallons per Day. Monthly Discharge Monitoring Reports (DMR) were filed with the State of Tennessee, Division of Water Quality.

Groundwater Monitoring

Activities in the groundwater monitoring program were limited to the further documentation of the groundwater monitoring program. Activities centered around a discussion with the State of Tennessee Division of Drinking Water. A representative from the state visited the CFFF in December and reviewed the CFFF well placement and groundwater monitoring systems. Further discussion and an additional information exchange is planned in January 1993 after they evaluate the data presented.

Terrestrial Ecology

Activity in this area for the quarter was limited to a review of the procedures and QA data by the environmental auditors.

Ambient Air Monitoring

The primary activity this quarter centered around participation in and responding to the DOE environmental audit. Permission was finally granted by Arnold Engineering Development Center for removal of vegetation around the ambient air monitoring stations. Additional efforts will be directed toward formal, site specific, documentation of operating procedures.

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

TESTING

A western coal long-duration, proof-of-concept (POC) test, LMF5-G, was completed on October 14, 1992, and achieved 314 hours on coal.

The primary objectives of the LMF5-G test were:

- Operate the LMF5 flow train on Rosebud western coal for approximately 300 hours with 1 percent potassium in the primary flow; seed added into the primary combustor as a 47 percent solution of potassium carbonate; nominal primary stoichiometry of 0.85; and nominal secondary stoichiometry of 1.10.
- Install and checkout the rotary vacuum filter and its effects on the wet ESP.

All primary objectives were accomplished. The rotary vacuum filter for the wet ESP, which arrived on September 29, could not be installed prior to test startup. It was, however, installed during the later part of the test run and checked-out successfully.

Table 1 shows the CFFF testing completed on eastern Illinois #6 coal, special tests conducted on western Montana Rosebud coal and the western coal POC testing completed through December 1992, and western coal POC testing projected through FY93.

UPSTREAM COMPONENT SYSTEMS

The upstream systems operated reliably in support of the LMF5-G test with two exceptions, both related to the vitiation heater. After approximately 75 hours into the test, a water leak in the vitiation heater burner plate led to a failure in an oil line and an accumulation of oil which subsequently detonated, propelling the burner plate downstream against the coal tube, which was damaged. The vitiation heater was repaired and the coal tube replaced with a spare. Later in the test, a small water leak in the exterior of the vitiation heater necessitated a brief shutdown for repair.

TABLE 1. CFFF Test Series

TEST CONFIGURATION	DATE OF COMPLETION	HOURS ON COAL
Completed Eastern Coal Tests - LMF4	05-91	2358
Shakedown - LMF5-A (Western Coal)	08-91	75
Corette Plant Conditions - LMF5-B	08-91	60
K ₂ CO ₃ /K ₂ SO ₄ /Fe ₂ O ₃ Addition - LMF5-C	09-91	50
Special test using all carbonate seed - LMF5-D	11-91	107
*POC-LMF5-E	04-92	91
POC-LMF5-F	08-92	290
POC-LMF5-G	10-92	314
		**
		TOTAL 3345
Projected POC-LMF5-H	04-93	225
Projected POC-LMF5-I	06-93	225
Projected POC-LMF5-J	11-93	225

* Proof-of-Concept

** Total test train operation time to date on coal is 3345 hours

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

(Total test train operation on western coal is 987 hours to date.)

(Total test train operation time to date is 3688 hours (including vitiation heater operation on oil only).)

As noted in previous reports, the lower viscosity of the Montana Rosebud coal slag led to reduced slag layer thickness compared with that of the eastern coal. This continues to be the case, as evidenced by heat flux measurements. However, all indications are that a uniform protective slag layer forms, but it is thinner than with the eastern coal. A photograph of the main coal combustor following completion of the LMF5-G test indicating this slag layer is shown by Figure 3.

DOWNSTREAM COMPONENT SYSTEMS

Details of the results from the LMF5-G test for downstream equipment and the high temperature air heater material trials are given below.

Superheater Test Module (SHTM) Corrosion

Accumulated exposure time on the LMF5 POC test section tubes with coal firing was brought to almost 695 hours during the LMF5-G test. Following the test, all tubes were removed from the test train. Sections were cut by band saw from the tubes for corrosion examination as detailed in Table 2.

Table 2. Sample Sections Cut from Test Section Tubes after 639 Exposure Hours

Tube	Pass	Location	Length, inches	Material
TS1-1C	2	Bottom	8	316
TS1-2C	2	Bottom	12	253MA
TS1-3C	2	Bottom	12	347H
TS1-4C	2	Bottom	12	304H
TS1-5C	2	Bottom	12	310
TS2-1C	2	Bottom	12	316
TS2-2C	2	Bottom	12	253MA
TS2-3C	2	Bottom	12	347H
TS2-4C	2	Bottom	12	304H
TS2-5C	2	Bottom	12	310
TS3-5C	1	Middle	12	T9
TS3-6C	1	Middle	12	T22
TS3-7C	3	Middle	12	T11
TS3-8C	1	Middle	12	304H
TS3-8C	4	Bottom	12	SA192

New sections of tube of the same alloy are to be welded-in to replace the removed sections prior to the next test. Thus, those pieces should have an accumulated exposure time of approximately 1361 hours at the conclusion of the 2000

**FIGURE 3. Photograph of the LMF Coal Combustor
Following the LMF5-G Test**

hour western POC tests. The length of alloy 316 cut from test section 1-1C (TS1-1C) was 8-inches instead of 12 because only an 8-inch length of the same tube remained from the initial tube fabrication for replacement. For TS2-1C, a 12-inch length of another tube will be used. Each of the removed tube sections contained two locations at which initial tube wall measurements were made by ultrasonics, except for the 8-inch length of alloy 316, which had only one such location. One-inch wide rings containing the ultrasonic measurement locations will be cut out, the outer and inner surfaces grit or glass bead blasted to remove oxide scale, and post-exposure wall thickness measurements made at the same locations with a tube micrometer. Adjacent sections with oxide scale unremoved will be microscopically examined to determine internal penetration depth, corrosion morphology, and scale composition. Sections from the removed tube pieces will also be sent to the Babcock and Wilcox Company and to the Argonne National Laboratory for examination.

