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

**For The Period
January 1, 1993 - March 31, 1993**

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

**Prepared for:
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**Prepared by:
The University of Tennessee
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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 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 cycle of the coal-fired MHD Steam Combined Cycle Power Plant. During this period, no testing was scheduled in the DOE Coal-Fired Flow Facility. The report covers facilities modification and maintenance in preparation for a 225 hour POC test that is scheduled for early next quarter. The modifications to the dry ESP to replace the electrodes with smaller diameter wires is discussed. Continued work on the rotary vacuum filter, which is designed to separate the more soluble potassium carbonate from the potassium sulfate and fly ash, is reported.

Environmental activities for the quarter are summarized. A report of the performance of advanced diagnostics, furnished by both UTSI and Mississippi State University (MSU), is included. Completion and reporting of the analyses of the candidate tube materials that were exposed in the superheater test module (SHTM) to 500, 1500 and 2000 hours of eastern coal-fired operation is discussed. Removal of samples from the material test sections for analysis after 695 hours of western coal firing is summarized. Plans for a laboratory investigation into the effect of potassium on secondary combustor ignition are detailed. Preparations and plans for the next POC test in the CFFF are described.

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

- **To insure continued compliance with environmental and safety requirements, several modifications in the CFFF were accomplished. Secondary containment basins were installed in the air compressor room and beneath the used oil tank. In addition, back flow prevention devices were installed on potable water lines in the test building, control building, and cryogenic steam vats. All inside potable water hose connections in the test building and control building were also fitted with back flow prevention devices. Run logs were placed in each of the boiler rooms to insure that an accurate record of boiler run time is maintained. To insure safe lifting operations, all lifting devices (chain falls, wire ropes, slings, etc.) were sent to a qualified outside facility for inspection, testing and repair as necessary.**
- **Higher and more effective current was obtained by decreasing wire size in the dry ESP down to approximately 1/8" dia. round. This modification should result in increased current, improving overall unit performance.**

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SECTION I

OBJECTIVE AND SCOPE OF WORK

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

The specific objectives of the DOE Coal-Fired Flow Facility (CFFF) are to resolve experimentally and analytically the key technical areas of concern which have been identified or which may be found to occur in direct coal-fired MHD systems with moderate to high ash carryover. The key areas involve (1) combustor performance, (2) ash/seed particle collection efficiency from the exhaust gas stream, (3) effects of plugging, fouling and corrosion during normal operation, (4) performance of candidate materials in a direct coal fired MHD environment and (5) the operation, conditions, procedures and equipment needed to meet pollution control requirements.

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

TASK 1 - CONSTRUCTION OF THE CFFF

This task was completed under a prior contract.

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

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

TASK 3 - BASE OPERATIONS FOR THE CFFF

Provides for the operation of the CFFF and supporting laboratories and services which, in addition to management of the facility organization, 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. The latter item is the main reason for this procurement.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

Provides for additional technology development services on a task order basis as approved by DOE. No specific activity was scheduled during 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. 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 January through March 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 January 1 through March 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.

TASK 3 - BASE OPERATIONS FOR THE CFFF

FACILITIES OPERATION, MAINTENANCE, AND REPAIR

Repairs to the raw coal bucket elevator which failed during the LMF5-G test were completed. To accomplish the repairs, a work platform was fabricated and installed around the coal auger. Buckets were replaced or straightened as required. Bearings and adjusters were also checked and replaced as necessary.

Repairs and additional modifications to the wet ESP rotary vacuum filter continued. An ash discharge chute for the filter was fabricated and installed. The filter was operated for 12 hours to clean some of the liquid (potassium solution) stored in the cyclone tank from the prior test. Final modifications to the wet ESP/rotary vacuum filter effluent processing system piping and valves were in progress.

Test train modifications and repairs also were accomplished. A stainless steel lining was installed in the vitiation heater coal tube penetration. A new coal tube was fabricated and installed in the modified penetration. The disperser plate was removed and hydro-tested. Repairs to disperser plate water passages were in progress.

To insure continued compliance with environmental and safety requirements, several modifications in the CFFF were accomplished. Secondary containment basins were installed in the air compressor room and beneath the used oil tank. In addition, back flow prevention devices were installed on potable water lines in the test building, control building, and cryogenic steam vats. All inside potable water hose connections in the test building and control building were also fitted with back flow prevention devices. Run logs were placed in each of the boiler rooms to insure that an accurate record of boiler run time is maintained. To insure safe lifting operations, all lifting devices (chain falls, wire ropes, slings, etc.) were sent to a qualified outside facility for inspection, testing and repair as necessary.

