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

**For The Period
October 1, 1993 - December 31, 1993**

June 1994

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

**Prepared for:
The United States Department of Energy**

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

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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 evaluating technology for the Steam Bottoming Cycle Program. The approach taken was to design test components that simulate the most important process variables, such as gas temperature, chemical composition, tube metal temperature, particulate loading, etc., to gain test data needed for scale-up to larger size components.

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

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

ABSTRACT

In this quarterly technical progress report, UTSI reports on progress in developing the technology for the steam bottoming portion of the MHD Steam Combined Cycle power plant.

The experimental program was effectively terminated and reoriented to preparation of reports on previous tests and maintaining the DOE facility. In this report, the results of tube corrosion studies for the samples removed after 500 hours of western coal testing are summarized. Plans for evaluating the tube samples after termination of the tests at 1,047 hours are discussed.

The status of development of models to predict ash deposition on conductive heat transfer tubes and their validation with experimental data is presented. Modeling and experiments to induce agglomeration of particulate are also discussed.

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

- In summary, corrosion measurements on typical, commercial stainless steels and on low and intermediate chromium steels after 639 hours of LMF5 exposure in the SHTM test sections revealed corrosion that was generally acceptable in magnitude if corrosion kinetics are parabolic, but, except for the higher chromium alloys 253MA and 310, not if kinetics are linear. The production of bilayer scales, and the large amount of scale separation and fragmentation make long term parabolic kinetics unlikely, and result in a high likelihood for breakaway corrosion.

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.....	6
DATA ACQUISITION SYSTEMS.....	6
ENVIRONMENTAL AND ANALYTICAL SERVICES	7
ENVIRONMENTAL MONITORING.....	7
Water Quality	7
Ambient Air Monitoring.....	7
Groundwater Monitoring	8
TASK 4 - OPERATION AT 8 LB/SEC TOTAL GAS FLOW HIGH SLAG THROUGHPUT TEST	8
TESTING.....	8
DOWNSTREAM COMPONENT SYSTEMS.....	9
Superheater Test Module (SHTM) Gas-Side Tube Corrosion.....	9
Pollution Control	19
CFFF Mass Balance, CFFF Data Reduction, Chemical Analysis Database.....	19
Ash Deposition.....	20
High Temperature Air Heater Materials Evaluation	21
ADVANCED MEASUREMENT SYSTEMS	23
TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS	25
TASK 6 - MODIFICATIONS/ADDITIONS TO THE CFFF	28

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM	28
TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES	28
TASK 9 - CFFF PROGRAM MANAGEMENT	28
MANAGEMENT AND ADMINISTRATIVE SUPPORT	28
REFERENCES	29
GLOSSARY	30
MAILING LIST FOR FINAL DISTRIBUTION OF REPORTS.....	31

FIGURES

1. Scheduled Tasks	4
2. CFFF Integrated MHD Bottoming Cycle Schematic.....	5
3. Wall Loss of LMF5 639 Hour Exposed TS1 and TS2 Tubes	12
4. Wall Loss of LMF5 639 Hour Exposed TS3 Tubes	13
5. Corrosion Scale Thickness and Penetration Depth for LMF5 639 Hour Exposed TS1 and TS2 Tubes.....	14
6. Corrosion Scale Thickness and Penetration Depth for LMF5 639 Hour Exposed TS1 and TS2 Tubes (all data for each alloy averaged over each test section)	15
7. Corrosion Scale Thickness and Penetration for LMF5 639 Hour Exposed TS3 Tubes	17
8. Corrosion Scale Thickness and Penetration Depth for LMF5 639 Hour Exposed TS3 Tubes (all data for each alloy averaged together).....	18
9. Location of Lanxide Materials During LMF5-J	22
10. Particle Temperature Versus Size Downstream of the SHTM Entrance	24
11. Predicted Particle Size Distribution Evolution	24
12. Predicted Effect of Adding Agglomeration Nuclei	26
13. Predicted Effect of Adding Polydisperse Nuclei	26
14. Variation of Agglomeration with Increased Nuclei Loading.....	27
15. Summary of Experimental Agglomeration Effects	27

TABLES

1. CFFF Test Series	8
2. Sample Alloys and Locations	10
3. Typical LMF5 Test Section Tube Temperatures at Corrosion Sampling Locations, °F	10

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 381 hours of long-duration, proof-of-concept (POC) testing on western coal was achieved during FY92 and 666 POC hours for FY93 for a total of 1047 POC hours on western coal. 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.