For the LMF5-G test, additional thermocouples were attached to the outer surface of TS1 tubes in order to obtain a better knowledge of the distribution of metal temperatures. Twenty-eight new thermocouples were used in addition to the 22 already present. These new thermocouples were temporary in that their leads traversed the gas stream to exit the duct, and, thus, at TS1 gas temperatures burned up within a few hours. The measured temperatures at the front side of tubes are given in Figure 4. The absence of temperatures for tube 4 was due to "permanent" thermocouple failure. A procedure was devised for repair of the thermocouples since replacement would require welding and grinding that would remove all effects of the corrosion exposure.

Work progressed on a topical report covering the corrosion evaluation of LMF4 tubes with 1500 and 2000 hours of exposure. Most of the results of corrosion measurements were already presented in previous topical reports. A brief summary and conclusions of the evaluations are given here.

Austenitic stainless steels, low and medium chromium steels, and carbon steel were tested as tubes for steam and intermediate temperature air heating in MHD power plants. Testing was conducted in a 20 MW_t facility with the firing of high sulfur Illinois #6 coal seeded with potassium carbonate. Tubes were located in three gas temperature zones and with tube metal temperatures ranging from 700°F to 1400°F. Corrosion occurred beneath deposits containing 75% or more K₂SO₄. Test exposures consisted of twelve different test runs over a period of three years. Tube samples were taken for evaluation at 500, 1500, and 2000 hour intervals. These evaluations included measurement of scale thickness and depth of internal penetration, comparison of remaining wall thickness with initial ultrasonic thickness measurements, and examination of scale, penetration, and deposit morphologies by means of optical and scanning electron microscopy and by energy dispersive x-ray spectroscopy. The following conclusions were made from the evaluations:

- Corrosion resulted from solid state interaction of tube metals and their scales with K₂SO₄ in the deposits.

Temperatures at the Leading Edge of TS1 Tubes at the Beginning of LMF5-G
(Temperatures in Parentheses were Obtained by Cubic Spline Interpolation.)

FIGURE 4. Temperatures at the Leading Edge of TS1 Tubes at the Beginning of LMF5-G

- Complex alkali trisulfates such as $K_2Fe(SO_4)_3$, responsible for potentially severe conventional coal ash corrosion, have been detected on rare instances in trace amounts in MHD tube deposits, but are not normally present, probably as a result of low SO_2 and SO_3 concentrations in the flue gas.
- Many of the corrosion characteristics were similar to those occurring in liquid phase coal ash corrosion. These included having the same corrosion precursor (K_2SO_4), the same type of scales, and the same migration of iron into the deposit to produce $FeSO_4$, and precipitation of iron oxide near the outer boundary of the $FeSO_4$ as a result of decreasing sulfur partial pressure and increasing oxygen partial pressure.
- Corrosion resulted in oxide scales containing sulfur either in solution or as discrete sulfides. Sulfur penetration of the scale resulted in enhanced outward metal ion migration and production of Cr-Fe scales often having multiple layers. Much separation of these scale layers and scale fracturing occurred, augmented by the relative large number and intensity of thermal cycling which occurred. $FeSO_4$ between the scale and the deposit appeared to be a brittle phase prone to spalling and to contributing to scale spalling. This scale damage resulted in further corrosion, and this process would eventually reach a break-away stage wherein scales could no longer be repaired due to subsurface chromium depletion and rapid attack would occur. However, cyclic conditions were far more severe in these tests than would be expected in actual service.
- Internal penetration of all the austenitic stainless steels occurred as a result of inward migration of oxygen and sulfur being faster than the outward migration of cations. This penetration resulted in subscale sulfides in some cases, in transgranular oxidation/sulfidation of the surface grains, and intergranular penetration to a depth of several grains, depending upon the chromium content.
- Resistance to corrosion increased with increasing alloy chromium content. Alloy 310 was the most resistant of those tested.
- For the austenitic alloys, corrosion appeared to be more somewhat more intense within 30-35 degrees of the leading edge.
- There were numerous cases in which 1500 hour corrosion was substantially more than 2000 hour corrosion, seeming to indicate some difference in initial exposure condition between the two sets of tubes.
- Data was too scattered to determine the corrosion kinetics, i.e. whether parabolic or linear with time. From the observed severe disruption of the scales in these tests, accelerated breakaway corrosion would be predicted for all of the alloys. However, much of the scale disruption was due to highly cyclic exposure conditions not typical of service in an actual plant.

- Monotonically increasing corrosion with temperature was expected but was not generally observed due to the large data scatter.
- There was no discernable difference in corrosion between TS1 with a gas temperature of around 2250°F and hard, thick deposits, and TS2, with a gas temperature of about 1700°F and friable deposits. There was, however, evidence of more scale spalling at the higher gas temperature.
- Of the alloys tested at superheater temperatures, only 310 had scale + penetration less than 0.5 mm/yr (for the first year) on a linear basis, and it appeared that none would meet that criterion at 1400°F for intermediate temperature airheater service. Alloy 253MA, in addition to alloy 310, data showed less than 0.5 mm/yr on a parabolic basis, at both temperatures, while data for the 18-8 stainless steels were variably above or below a parabolic 0.5 mm/yr rate.
- For the stainless steels, little or no difference was found, at a given metal temperature, between corrosion at the leading and trailing edges of tubes. But carbon and low chromium steels in TS3 showed less corrosion at the trailing edge.
- None of the ferritic alloys had internal penetration, but all had thick scales. Linear scaling rates were above 0.5 mm/yr for all alloys. Corrosion of alloys T22 and P5 was generally below a parabolic 0.5 mm/yr, while T11 and carbon steel were believed to be above, considering suspected scale losses.