FIGURE 2. CFFF Integrated MHD Bottoming Cycle Schematic

The following additional maintenance items were accomplished:

- Cooling water pumps were disassembled and rebuilt.
- Annual maintenance was performed on the oxidizing air compressors.
- New ID fan inlet ducting was fabricated and installed.
- The coal system condenser cooling tower pump was repaired.
- Inlet ducting to the pulverizer was insulated and weatherproofed.
- Seven additional ports were installed on the primary and secondary furnaces.
- The window cleaning manifolds of the Babcock & Wilcox (B&W) ports were removed, cleaned, and reinstalled.
- Three gas sampling probes were fabricated.

TEST CONTROL AND SUPPORT

The major activities this quarter involved planning and preparation for the LMF5-H test. An apparatus for calibrating cooling water orifice meters was designed and assembled. Calibration of all facility cooling water orifice meters was in progress.

A failure mode and effects analysis for the wet ESP rotary vacuum filter was conducted. As a result of the analysis, pressure switches were installed in the cooling water/seal water line of the vacuum pump and the cooling water line of the receiver pump. In addition, indicator lights, to alert operators of pump failure, were installed in the control room.

The checkpoint computer program was rewritten to validate data acquisition system (DAS) calculations prior to testing. Debugging of the revised program was in progress.

DATA ACQUISITION SYSTEMS

Coal feed system indicator lights were installed in the control room to show the raw coal inlet valve position, raw coal auger operating status, and the raw coal elevator operating status. In addition, a feed tank isolation valve status indicator was installed. The output signal from this indicator is recorded on a DAS channel.

Calibrations of the data system continued this quarter. Periodic calibration of the data acquisition system was performed to insure that the system was reading correct voltage signals 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 DAS computers. Modifications to the DAS database that are required to support new test requirements and hardware changes were accomplished.

ENVIRONMENTAL AND ANALYTICAL SERVICES

During this quarter, the chemistry laboratory was relocated to a new building. This relocation will be essentially completed prior to the next scheduled CFFF test.

ENVIRONMENTAL MONITORING

Principal focus of activities during this quarter included a review of 1992 monitoring data, a review of groundwater monitoring results with respect to the State of Tennessee requirements, and the continual monitoring and treatment of the holding ponds to maintain effluent conditions within permit limits.

Water Quality

The collection and analyses of monthly water samples was suspended due to lake/weather conditions (high runoff) which prohibited the collection of samples. During the first quarter of CY93 a noncompliance was noted with regard to suspended solids. The monitored value for suspended solids was 70.3. The effluent limit under the National Pollutant Discharge Elimination (NPDES) permit for the holding pond effluent is 40.0. The noncompliance was attributed to facility washdown and lack of seasonal precipitation. Parameters continuously monitored indicated no problems with pH or temperature (Figure 3). The noncompliance was reported to DOE via an Occurrence Report as per DOE Order 5000.3A.

Terrestrial Ecology

No activity was conducted during this quarter. Soil sampling will be continued next quarter.

Groundwater Monitoring

A meeting with the State of Tennessee, Division of Solid Waste Management to discuss groundwater monitoring results and setting forth future monitoring requirements was postponed due to inclement weather conditions. To date, information was forwarded to the State with respect to monitoring results, well construction details, and the presence of drinking water wells within one mile of the UTSI groundwater monitoring network. A future date for the meeting was being arranged. The State will prescribe the future monitoring requirements with respect to scope of analyses, sampling methods and reporting requirements.

Ambient Air Monitoring

Data collection continued to document baseline conditions as well as seasonal variations in various atmospheric parameters. Recent results have indicated elevations in ambient SO₂ concentrations which are not associated with CFFF

FIGURE 3. Typical Holding Pond #2 Effluent Measurements During February

activities. The excursions from ambient baseline conditions have been associated with northerly wind directions(Figure 4). The reason for the excursions have not been identified to date, but there is a major coal-fired power plant upwind.