A Busek Company MHD generator test module was installed in the CFFF upstream flow train during the LMF5-J test to gather data for materials evaluation. The unit and data were to be returned to Busek for evaluation.

TASK 6 - MODIFICATIONS TO THE CFFF

All major test components of the downstream subsystem (radiant boiler, secondary combustor, superheater, air heater, baghouse, wet and dry electrostatic precipitators, auto ash/seed handling system and modified coal processing system) have been installed and checked-out. For the FY93 period a major program goal was to deal with the modification or replacement of components in the CFFF and test train as the need arises in order to fulfill the objectives for the long-duration, proof-of-concept testing on western coal.

Modifications/additions in the CFFF were the following:

- Modifications to the facility systems to process western coal included: the EL modification to the E-35 pulverizer needed for higher primary gas temperatures required for drying a higher moisture coal; a direct-contact water-cooled packed column condenser system to remove moisture (down to a 90°F dew point) from the process gas exiting the baghouse and prior to the blower; a process blower required for higher flow and pressure-drop conditions (30,000 lb/hr at 5 psig pressure-drop); an indirect-fired air heater which heats to a higher flow and temperature condition; ducting required for connecting the baghouse exhaust to the condenser inlet; various control valves, pressure transducers, thermocouples, gas analyzers, etc. required to control the system at desired setpoints.
- 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, was continued during FY93 with the evaluation of test specimens for tube construction with promising composite materials.

- The addition of a wet electrostatic precipitator and rotary drum vacuum capable of recovering potassium sulfate and potassium carbonate separately was installed and used during FY93 tests.
- A separate liquid seed injection system to inject K_2CO_3 and K_2SO_4 directly into the combustor as opposed to adding seed to the coal during pulverization was developed and installed in FY92. This system allows for a significant improvement in the control of the amount of seed added to the coal during combustion. This system was utilized for the FY93 POC test series.

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 for FY94.

TASK 8 - TEST INTEGRATION AND INTERFACE

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

TASK 9 - PROGRAM MANAGEMENT

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

CFFF PROGRAM GOALS AND SCHEDULE

Figure 1 shows the major scheduled program tasks completed during the October through December 1993 period.

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FIGURE 1. SCHEDULED TASKS

SECTION II

SUMMARY OF TECHNICAL PROGRESS

This section addresses the technical progress of work conducted during the period October 1 through December 31, 1993, according to the objectives and scope of work tasks outlined in Section I. Tasks 1 and 2 are completed and no further effort is being expended in these areas. Figure 2 is a schematic of the current LMF test train.

FIGURE 2. CFFF Integrated MHD Bottoming Cycle Schematic

TASK 3 - BASE OPERATIONS FOR THE CFFF

FACILITIES OPERATION, MAINTENANCE, AND REPAIR

The major activities this quarter were cleanup, winterization, and facility maintenance and repairs.

The Busek ceramic module installed in place of CD-1 was removed after the LMF5-J test and packed and shipped.

Clean-out of the superheater, baghouse, wet and dry electrostatic precipitators (ESP) and densevayor systems was completed and the ash was hauled to the landfill.

Winterizing of the facility cooling water systems, coal tower condenser system, rotary vacuum filter and wet ESP was completed this quarter.

The following maintenance and repairs were completed:

- Completed fabrication, welding, and installing new stairway for superheater.
- Installed tramp metal magnet in coal weigh feeder.
- Repaired broken potable water main.
- Completed installation of water regulator and manifold for potable water system main.
- Fabricated metal top for potable water pit.
- Completed repairs to slag screw conveyor.
- Repaired diesel fire pump fuel injector pump and recalibrated pump.
- Repaired instrument air dryer.
- Started repairs to coal pit sump pumps.

A study of facility electric heating requirements was conducted. As a result of the study, we were able to cancel supplemental power requirements until ambient temperature drops below 20°F.

TEST CONTROL AND SUPPORT

The major activities this quarter were devoted to post-test (LMF5-J) activities, improvements in instrumentation and data requirements documentation, and revision of the CFFF computerized Preventative Maintenance Schedules.

After completion of the LMF5-J test, port opening times were compiled from port logs and official oil and coal times were tabulated and published. Runlog and test data were reviewed for discrepancies and were being corrected.

Streamlining of the CFFF computerized maintenance program was begun. Maintenance frequencies were revised due to reduced staffing. The CFFF preventative maintenance database was revised to reflect these schedule changes. In some instances maintenance cards were combined to reduce paperwork.