SEM micrographs and x-ray dot maps for Fe, Cr, and S are presented in Figure 5 for a typical alloy, 310 stainless steel. The following observations were made:

1. Oxide scales were produced on both the austenitic and ferritic alloys, as inferred from the oxidizing atmosphere of the tests and the absence of large amounts of sulfur in the scales.
2. No differences were found in the corrosion morphologies or scale compositions with respect to gas temperature. That is, TS1 and TS2 appeared to be the same, and TS2 and TS3 appeared to be the same, for the cases where an alloy was present in both banks.
3. Scales generally exhibited much spalling and fracturing. This often resulted in voids between scale layers or in areas where part or all of the scale was missing, as in Figure 5a. None of the alloys demonstrated any noticeable superiority with regard to scale retention or resistance to fracturing.
4. Scales were non-uniform in thickness, on a microscopic level, aside from spalling. Alloy 310 and 253MA scale thicknesses were particularly variable, and at the lower metal temperatures showed indications of an early stage of

a. SEM Micrograph

b. Fe

c. Cr

d. S

L-1536

FIGURE 5. SEM Micrograph and x-ray dot maps for alloy 310 (TS2-2, P1,1')

oxidation prior to spreading of scale from nucleated sites over the entire surface.

5. Binary scale layers (i.e. Type B scales) were sometimes present for the 18-8 stainless steels with higher chromium content in the inner layer than in the outer layer. This was often not the case, however, since there either was only one layer, or else two or more separated layers of the same composition. The absence of an outer low chromium layer in such cases was believed to be often attributable to spalling and loss of the outer layer rather than the existence of a single Type A scale.
6. Fine oxide precipitates which appeared to be of about the same composition as the scale were often found distributed in the K_2SO_4 deposit near to the scale, as seen in Figure 5a. Where these precipitates were present, the outer surface of the scale was very irregular and the outer region of the scale was discontinuous, consisting of islands and peninsulas of scale surrounded by deposit. This gave the appearance of the scale's outer surface having been dissolved in the deposit and reprecipitated. Whether or not these precipitates were formerly part of the scale, they represented in some cases a significant amount of metal loss. When the precipitates were at the polished plane, they had the same light gray appearance as polished scale oxide. In locations with a high fraction of precipitate, if the area was recessed below the polished plane due to crumbling of the brittle deposit, the color was dark gray with granular speckles, the same appearance as scale oxide recessed below the polished plane. This resulted in frequent difficulty in performing corrosion thickness measurements due to inability to visually distinguish between recessed areas which were all scale and areas which were precipitated scale in deposit. This behavior was true of all the alloys in all of the test sections.
7. Another morphological feature resulting from diffusion of tube metal elements into the deposit was a zone of deposit adjacent to the scale having a high iron content as determined by EDS and characterized by a red color under polarized light microscopy. No chromium was detectable in these deposit regions. The oxide precipitates described above were generally, but not always, surrounded by the red, high-iron deposit. However, precipitates were not always present in the red deposits.
8. In polished corrosion samples, a gap was commonly present either between the scale and the deposit, or within the deposit a short distance (up to a few hundred micrometers) from the scale. Where the gap existed between the scale and deposit, it was often apparent that some or all of the scale had also spalled. The prevalence of this gap and its location led to speculation that the deposit in this region was embrittled either by high iron content or by the presence of oxide precipitates, or both.
9. Internal penetration of the austenitic alloys occurred at most locations and temperatures. This occurred as intergranular or transgranular oxidation, or

both. As with scaling, resistance to internal penetration in these alloys increased with chromium content. Transgranular oxidation was generally limited to surface metal grains, and for some grains, had proceeded until those grains were totally converted to oxide. Intergranular penetration, on the other hand, often extended several grain diameters from the surface. Thus, metal recession occurred partially by inward diffusion of oxygen through the scale and into the metal. This type of behavior occurs when scales are not very protective, either due to a high concentration of lattice defects such as cation vacancies, to a large compositional range such as with spinel oxide, or to physical defects such as cracks or voids. No difference could be seen from EDS spectra between the composition of intergranular oxide and the scale adjacent to the metal surface. A small amount of sulfur, generally just above the EDS detection limit, was present in the subsurface metal, as in the scales, and was suspected of playing a major role in reducing the protectiveness of scales and increasing the extent of internal penetration. There was no internal penetration of any of the ferritic alloys.

Superheater Test Module (SHTM) Ash Deposition

Computer Control of Sootblowing

Heat transfer data related to sootblowing effectiveness is still being evaluated, but preliminary indications are that the SMARTBLOW computer program is capable of regulating gas temperatures sufficiently in the west (upstream) leg of the SHTM to protect the air heater and baghouse materials during periods of high thermal input. This is accomplished by using the gas temperature-drop across each of three designated control zones for determining the sootblowing requirements in each zone. The gas temperature-drop across each zone is used as an indicator of fouling since the last cleaning cycle (i.e. increased fouling $\Rightarrow$ less heat removed $\Rightarrow$ less of a drop in gas temperature).

By using running averages in determining the changes in gas temperature-drops across each control zone, the computer program is made less sensitive to normal fluctuations in thermal input compared to using single data point changes. The averaged temperature-drops are then compared with set point references to determine when the fouling has reduced the cooling efficiency to a point where sootblowing is desired, to bring the downstream gas temperatures back within a nominal range. The set points were initially derived from averaged data of past tests. They can now be adjusted during a test whenever greater or lesser cooling is desired, or if increased or decreased cycle times are desired.

It is planned to expand the SMARTBLOW control logic to incorporate more of the SHTM sections as confidence is developed in its ability to avoid problems or conflicts with other process control functions.

Two effects were noted in the LMF5-G test which had not been fully accounted for in the program. The first was the secondary effect of SHTM upstream sootblowing

on the SHTM downstream gas temperatures and therefore the measured "delta T" values of these other SMARTBLOW sections. The second effect was the duration of these gas temperature fluctuations. Upstream sootblowing was expected to cause a short duration gas temperature-drop in the downstream due to cold air input and the increased heat transfer of the cleaned tubes. Thus a 15-minute wait was expected to be sufficient to allow the gas temperatures to recover and stabilize. However, post test examination of the LMF5-G test gas temperature data indicated that 20 minutes or more may be required, depending on the location of the sootblower in the flow train and the type (retractable or fixed) sootblower which just was used upstream. Lowering the delta-T set points can also reduce some of these secondary effects, but in order to stay in the "nominal" heat transfer range, there is a limit which must be determined from fouling profiles of each section of the SHTM.

The influences of sootblowing on downstream gas temperature changes and the length of that change upon computer control logic indicate the need for a better understanding of how the reference values are to be used. Future work also requires further refinement of the program to either take the known variables into the logic loop or increase the delay between a sootblowing cycle and the start of the next evaluation loop in steps until a sufficient safety margin is reached.

Superheater Test Module Ash Deposits

Since the start of the LMF5 test series on Montana Rosebud coal, SHTM tube ash accumulations have maintained fairly consistent physical characteristics and have been effectively removed from tube surfaces by standard sootblowing in all sections of the SHTM. During this quarter increasing amounts of a blue color in all of the upstream deposits (TS1, CS1, CS2, TS2, CS3, and TS3) were observed. Deposits downstream of CS3 were primarily white and powdery (as in the past) although blue samples were observed in particulate control inlet samples. During the LMF5-G test large amounts of the blue deposit were observed downstream of the TS3 tubes. The deposits were apparently molten and flowing down the tubes in several temperature zones during the tests. Analyses indicated potassium carbonate and sulfate, with an excess carbonate above that needed to react with potassium. The blue color is more prominent in smaller particle sizes when the samples were heated to 750°C in an air atmosphere, indicating the color is not the result of reducing conditions.

Ash/Seed Hopper Gas Bypass Line

A gas bypass line was installed prior to the LMF5-E test to maintain a flow of hot gas through the ash/seed tap to keep the molten K_2SO_4/K_2CO_3 deposits from freezing and bridging the tap hole. The ash/seed hopper gas bypass line was not able to keep the seed tap open for the duration of any test in this quarter. It was observed that after approximately 100 hours on coal, the seed tap starts to develop bridging problems. Post test inspections found some indication that large slabs of refractory (as shown in Figure 6) and/or sulfate/carbonate deposits may have fallen across the tap before it filled with molten material. It is now suspected that thermal shock (at start-up/shutdown/restarts) may have caused some of the material normally left attached to the SHTM inlet transition and hopper walls to spall off in large enough

FIGURE 6. Photo of Deposits and Refractory Slabs Above Ash Seed Tap After LMF5-G Test

sections. Unless these slabs are broken up as soon as they reach the tap (or shortly thereafter), they restrict the flow of the molten material where it then freezes and bonds several chunks together. Unfortunately, it is not possible to view the tap except when there is sufficient radiation present in the region above the tap. By the time the system is stable on coal, the tap may already be partially bridged with several large pieces of spalled material. The viewing port will be relocated to provide better access during testing.

Summary

Ash deposits from the Montana Rosebud coal combustion have caused no handling or removal problems in the SHTM using computer control of the upstream sootblowing. The SMARTBLOW program appears to be effective in maintaining the desired gas temperature ranges in each section by controlling the buildup of deposits on the CS (Control Section) tubing in the upstream region of the SHTM.

The molten ash/seed tap at the Secondary Combustor - Inlet Transition point of the flow train is still developing problems in spite of the bypass line. We believe that large pieces of refractory/sulfate are spalling from the walls above the tap due to the thermal shock associated with restart after shutdown and partially blocking the tap area.

PARTICULATE REMOVAL SYSTEMS

Dry Electrostatic Precipitator (ESP) Performance

The dry ESP was operated during the LMF5-G test. Performance of the device was marginal partially due to the high gas flow conditions and to a measurable decrease in particle size distribution. To meet the CFFF particulate emission operating permit, the dry ESP was forced to process more than 50% of the flow for most of the test.

Emissions from the dry ESP ranged from 0.365 - 0.707 lb/MBTU for gas flows of 7200 - 12600 cfm (see Table 3). The nominal design flow for this ESP is only 6300 cfm; therefore, the efficiency was not expected to be good when many of the tests were conducted at a much higher throughput. The particle size distribution has shown an increase in the number of small particles when using Montana Rosebud coal with a K_2/S of approximately 4.0 compared when using Illinois coal with a K_2/S ratio of 1.0. The mass mean diameter, as measured by a 5 Stage Series Cyclone Sampler, decreased from 0.7 to 0.2 micrometers, which is likely a contributing factor in the low dry ESP collection efficiency. This decrease in particle size is believed to be related to the presence of significant quantities of potassium carbonate in the collected ash.

Table 3. Dry ESP Performance during LMF5-G

<u>Particulate Emissions lb/MBTU</u>	<u>Gas Flow acfm</u>	<u>SCA</u>	<u>Efficiency %</u>
0.689	11800	254	82.6
0.572	11140	269	92.0
0.443	10840	277	93.8
0.470	11160	269	96.2
0.656	8900	337	86.9
0.365	8550	351	93.3
0.405	7210	416	93.3

The dry ESP electrical conditions were typically 60 - 70 kV in each field with increasing current in successive fields. High current, especially in field 4, is a good indicator of collection efficiency. Presence of particulate in the gas stream tends to slow the flow of electrons from the discharge electrodes to the collection plates. Therefore, high current indicates low concentration of particles in the gas and high collection efficiency. Field 4 current generally varied between 10 - 20 mA (see Figure 7) which has been typical of marginal performance. High collection efficiencies usually are associated with 40 - 80 mA in field 4.

Based upon research conducted by ADA, Inc., the dry ESP efficiency can be increased substantially by replacing the discharge wires with smaller diameter wires. Because of the relatively large diameter electrodes currently installed in the dry ESP (1/4" round and 5/16" square), it is difficult to maintain the high current conditions necessary for high particle collection efficiencies. Bench scale tests conducted by ADA, Inc. suggested that most of the corona discharge was at the ends of the electrodes which are outside the usable portion of the dry ESP. Replacing the electrodes with 1/8" round wires will substantially improve corona patterns and, therefore, increase performance. Round 1/8" electrodes will be installed prior to the next test.