Development of a CFFF data system setup file maintenance program was completed this quarter. This program reduces the amount of time required to provide hard copy documentation of all modifications made to data channel parameters and operational limits.

DATA ACQUISITION SYSTEMS

Activities for this quarter included support of LMF5-J post test activities, checking calibration and storage of outside transducers, and repair and maintenance of electrical equipment.

All test instrumentation, data acquisition, and electrical equipment installed for the Busek channel was restored to the normal CFFF configuration. Data listing and summary tapes of the LMF5-J test data were produced.

Calibration of the data system was 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 potential new test requirements and hardware changes were accomplished. Also this quarter, development of an Ethernet driver for PC to Data General communication was begun.

The following additional electrical maintenance items were accomplished:

- Repaired emergency lights.
- Repaired faulty building lighting.
- Installed emergency and building lights in warehouse.

ENVIRONMENTAL AND ANALYTICAL SERVICES

During this quarter, the chemistry laboratory continued the analysis of the LMF5 test samples. Ambient water sampling was suspended during this quarter due to manpower and budgetary constraints. Water sampling is planned to be reinitiated during the next quarter. The Perkin-Elmer 240B Elemental Analyzer and the Digital Beam interface on the Scanning Electron Microscope (SEM) are inoperative and were not repaired because of budget constraints. A significant reduction in force has substantially reduced efforts in these areas.

The National Pollutant Discharge Elimination System (NPDES) permit was maintained on a monthly basis with no reportable excursions.

ENVIRONMENTAL MONITORING

Water Quality

Collection and analysis of lake water samples were suspended temporarily due to manpower limitations. Holding pond effluent and treatment as necessary to maintain effluent within permit limits were continued.

Ambient Air Monitoring

Impact I monitoring station was shutdown and sensitive instrumentation was removed. Electrical service for both Impact I and the Base Monitoring site have been disconnected. Particulate sampling equipment from various locations were removed and stored within the Impact II monitoring site enclosure. The compiling of existing ambient air data and calibration records was continued.

Participated in the quarterly Quality Assurance audit by the State of Tennessee.

Groundwater Monitoring

Completed water level measurements for all 8 wells on a monthly schedule. Met with representatives of a consulting firm, employed by the University which were on-site touring the wells and exchanging information. All activities with regard to the groundwater program have been suspended until the consulting firm has developed a plan of action and determined what, if any, remediation steps are necessary to comply with the pertinent State of Tennessee directive.

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

TESTING

Table 1 shows the CFFF testing completed through September 1993. No testing in the CFFF is scheduled for FY94.

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
*POC-LMF5-H	04-93	88
*POC-LMF5-I	07-93	212
*POC-LMF5-J	09-93	52
TOTAL		3697 **

* Proof-of-Concept

** Total test train operation time to date on coal is 3697 hours

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

(Total test train operation on western coal is 1271 hours to date of which 1047 hours are POC.)

(Total test train operation time to date is 4049 hours (including operation of the vitiation heater).)

DOWNSTREAM COMPONENT SYSTEMS

Data analysis and reporting on POC tests were continued during this period. A substantial reduction in personnel was implemented this quarter including leaders of some projects or identifiable subprojects. These responsibilities were reassigned to remaining personnel. A Test Summary Report for the LMF5-J was being prepared and will be issued next quarter.

Superheater Test Module (SHTM) Gas-Side Tube Corrosion

Corrosion evaluations were completed on tubes from the test sections (TS) of the Superheater Test Module (SHTM) after an accumulated test exposure of 639 hours to fireside conditions representative of those in MHD secondary and primary superheaters, reheater, and the intermediate temperature air heater (ITAH). Results showed that corrosion was generally acceptable in magnitude if corrosion kinetics are parabolic, except for the higher chromium alloys 253 MA and 310, but not if kinetics are linear. However, the production of bilayer scales, and the large amount of scale separation and fragmentation make long term parabolic kinetics unlikely, and result in a high likelihood for breakaway corrosion. Future corrosion evaluations will concentrate on wall loss measurements, as a result of the demonstrated problem of using scaling and penetration data, because of scale spalling.

Initial plans called for evaluations at 500, 1500, and 2000 hours. Since 500 accumulated hours occurred during the midst of a lengthy test run, sample sections were removed from the tubes following that test for evaluation. The sample alloys and locations are given in Table 2. In most cases, two sample sections, 6 inches apart, were examined at each position indicated.