Baghouse (BH) Performance

The CFFF baghouse was operated successfully during the LMF5-G test. As in previous tests, the bags were cleaned using reverse air with sonic horn assist. The nominal filtration velocity through the Gore-Tex bags is 2 ft/min. Emissions from the baghouse ranged from 0.0008 - 0.005 lb/MBTU which is well below the NSPS allowable limit of 0.03 lb/MBTU.

New Gore-Tex bags were successfully tested during the LMF5-F and LMF5-G tests. Four of the carbon steel thimbles which attach to the bags at the bottom had corroded to the point of failure just prior to the LMF5-F test and were

FIGURE 7. Typical Dry ESP Operating Conditions During LMF5-G

capped. The baghouse was operated with only 26 bags during this test. However, replacement stainless steel thimbles arrived prior to the LMF5-G test, and the baghouse was once again operated with 30 bags.

Short durations between the required cleaning cycles were prevalent during the LMF5-G (as well as the LMF5-F) test. At 5400 cfm (2 ft/min filtration velocity), the cleaning cycles were required at intervals of less than 30 minutes apart. With tests conducted using the Illinois #6 coal and at much lower K_2/S ratios, 90 minutes between cleaning cycles were normal. The reverse air fan was replaced at the same time this increase in cleaning cycle frequency occurred. The replacement fan is specified to be identical to the original one. Also, the reverse air ductwork has been replaced with a different design, but this too is not suspected to be causing the problem.

The initial cleaning cycle during the LMF5-G test was approximately 110 minutes in duration. Residual pressure-drop is the pressure-drop across the tube sheet immediately after a cleaning cycle. After only a few cleaning cycles the residual pressure-drop had increased from 1-2-inches wc to over 5-inches wc. This indicates that the ash is not being removed efficiently from the bags or is being reentrained after the cleaning cycle. After periods when the baghouse was taken off-line for several hours for inspection, the initial time between cleaning cycles was approximately 90 minutes (see Figure 8), but continually degraded afterwards. Also, cleaning the bags two or three times instead of only once also improved the bag condition (see Figure 8). More investigation during future tests will be necessary to resolve this problem.

MASS BALANCE AND AUTOMATIC DATA SCREENING

During the quarter work continued on data reduction and filtration efforts in support of CFFF testing. Data from recent testing, which extend over several storage disks, required new programming efforts. Several data reduction programs were modified to generate intermediate outputs to allow for reducing the data in several steps. In addition, it was noted that, with the start of the LMF5 test series, a variety of data channels were added and others were reassigned. The existing programs which rely on advance knowledge of the relationship between parameters and channel numbers were not able to "capture" all of the data required. Programming efforts, therefore, have begun that enable parameter names to be used as data request input parameters, in place of channel numbers. This method should quickly identify changes to the channel numbering sequence, while being able to obtain requested data despite channel number reassignments.

Work on individual LMF5 series tests continued. The multi-test mass balance program was completed, though some additional testing against manual calculations is planned for the upcoming quarter. A significant reorganization of the data files to allow a more automated access to the data was also accomplished during the current quarter, though some additional modifications to permit easy access to multi-test input data are still required. Modifications to the individual test mass balance computer program to deal with changed inputs for western coal testing were completed. A

FIGURE 8. Typical Baghouse Operating Conditions During LMF5-G

preliminary run of the mass balance program for all Illinois #6 coal POC testing was completed. This run will be repeated using (improved) chemical analysis data.

Data from the chemical analysis database system, operating on the VAX, is now successfully being transferred to the VAX database. The CHEMUPDATE program for transferring the data was successfully tested and is now being used to transfer the data. In addition, the database program was successfully ported to the FileMakerPro software package on the Macintosh computer. This led to the inclusion of some new features/tools that could not easily be implemented on the VAX, such as automatic calculation of mean data for groups of analyses and the ability for users to apply additional sample selection criteria. The new program can also be accessed by more users than before, and seems to have been very successful. Attempts will soon be made to develop some additional tools for the Macintosh database, including the automatic calculation of standard deviations for grouped data.

Secondary Combustor

Work continued on implementation of a detailed secondary combustor performance computer model including chemical reactions, fluid mechanics and heat transfer. This model is based on the KIVA-II computer code¹. KIVA modifications were tested. Modifications to the inflow boundary conditions are working correctly, however, the wall jet modifications are not calculating reasonable jet penetration. Work will continue on the computer code development.

Work also continued on the potassium-sulfur chemical kinetics study. The literature survey and experiment planning continued. In particular, diagnostic and analytical requirements for the experiments were reviewed.

Ash Deposition Modeling

Work continued on the development of the analytical model for evaluating and predicting the effect of fireside ash deposits on superheater tubes. When completed, this engineering model could provide a tool for generating very useful predictive information for future superheater and scale-up activities. The FuelCalc module was expanded significantly to include a database of coal analyses and allow input of five-stage cyclone data for particle size distribution of fly ash and corresponding elemental analyses. In addition, new output capabilities for FuelCalc include calculated viscosity as a function of temperature and composition for flue gas and coal ash, and regression-correlated particle data by narrow ash-diameter-range bins.

More of the calculation for inertial impaction of particles on a superheater tube is functioning now. Additions were made to account for effects of high gas temperatures and density of ash particles. Also image analysis work was started for evaluation of characteristics of ash particles, including determining diameters and quantifying cohesive strengths via measurement of sinter-bond development.

Initial code writing for temperature and heat-transfer effects concentrated on mass transfer via vapor condensation and thermophoresis. A major part of the general

code was completed for these temperature-driven mass-transfer mechanisms. The development of two-dimensional finite-element routines will come next for description of localized effects.

Plans are to continue work to expand the capabilities of FuelCalc and Image analysis, and to continue with the development of the finite element code.