Sample locations for TS1 and TS2 near the bottom of the second tube pass corresponded to typical steady state tube metal temperatures ranging from approximately 900°F to 1135°F, as detailed in Table 3. For the most part, the temperatures were near the upper end of the expected range for secondary superheater or reheater service, but well below the peak ITAH temperatures of around 1400°F. Samples at higher metal temperatures from the hot end of the first tube pass were not taken because to do so would have necessitated cutting through thermocouple leads and replacing the thermocouples. The handling, grinding and welding operations required for their replacement would have altered tube surfaces and the course of corrosion.

Three types of corrosion determinations were made, all from microscopic observation of polished tube cross-sections: 1) measurement of wall thinning with respect to pre-exposure ultrasonic wall thickness measurements, 2) measurement of corrosion scale thickness and metal penetration depth, which singly or in combination were used as a measure of corrosion extent, and 3) morphological characterization of corrosion scale, metal penetration, and scale/deposit interactions. Since each sample section was further cut, dividing it into four quadrants constituting the leading, left, trailing, and right sides, a total of 181 samples were examined microscopically.

TABLE 2. Sample Alloys and Locations

TS	Tube	Pass	Elevation	Alloy	TS	Tube	Pass	Elevation	Alloy
1,2	1	2	Bottom	316	3	5	1	Middle	T9
1,2	2	2	Bottom	253MA	3	6	1	Middle	T22
1,2	3	2	Bottom	347H	3	7	3	Middle	T11
1,2	4	2	Bottom	304H	3	8	1	Middle	304H
1,2	5	2	Bottom	310	3	8	4	Bottom	SA192

TABLE 3. Typical LMF5 Test Section Tube Temperatures at Corrosion Sampling Locations, °F

Tube Number	TS1		TS2		TS3 Leading Edge		
	Leading Edge	Trailing Edge	Leading Edge	Trailing Edge	Elevation	Pass	°F
1	902	968	1006	1069	middle	1	987
2	940	975	1018	1091	middle	3	878
3	1043	1008	1033	1117	bottom	4	822
4,5	1072	1013	1042	1133			

Wall loss results for TS1 and TS2 tube samples are given in Figure 3. The plots are of wall loss in mils versus angular degrees from the leading edge. No trend with respect to angular position was evident. A high level of scatter was exhibited with some large loss values, particularly for the 253MA and 310 alloys, which should have been, and in fact were from microscopic observation, the most corrosion resistant. This behavior is attributed to the fact that the 253MA and 310 were actually pipe with quite large variations in original wall thickness, particularly with respect to angular position. Thus, even rather minor differences between initial and final measurement positions could account for the indicated, but erroneous, large losses for 253MA and 310. This problem was more acute for 253MA, which was smaller diameter pipe (1.315 inch OD, as opposed to 1.66 inch for 310). In addition to mislocation, the error could partially stem from the relatively large ultrasonic transducer size (0.25 inch). That is, the ultrasonic transducer reading was an average over some sizable area, whereas the final microscopic measurement was at one discrete point. Ultrasonic TS2 data for alloy 347 was found to be obviously and greatly in error. Also, a small error from some source existed in results for TS1 alloy 347, since the average indication is a small increase in wall thickness. Average losses for alloy 316 was 3.2 mils at TS1 and 2.7 mils at TS2. For linear kinetics, these correspond to 44 mils/yr and 37 mils/yr, respectively, while for parabolic kinetics, they would be 12 mils/yr and 10 mils/yr, respectively. Average losses for alloy 304H were 1.7 mils at TS1 and 0.7 mils at TS2. For linear kinetics, those correspond to 23 mils/yr and 10 mils/yr, respectively, while for parabolic kinetics, they would be 6 mils/yr and 3 mils/yr, respectively. As for the LMF4 corrosion test program, losses in excess of 20 mils per year were considered to be unacceptable. However, it must be recognized that these values, based on such a short exposure time, even if obtained by perfectly accurate measurements, may not be entirely valid for long term service, because an initial corrosion incubation period often exists during which the rate behavior is different than subsequently.

Figure 4 gives the wall loss results for three tube alloys, T9, T22, and 304H in TS3, for which losses averaged 8.2 mils, 2.2 mils, and 0.0 mils, respectively. All samples were from the middle of the first and hottest tube pass with a typical temperature of around 1000°F. In terms of linear kinetics, these average measured losses corresponded to 112 mils/yr for T9, 30 mils/yr for T22, and 0 mils/yr for 304H, while in terms of parabolic kinetics, they were 30, 8, and 0 mils/yr, respectively. The poorer performance indicated for T9 compared to T22, despite its higher chromium content, is in keeping with their typical relative performance observed in conventional pulverized-coal-fired ash corrosion. Wall loss data (typified by 304H) show less corrosion with decreased gas temperature and heat flux, in going from TS1 to TS3. T22 at TS3 showed similar or less wall loss than 316 at TS1 and TS2, at similar metal temperatures, but much lower heat fluxes.