ADVANCED MEASUREMENT SYSTEMS

An evaluation was conducted of the single wavelength line reversal system measurements at superheater test section 1 (TS1). The accuracy of the single wavelength measurements was examined by comparing the line reversal temperature readings with multiple-shielded high velocity thermocouple (MHVT) LMF5-F measurements acquired adjacent to the line reversal lamp port location. The MHVT probe was developed by the Babcock and Wilcox Company in the 1950's for application to temperature measurements in boilers where, like TS1, the gas temperatures are high enough to require probe design compensation for probe radiation cooling to temperatures significantly below the gas temperatures². The Babcock and Wilcox MHVT probe design was modified at UTSI to provide effective radiation shielding and heat transfer augmentation in the CFFF with the associated rapid blockage of aspirated probes and potassium attack on thermocouples, lead-wires, and shield materials³.

Figure 9 shows a time trace of the simultaneous line reversal and MHVT measurements, along with sheathed thermocouple measurements at different vertical positions just ahead of the TS1 steam tubes and 0.94m downstream of the MHVT location. Unaspirated MHVT measurements refers to measurements made with the MHVT probe used only as a shielded probe (i.e., without gas aspiration across the MHVT sensor to enhance sensor heating as partial compensation for cooling losses.) The second of the 4 MHVT measurements obviously was taken during a period where the TS1 gas temperature was changing significantly and, thus, was not relatively constant as needed for reliable MHVT measurements. The significant changes (>100°F) seen in the TS1 gas temperature during the LMF5-F test correspond to significant jumps in coal flow during this period which were traced to erosion of the Moulder valve used to control the coal flow. The three MHVT measurements made during "stable" gas temperature periods are typically 60°F less than the simultaneous line reversal measurements. As indicated by the sheathed thermocouple measurements, the position difference between the line reversal and the 0.37m higher MHVT will cause approximately a 25°F temperature difference between the line reversal and MHVT if the same temperature profile exists at the line reversal-MHVT axial position as at the sheathed thermocouple axial position 0.93m downstream of the MHVT penetration. The remaining 35°F (20K) difference between line reversal and MHVT measurements at TS1 is slightly less than the expected measurement uncertainty of either the line reversal or the MHVT measurements. Obviously, the line reversal system at TS1 provides as good a gas temperature monitor as the best available thermocouple configuration, without the susceptibility to rapid plugging experienced with the MHVT at the CFFF.

FIGURE 9. Line Reversal Evaluation at TS1 Inlet

The TS1 line reversal system operated for both the LMF5-F and LMF5-G tests as alternately a single wavelength temperature monitor and a scanning optical emissions and transmissions monitor. As indicated last quarter, emissions and absorption from gas phase sodium are detectable for typical POC conditions at TS1, but emissions and absorption from gas phase potassium are considerably greater at these POC conditions. The low sodium emissions cause concern because a modest decrease in gas temperature could easily make them undetectable and thereby negate accurate sodium line reversal measurements. Indeed, during the LMF5-G test it appeared sodium line reversal measurements did not seem to be possible for TS1 at below about 1420K (2100°F). Operating the line reversal system as a potassium system may provide significantly lower temperature monitoring capabilities for this system. To examine the possibility of using potassium line reversal at TS1, calculations were performed using the NASA SP-273 chemical equilibrium computer code⁴ to determine the equilibrium amounts of condensed potassium species at various temperatures. Results are plotted in Figure 10. For typical low sulfur western coal POC conditions, over 80% of the potassium is in gas phase at temperatures above 1950°F, and most of the remaining 20% changes to gas phase between 2200°F and 2400°F. For conditions where K_2/S is 1 or less, almost all of the potassium is in the condensed phase at temperatures below 2200°F, but there may be sufficient gas phase potassium to allow line reversal measurements down to 2000°F even at this low K_2/S condition for typical low sulfur western coal.

FIGURE 10. Predicted Fraction of Potassium in Condensed Phase

For further testing using potassium line reversal at TS1 the remote spectral scanning capability of the new TS1 system was used to generate spectral emission and transmission scans for different test conditions during the LMF5-G test. Figure 11 shows scans for low TS1 gas temperature conditions and Figure 12 shows scans for the nominal 1535K (2300°F) typical POC TS1 gas temperatures at different potassium injection levels. Figure 11a shows an almost nonexistent sodium doublet at a nominal TS1 gas temperature of 1380K (2025°F) and Figure 11b shows no detectable sodium emissions at a nominal TS1 gas temperature of 1190K (1685°F), while both figures indicate a strong potassium doublet for a $K_2/S=4.2$. Figure 12 indicates the potassium doublet increases in strength as the K_2/S ratio increases, but provides a strong, distinct signal even at low K_2/S . A single wavelength between 762-766nm should provide good line reversal TS1 gas temperatures for all LMF5 test conditions envisioned, while the wavelength of 588.9nm used for the LMF5-F and LMF5-G tests always provides less, and sometimes no line reversal signal.

Additional software and hardware developments for multiwavelength simultaneous data acquisition and analysis will continue over the next several months. This primarily involves implementing the multichannel detector to provide time resolved spectral measurements. The system then will be capable of evaluating gas phase potassium concentrations and of correcting line reversal measurements for particle scattering and particle emission/absorption influences without increasing the non-simultaneous sampling error. The system will also be configured to remotely

a. 16 MW, Thermal Input, 0.85 Stoichiometry, $T_g = 1380K$

b. 19 MW, Thermal Input, 0.95 Stoichiometry, $T_g = 1190K$

FIGURE 11. Spectra for Low TS1 T_g Conditions, $K_2/S = 4.2$

a. $K_2/S = 0.8$

b. $K_2/S = 1.2$

c. $K_2/S = 4.2$ (POC)

FIGURE 12. TS1 Spectra for Different K_2/S Ratios, $T_g \sim 1535K$

switch between single and multiple wavelength operation and between visible and infrared spectral scanning operation.

Particle Sampling and Dilution System

Work continued on shakedown and data analysis for the on-line near-real-time particle sampling extraction dilution system (SEDS). The SEDS is required to evaluate the performance of particulate control devices (dry and wet ESPs, and baghouse) as CFFF operating conditions change because existing commercial on-line particle monitors can not handle the extreme particle number densities (10^8 particles/cc) and small particle sizes (mass mean diameter 0.2-0.7 μm). The SEDS was modeled on the Southern Research Institute developed system⁵ which reduces the sampled flue gas moisture content and particulate loading as needed to allow direct, near continuous measurement using commercially available instrumentation. For the SEDS a Particle Measuring Systems Active Scattering Aerosol Spectrometer ASASP V instrument was selected. Because the particles which present the greatest difficulty for successful cleaning by an electrostatic precipitator are the 0.1-1.5 μm particles which are most difficult to charge, and five stage cyclone measurements have indicated that most of these particles are of sizes less than 3 μm , the SEDS was designed to measure primarily the .01-3 μm particle size range.

A typical particle size bin versus particle number count versus time is shown in Figure 13. The time axis was plotted right to left to assist in illustration of pertinent data features. Figure 13 indicates that gradual plugging occurs after about 190 sec, but a different phenomenon, one of occasional depletion of the smaller particle sizes in the sequential size distributions, also occurred (near both 50 sec and 100 sec in Figure 13). The Particle Measuring Systems (PMS) optical sizing instrument is known to bias measured size distributions when the system measurement activity is too high, so the system activity versus time was examined, as plotted in Figure 14. Comparing Figures 13 and 14 shows that the decrease in small particle counts corresponds to an increase in percent activity to a level over 80%. The PMS manual indicates that 80% activity corresponds to instrument saturation, and operation in any size bins with activity levels approaching 80% will, due to multiple particle events, reduce the measured counts for those particle sizes. It is hypothesized, therefore, that high (greater than 80%) instrument activity occurs primarily in the small size bins so that the PMS instrument sees those small particles mostly as multiple particle events which biases the measured size distributions to larger particle size counts and decreases the small particle counts. Tests of the instrument system will continue, to better determine limitations on instrument overall activity along with appropriate (increased) SEDS dilution ratios which will prevent a drop in small particle counting. This limitation will be defined in time for sufficient particulate data to be acquired during the remaining POC tests.

Mississippi State University (MSU) diagnostics data were examined from the LMF5-F and LMF5-G tests when this data was received. Data contained in the MSU report, but not discussed in this report, where it pertains to other CFFF test activity includes coherent anti-Stokes Raman spectroscopy (CARS) used to measure both gas temperature profiles and CO levels at the diffuser and at the aerodynamic duct

FIGURE 13. Particle Number Count vs. Size Bin vs. Time

FIGURE 14. Change in Instrument Activity with Time

instrument ring; the potassium emission absorption system (PE/AS) used in a dual beam, high velocity configuration at the instrument ring also; and a laser Doppler velocimeter (LDV) employed to measure gas velocities at the instrument ring; in the secondary furnace HTAH location, and in the secondary combustor where velocity fluctuations are essential to the combustor mixing. The UTSI LV system was also used to examine secondary combustor mixing and a silicone diode array (SiDA) probe was tested for wall temperature monitoring capabilities at the TS1 inlet transition. A significant finding with the CARS experiments was an indication that increases in potassium carbonate solution flow to increase K_2/S produced an increase in particulates and free carbon in the gas stream. This finding is preliminary and is subject to further validation. It will be investigated in future tests if testing plans do not interfere with POC objectives. The SiDA probe measurements compared favorably with simultaneous TS1 line reversal gas measurements about 2m downstream, as shown in Figure 15. More temporally precise measurement correlations are needed to adequately evaluate the SiDA probe, but it appears able to assist in monitoring the TS1 inlet conditions. Successful MSU measurements that are reported elsewhere include surface temperature and emissivity of a candidate high temperature air heater (HTAH) tube, until it fractured, with multi-color pyrometers (MCP) and a visible-infrared emission spectrometer (VIES). MCP's were also used to monitor gas side slag temperatures on heat flux sensors. The MSU particle size distribution (PSD) and two-color laser transmissometer (TCLT) particle diagnostics were used in conjunction with Insitex, Inc. in-situ probes to study DESP particle loadings, size distributions and efficiencies. Details of the MSU measurements are provided in the MSU LMF5-F and LMF5-G post test reports. Details of the Insitex measurements will be provided in their annual report scheduled to be received early in 1993.

FIGURE 15. MSU SiDA Probe Versus TS1 Line Reversal Measurements

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

No activity was planned or carried out during the quarter.

No activity is currently planned for FY92.

TASK 6 - MODIFICATIONS TO THE CFFF

TEST FACILITY MODIFICATIONS/ADDITIONS

High Temperature Air Heater Development

The major activities this quarter were on materials analysis, heat transfer enhancement, and LMF5-G testing (see Figure 16). In addition, a summary report was in process on the results of the tests that involved the Lanxide composite material over the last three years.

Material Analysis

A report involving the analysis of a Lanxide composite specimen that had been exposed to 3000°F gases for 106 hours was completed. The composite is made of silicon carbide particles (45%) in an alumina matrix (45%) and the remainder is aluminum (10%). Analysis of the data concluded that there was no evidence of corrosion, however, there was an increase in porosity. To ensure that UTSI's samples were adequately prepared, the porosity of an as-received sample prepared and polished by Lanxide was compared to a sample prepared and polished by UTSI. The results showed that the Lanxide sample and UTSI's sample were within 0.2%.

Heat Transfer Enhancement

An automatic data acquisition system was incorporated into the heat transfer laboratory set-up. This will greatly increase the productivity of the experimentation and improve the quality of the data. It now should be relatively easy to compare the effectiveness of a variety of heat transfer enhancement devices.

LMF5-G Testing

Two Lanxide DIMOX(TM) tubes were tested this quarter. One DIMOX(TM) tube was tested in the 1632°C (2970°F) zone of the radiant furnace. This tube had previously been exposed 381 hours on coal in two prior LMF5 tests. During the third step setting of the radiant furnace #1 preheat burner, the tube failed and thus only the ends were subject to the 314 additional hours on coal. One of the end pieces was removed after the test and will undergo analysis. The other tube will be left in the furnace until it accumulates 1000 hours on coal. A DIMOX(TM) tube was also tested in the 1871°C (3400°F) zone of the furnace. A piece of the tube that broke-off during the

FIGURE 16. Location of Test Materials During LMF5-G

LMF5-F test (after 479 total coal-on hours) was remounted on the north wall. The tube began the test with a longitudinal crack and photographs taken during the test revealed further deterioration as the test progressed. The sample has now accumulated 797 coal-on hours and it will remain in the furnace until it reaches 1000 hours.