Corrosion scale thickness and penetration depth data for TS1 and TS2 tube samples are given in Figure 5. Corrosion scale thicknesses are given for both the fireside and for the steamside. Figure 6 shows the same results but with all data for each alloy and for a given test section averaged together. Four conclusions are

FIGURE 3. Wall Loss of LMF5 639 Hour Exposed TS1 and TS2 Tubes

FIGURE 4. Wall Loss of LMF5 639 Hour Exposed TS3 Tubes

FIGURE 5. Corrosion Scale Thickness and Penetration Depth for LMF5 639 Hour Exposed TS1 and TS2 Tubes

FIGURE 6. Corrosion Scale Thickness and Penetration Depth for LMF5 639 Hour Exposed TS1 and TS2 Tubes (all data for each alloy averaged over each test section)

apparent from the plots. 1) As, with the wall loss data, no dependence of scaling or penetration on angular position around the tubes was seen. 2) Indicated fireside scaling, steamside scaling, and penetration were all generally less for TS1 than for TS2, just the opposite of the trend indicated by wall loss. Alloy 310 is the exception, indicated corrosion being similar for both sections. The lower TS1 indicated scale thicknesses are explained on the basis of more scale spalling at TS1 caused by greater thermal stresses and weaker scales due to more aggressive corrosion. Less TS1 penetration is explained by the fact that scale spallation actually inhibits internal penetration, because the replacement scale grown is a lower chromium-content, thicker scale through which outward cation diffusion is greater than for the initial high chromia scale, and inward anion (oxygen and sulfur) diffusion is less. Thus, corrosion is believed to be, in fact, greater at higher gas temperatures and heat fluxes, as indicated by the wall loss data. The high incidence of scale spallation makes the use of scale thickness and penetration depth of little direct value as indicators of corrosion extent. 3) The indicated steamside scale thickness was in most cases greater than the fireside scale thickness. This was partly due to greater fireside scale spallation. However, the high oxygen content of the steam from the open loop package boiler steam supply system would be expected to produce rather heavy oxidation. 4) For TS2 with better results due to less scale spalling, a general trend was shown of less scaling and penetration as the alloy chromium content increased from left to right on the plots. Alloy 347, however, because of its niobium content which contributes to a more adherent, protective scale, performed better than the other 18-8 stainless samples, in keeping with conventional coal-ash corrosion behavior.

Corrosion scale thickness and penetration depth for TS3 alloys are shown in Figures 7 and 8. Again, no angular position dependence was evident. Some penetration was found for most of the material, although for the ferritic alloys it was of a pitting type. For the three alloys, T22, T9, and 304H, at the highest metal temperature, linear corrosion rates based on the sum of scale thickness and penetration depth were 47, 50, and 7 mils/yr, respectively. Corresponding parabolic corrosion rates were 13, 14, and 2 mils/yr. Thus, the data indicated that neither T22 or T9 at 1000°F would meet a 20 mil/yr criterion with linear kinetics, but both would meet it if parabolic kinetics applied. Alloy 304H would easily meet the criterion by either kinetics. As at TS1 and TS2, the large steamside scale thicknesses relative to fireside scale thicknesses indicated either highly oxidizing steamside conditions, or spalling loss of fireside scale, or both.

Microscopic inspection revealed that the 18-8 stainless steel alloys generally possessed bilayer scales with much separation between layers as well as much fragmentation. The inner scale would be spinel and the outer scale iron oxide with little chromium. Such a scale develops when the surface chromium content is insufficient to develop a high chromium oxide scale or when sulfur makes the scale porous and relatively unprotective against outward cation diffusion. The tendency of these scales to spallation and fragmentation produces a high likelihood of breakaway attack when chromium has been locally depleted by repeated regrowth of spalled scales. Cases were found where such breakaway already appeared in progress in

FIGURE 7. Corrosion Scale Thickness and Penetration for LMF5 639 Hour Exposed TS3 Tubes

FIGURE 8. Corrosion Scale Thickness and Penetration Depth for LMF5 639 Hour Exposed TS3 Tubes (all data for each alloy averaged together)

that thick scales had formed of the same sort normally associated with low chromium steels. In those locations, the inner scale contained considerable sulfide, and the outer scale layer was quite thick and had grown outward incorporating flyash and usually had been partially dissolved and reprecipitated in the deposit. Internal penetration of the 18-8 alloys was both intergranular and transgranular, normally of a depth of less than one grain diameter. Alloy 253MA had a thin scale which was variably one or two layers, again with much fragmentation. Alloy 310's scale was very thin and generally single layered. Scale characteristics of the low chromium steels were similar, there being three layers, an inner dense one, a middle very porous one with embedded ash spheres and both sulfides and iron sulfate, and an outer, relatively thin and dense layer. The T11 alloy's scale thickness was less uniform, there being many relatively thick or deep inward protrusions. SA-192 carbon steel's scales were largely missing due to spallation.

In summary, corrosion measurements on typical, commercial stainless steels and on low and intermediate chromium steels after 639 hours of LMF5 exposure in the SHTM test sections revealed corrosion that was generally acceptable in magnitude if corrosion kinetics are parabolic, but, except for the higher chromium alloys 253MA and 310, not if kinetics are linear. The production of bilayer scales, and the large amount of scale separation and fragmentation make long term parabolic kinetics unlikely, and result in a high likelihood for breakaway corrosion.

A plan was devised for corrosion evaluation of the test section tubes removed after the LMF5-J test with close to 1000 hours exposure. The evaluation will concentrate on wall loss measurements as a result of the demonstrated problem of using scaling and penetration data because of scale spalling. Wall loss measurements will be made at eight angular positions around the tube and at one foot intervals along the tube. One or more microscopic sections will be prepared from each tube pass to determine retained scale thickness, penetration depth, and corrosion morphology. The marking of tubes for cutting was started and the actual cutting will be performed next quarter.

Pollution Control

The initial draft of the topical report on the dry electrostatic precipitator testing experience during Illinois #6 coal testing was completed and will be issued next quarter.

CFFF Mass Balance, CFFF Data Reduction & Chemical Analysis Database

Due to staff reduction, reassignment of this work will be made and the effort continued as appropriate.

Ash Deposition

Work continued at a reduced rate in the modeling effort due to staff reductions.

Work continued on the development of the overall analytical model, "AshEffects," for evaluating and predicting the effects of fireside ash deposits on superheater tubes. When completed, this engineering model could provide a tool for generating very useful predictive information for performance of specific commercial superheater designs and for scale-up of CFFF test data. Both mass and heat transfer will be considered as a function of deposition time.

Work continued on the development of the finite-element control-volume mesh and on adding the calculation of heat transfer to the computerized deposition model. A simplified trial-calculation of real-time heat-transfer effects compared very favorably with measured data for alumina particles that were injected and deposited on a superheater tube during previous natural-gas-fired tests in the DOE/PETC state-of-the-art Fuels Evaluation Facility. The first 2-D output of elemental composition was obtained this quarter. It showed compositional gradients for individual elemental oxides as a function of deposition time steps for the mass-transfer mechanism of inertial impaction. This new capability would permit future calculations of local slag-viscosity distributions and, in turn, tracking development of local particle-to-particle ash-bonding strength via the mechanism of viscous-flow sintering. The calculation capability additions made also included evaluation of local staying probabilities (deceleration and capture) for particles in individual particle-diameter bins for the mass-transfer mechanism of inertial impaction. Probabilities were calculated for individual ash particles staying after contact either with a clean superheater tube or with the surface of a fireside deposit.

Other work this period involved evaluating fire-side deposits as they formed on a rotatable superheater ash deposition probe (ADP) in the LMF5-J test during two six-hour periods following sootblowing. Dimensions of deposit thickness and width were obtained using computer image-analysis to measure video-taped images. A report was issued covering the results of image analysis.

Work also continued on measuring sintered bond strength (via cold crushing strength) of ash particles after sintering in a laboratory furnace for a controlled time/temperature period. Sintering tests have been completed at 1400, 1500, 1600, 1700 and 1800°F. The average number of specimens was four (4) per temperature level, and all data were within +/- 1.5 standard deviations. Sintering strength increased at higher sintering temperatures. As sintering temperature was increased in an air atmosphere, the outside surfaces of the cylindrical fly-ash specimens from Rosebud-fired tests developed colors, ranging from light green at lower temperatures to dark blue at the higher temperatures. The darkest colors occurred at the highest temperatures. Examination of sintered fly ash particle-to-particle bonds also continued using scanning electron microscope (SEM)/computer-image-analysis.