A mullite ($3 \text{ Al}_2\text{O}_3 \cdot 2 \text{ SiO}_2$) tube supplied by Hague International was mounted in the 1371°C (2500°F) gas zone below the secondary combustor. Although the thermocouple inside the tube failed after 15-hours, a nearby thermocouple indicated an average temperature of 1316°C (2400°F). Half the tube was missing after the test. The fracture surfaces indicated the failure was probably from thermal shock or mechanical impact with falling nurdles.

Forecast

The upcoming LMF5-H test will involve the testing of a threaded two-inch OD bayonet DIMOX(TM) tube in the 1926°C (3500°F) zone of the furnace. Pressurized, preheated air will be introduced into the tube. Additional exposure will be given to two DIMOX(TM) specimens that were left in the furnace. Samples from the Babcock & Wilcox Company and Composite Ceramics Incorporated may also be tested.

Convection enhancing techniques will be tested in both the low temperature and high temperature tube furnaces. A three-inch OD DIMOX(TM) bayonet tube with a bonded metal screw-on fitting will be also be tested in the heat transfer laboratory so that an actual HTAH tube can be correlated with the simulated HTAH test apparatus.

A technical paper describing the analysis of the DIMOX(TM) material will be presented at the 17th Annual Conference and Exposition on Composites and Advanced Ceramics in January 1993. Additional materials analysis will continue and the next specimens will be those which were subject to more severe (hotter) testing conditions.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

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

TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES

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

TASK 9 - CFFF PROGRAM MANAGEMENT

MANAGEMENT AND ADMINISTRATIVE SUPPORT

The September 1992 Monthly Contract Status Report was issued to DOE.

The October 1992 Monthly Contract Status Report was issued to DOE.

The November 1992 Monthly Contract Status Report was issued to DOE.

The semi annual property report was issued to DOE.

The draft July-September 1992 MHD Quarterly Technical Progress Report was sent to DOE for review/approval.

The draft FY93 Management Plan was sent to DOE for review/approval.

Modification A098 for incremental funding of the contract was received and processed. This increases the allotted funding by \$1,700,000 through December 31, 1992.

The lease agreement for the DOE CFFF facility site, covering the period January 1, 1993 to December 31, 1993 was sent to DOE/CH.

Per discussions with DOE, a contract extension proposal is being developed for the period April 1, 1993 through March 31, 1994.

The semi-annual precious metals inventory was completed (no change) and a letter report was issued to DOE/CH.

The DOE Environmental Audit Team arrived on-site and the UTSI staff responded to the team's inquiries, presented requested documentation, explained environmental related procedures, and reviewed/discussed/responded to draft audit findings.

REFERENCES

1. Amsden, A.A., et al., 'KIVA-II: A Computer Program for Chemically Reactive Flows with Sprays', LA-11560-MS, Los Alamos National Laboratory.
2. Anon, Steam/Its Generation and Use, 39th Edition, The Babcock and Wilcox Company, Alliance Research Center, Alliance, Ohio (1953).
3. Schulz, R. J., et al., "Application of an Aspirated Thermocouple Probe to High-Temperature, Particle-Laden Exhaust Streams," Proceedings of the Twenty-Ninth Symposium on Engineering Aspects of Magnetohydrodynamics, Baltimore, Maryland, June 1992, pp. XIII.4.1-XIII.4.5.
4. Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations," NASA SP-273, the NASA Lewis Research Center, 1971.
5. Ragland, J. W., McCain, J. D., and Smith, W. B., "Design, Construct, and Test a Field Usable Prototype System for Sizing Particles Smaller than 0.5 Micron Diameter," Draft EPA Contract Report SORI-EAS-78-234, Southern Research Institute, April 1978.

GLOSSARY

AH	• Air Heater
ASTM	• American Society for Testing and Materials
BGC	• Bendix Gas Chromatograph
BH	• Baghouse, particulate capturing device using a fabric type filter bag
B&W	• Babcock & Wilcox
CARS	• Coherent anti-Stokes Raman spectroscopy
OFFF	• Coal Fired Flow Facility
CS(n)	• Cooling Section where n = number of section
CDIF	• Component Development Integration Facility
DOW	• Diagonal Conducting Wall
DDAS	• Digital Data Acquisition System
Diagnostic Channel	• A substitute channel in place of generator channel
DNCF	• Dry Normal (i.e. standard pressure and temperature) cubic foot
Downstream	• From exit of diffuser outlet to stack
DFO	• Diffuser outlet probe
DG	• Data General Computer
ϵ	• Emissivity or velocity fraction
ECF	• Energy Conversion Facility
EFM	• Electric Field Meters
EPRI	• Electrical Power Research Institute
ESP	• Electrostatic Precipitator
EDX	• Energy Dispersive X-ray
Flow Train	• Test facility including all components from the vitiation heater to the stack
GC	• Gas Chromatograph
GC/MS	• Gas Chromatograph/Mass Spectrometer
GIS	• Geographic Information System
HPT	• High Pressure Test
HR/SR	• Heat Recovery/Seed Recovery
HTAH	• High Temperature Air Heater
HVT	• High Velocity Thermocouple
ICAP	• Inductively Coupled Argon Plasma
IMPS	• Intrusive Multi-Probe System
IT	• Inlet Transition
ITAH	• Intermediate Temperature Air Heater
ITC	• Integrated Topping Cycle
LDV	• Laser Doppler Velocimeter
LMF(n)	• Low Mass Flow Test, where n = number of test
LPS	• Light Pipe Sensor
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
PQC	• Perkin Elmer Gas Chromatograph
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
T/C	• Thermocouple
TCLT	• Two Color Laser Transmissometer
TGA	• Thermogravimetric Analyzer
TB(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
WESP	• Wet Electrostatic Precipitator

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