Next quarter's activities will be limited due to staff reductions. The two-dimensional finite-element code will not be completed. Some areas of the code that will be incomplete include items such as small-particle thermophoresis, vapor condensation on the fireside surface of superheater tubes, associated heat-transfer effects, sintered bond-strength correlations, sootblower effectiveness, deposit sintering/densification/thermal-conductivity/emissivity effects, and input/output capabilities.

High Temperature Air Heater Materials Evaluation

Analysis of the results of the LMF5-J test was continued this quarter. There were three secondary objectives for the test. These objectives are stated below with the results following.

1. Test two HTAH sealing techniques (based on a compression fitting) in the 3600°F zone of the furnace.

A compression fitting on the open end of a closed end Lanxide tube was coupled to a U tube to indicate volume changes and thus leakage. After small leaks at the various fittings were eliminated, the sealing system withstood a pressure of 212 PSIG for one hour with no measurable leakage. After the test, the sealing assembly was submerged in water while pressurized to 110 PSIG. Two extremely small air streams were noted in the water. One was coming from the seal area and the other from the end of the tube. Although the assembly was water tested prior to the test, the leaks noted during the post-test check were so small that they could have been present but unnoticed during the pre-test water check.

This technique would be suitable for industrial applications and additional testing should be conducted to develop the technology.

2. Test a HTAH sealing technique based on a flared flange in the 3000°F zone of the furnace.

The flared fitting was tested cold at 100 psig with no noticeable leakage. The entire fitting and flange assembly was then screwed on at the furnace port, but the tube was eccentric, so that as it was turned it rubbed against the side of the opposite port. Although it was being turned slowly and carefully, there was too much stress caused by this contact and the tube cracked at its base. The base of the tube was then cut off and the remainder of the closed end tube was fitted with a compression fitting. The compression fitting was tested in water and showed negligible leakage. There was a small leak during the test, however, since sealed tube assembly could only maintain a pressure for a few hours.

3. Test up to five Lanxide tubes for corrosion in various locations in the furnace and below the secondary combustor. (Figure 9).

FIGURE 9. Location of Lanxide Materials During LMF5-J

These tubes were tested in support of a DOE grant concerning the evaluation of the Lanxide material in a coal slag environment. The tubes survived intact and they will be analyzed under funding from the grant. Continual video coverage was obtained on the bottom tube (T-1) which documented buildup of slag on the tube surface. The tubes temperatures were as follows:

1399°C (2550°F)
1260°C (2300°F)
1093°C (2000°F)

1093°C (2000°F)
1149°C (2100°F)

ADVANCED MEASUREMENT SYSTEMS

The preliminary modeling of particulate evolution for gas cooling typical of the CFFF superheater and air heater components was completed this quarter. The model was developed to identify and evaluate potential particulate agglomeration enhancement mechanisms that might be employed to modify the particulate size distribution at the entrance to the particulate cleanup devices. These devices, the dry and wet electrostatic precipitators (ESP) and the baghouse (BH), will operate more efficiently under standard CFFF operating conditions if the entering particulate size distribution has a significantly reduced submicron particulate content. Effective agglomeration of submicron particles will reduce the submicron particulate content and will also reduce the particulate loading entering the particulate cleanup devices. The particulate evolution model considered condensation, nucleation, and thermophoresis, typically the major coagulation mechanisms for this type of gradually cooling particle laden flow. The CFFF, after the secondary combustor, was simply modeled as a gas at typical CFFF downstream velocities and average cooling rate, without accounting for particulate size distribution changes from adhesion and shearing of particles off heat exchanger surfaces. The particles forming in the gas stream were assumed to be at the gas temperature when formed near the secondary combustor, and to cool by radiation to the cooler walls while being heated by convection from the hot gas. This leads to the particle temperature versus size distribution shown in Figure 10 for conditions downstream of the superheater test module (SHTM) entrance. This variation of particle temperature with size will drive agglomeration by thermophoresis, and the agglomeration model indicated thermophoresis was an influential agglomeration mechanism.

The model was used to predict the growth of particles in the CFFF flowtrain after the gas begins to cool following secondary combustion. An initial secondary combustor particulate size distribution as theoretically predicted for an MHD system by K. H. Im and P. M. Chung¹ was used, with adjustments for coal loading, flow velocity and flow train structure by fitting the very limited 5 stage cyclone secondary combustor data. Better measurements of the initial distribution (which aren't influenced by sampling system condensation as are the secondary combustor 5 stage cyclone data) are needed to improve the model dependability. Figure 11 shows the model predictions for temporal changes in the particulate size distribution assuming new

FIGURE 10. Particle Temperature vs. Size Downstream of the SHTM Entrance

FIGURE 11. Predicted Particle Size Distribution Evolution

submicron particles don't appear through condensation, nucleation and other mechanisms. The initial distribution is the $t = 0$ data, the evolution after 0.5s and 1.0s are also presented in Figure 11. The standard particle size distribution presentation for linear-linear plots (normalizing the ordinate with μm to correct for non-uniform bin widths) is used.

The model allowed for the addition of particles as nuclei for enhanced agglomeration and a parametric study of the effects of injecting different size particles with different velocities and loadings was completed. As shown in Figure 12, injecting different size nuclei does modify the final particle loading, with smaller nuclei appearing to have the greatest effect. This apparent nuclei size effect is mostly a nuclei loading effect, as shown when nuclei number count was held constant, instead of nuclei mass flux as associated with Figure 12. The greatest effect found was the effect of nuclei loading.

The model was also used to study the effect of injection of polydisperse nuclei as shown in Figure 13. Nuclei injection obviously promotes agglomeration of the submicron particles. Again, increasing the loading of the nuclei increases the submicron particulate agglomeration as illustrated in Figure 14. This model, with preliminary calculations, led to the recent agglomeration experiments during the LMF5 testing, and those experimental results shown in Figure 15 provided partial validation of the model. Figure 15 shows 5 stage cyclone data acquired during four different test periods at the particle removal systems entrance for no nuclei injection and for nuclei injection. Ash extracted from the particle removal systems was injected at a low mass flow rate as the nuclei. Model data is not compared with these experimental results since the model complexity is currently insufficient to handle interaction of the nuclei with the CFFF mechanical hardware. More data will be needed for complete validation of the model and inclusion of particle agglomeration, shattering, etc. induced by the superheater and airheater tubes and walls need to be included in the model. Attempts to experimentally verify the influence of nuclei loading on agglomeration during the LMF5 testing were unsuccessful due to unsatisfactory operation of the particle sample extraction/dilution system (SEDS) being developed for the CFFF. Analysis of this instrumentation indicates that insufficient extraction vacuum as well as high particle adhesion effects with the MHD ash kept the current version of the sample extraction/dilution system (SEDS) from operating properly.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

The Busek Company generator module tested in the CFFF flow train during the LMF5-J test was removed and returned to Busek. Data collected during the test and UTSI's technical comments were also forwarded.

No other work was planned under this task in FY94.

FIGURE 12. Predicted Effect of Adding Agglomeration Nuclei

FIGURE 13. Predicted Effect of Adding Polydisperse Nuclei

FIGURE 14. Variation of Agglomeration with Increased Nuclei Loading

FIGURE 15. Summary of Experimental Agglomeration Effects

TASK 6 - MODIFICATIONS/ADDITIONS TO THE CFFF

No activities were planned for this task during FY94.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

No activities were planned or carried out this period.

TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES

Dr. Joel W. Muehlhauser, Program Administrator, visited DOE/PETC to discuss program activities and funding requirements.

TASK 9 - CFFF PROGRAM MANAGEMENT

MANAGEMENT AND ADMINISTRATIVE SUPPORT

In accordance with reduced budget allocations from DOE, staffing on the MHD contract was assessed for downsizing and the announcement of a major reduction in personnel to be effective on November 30, 1993 was made.

The draft FY94 Management Plan incorporating a downsizing of work and staffing was issued to DOE/CH. It reflected a total budget of \$2.2 M (based on an estimated 1.8 M in FY94 funding plus \$400K in carryover funds) for the 12-month period.

The September 1993, October 1993 and November 1993 Monthly Contract Status Reports were issued this period to DOE/CH.

The July-September 1993 draft Quarterly Technical Progress Report was issued.

The Annual Government Property Inventory Report was completed and sent to DOE.

The renewed UT-DOE lease agreement for the period January 1 - December 31, 1994, was signed and sent to DOE for signature.

The semi-annual and annual Small Business Subcontracting reports were completed and sent to DOE.

REFERENCES

1. Im, K. H. and Chung, P. M., "Nucleation and Evolution of Slag Droplets in Coal Combustion," *AIChE Journal*, July 1980.

GLOSSARY

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

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