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

TESTING

No testing was conducted in the CFFF this period. Intensive effort was underway to prepare the flow train and supporting systems for the LMF5-H test scheduled to start approximately April 20, 1993. This will be a western coal proof-of-concept (POC) long-duration test of 225 hours minimum. The primary objective of this test is:

- Operate the LMF5 flow train on Montana Rosebud western coal for 225 hours minimum with 1% potassium in the primary flow, seed added into the primary combustor as a 47% solution of potassium carbonate, nominal primary stoichiometry of 0.85, and nominal secondary stoichiometry of 1.10.

Some secondary objectives are:

- Determine effect of inlet gas temperature, primary stoichiometry, and potassium seed on secondary combustor performance. Primary stoichiometry will be varied from 0.80 to 0.95 and seed flow will be turned off and on during periods when the secondary combustor gas inlet temperature (indicated on thermocouple) is about 1600°F, 1800°F and 2000°F.
- Evaluate performance of dry electrostatic precipitator with newly installed smaller diameter (1/8") wires.
- Determine the effect of furnace draft on oxygen content at the secondary combustor outlet (SCO) to improve the understanding of air leakage to the furnace. Furnace pressures are to be varied between 2" draft and 14" draft (water column).
- Investigate the effect of stoichiometry and thermal input on NO_x emissions at the SCO for nominal thermal input at 80, 85, 90, and 95 percent stoichiometry, and at a lower thermal input at 85 percent stoichiometry.
- Continued evaluation of candidate composite tube samples for a high temperature air heater (HTAH).

FIGURE 4. Impact 1 Monitoring Station Ambient SO₂ Concentrations

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

DOWNSTREAM COMPONENT SYSTEMS

Activities this period centered around the analysis of past data and preparation for the LMF5-H test.

Superheater Test Module (SHTM) Gas-Side Tube Corrosion

Fifteen tube sections, each one-foot long, were removed for corrosion evaluation from the SHTM test section tubes after the LMF5-G test. Accumulated exposure time was 695 hours with seeded coal firing. After measurement of wall thickness at 16 locations, new pieces of the same alloys were welded in place. Two samples, each one-inch long, were cut from the removed pieces centered on the locations where pre-exposure ultrasonic wall thickness measurements were made. Of the remaining tube from the removed sections, pieces were sent to the Argonne National Laboratories (ANL) and the Babcock & Wilcox Company (B&W) for further corrosion evaluations.

All of the tube metal thermocouples at SHTM test section 1 (TS1) were heat destroyed during the LMF5-G test as a result of refractory loss at the top plate where the thermocouples exited the duct. Repair of these thermocouples by splicing was accomplished and stainless steel shields were welded over the thermocouples to their point of exit to prevent a repeat of this occurrence. TS2 tubes, for which the top refractory was cracked but still in place after the LMF5-G test, were also modified with shielding over the entire length of thermocouple lead. Test section tubes have been reinstalled in the test train in preparation for the LMF5-H test. At the tops of the tubes, new refractory was installed to a thickness of four to six inches. The refractory is a 57% alumina, andalusite base, ultra low cement castable installed with 2% by weight of 406 stainless steel fibers.

The initial draft of a topical report entitled "Superheater/Intermediate Temperature Airheater Tube Corrosion Testing in the MHD Coal Fired Flow Facility" was completed and will be issued for DOE review/comment in the next quarter. This report covers UTSI's corrosion evaluations of SHTM test section tubes with 1500 and 2000 exposure hours at the conclusion of the LMF4 test series with Illinois #6 coal firing. A meeting among UTSI, B&W and ANL investigators to discuss and review tube corrosion studies will be arranged for early next quarter.

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 of which 695 hours are POC.)

(Total test train operation time to date is 3688 hours (vitiation heater).)

Superheater Test Module (SHTM) Ash Deposition

SHTM ash deposition studies included modification of the radiant furnace ash/seed hopper to allow removal of molten seed, evaluation of sootblowing, and evaluation of SHTM ash deposition using an ash deposition probe.

After the LMF5-G test, the gas bypass line running from the ash/seed hopper to SHTM cooling section 10 (CS10) was found to be blocked in the region immediately outside the CS10 penetration. The deposits had formed into a semi-hardened mass of the ash/spent seed mixture. It is not known if the semi-hardened condition was present at the time that the LMF5-G test was terminated, since it was several weeks after this test before the bypass line was removed and inspected. It was likely a damp agglomeration which had hardened during the downtime. Since the blockage did not appear to be directly due to water splashing from the quench tank as originally assumed, it is more likely due to excessive cooling in the bypass line. Based on this conclusion, the water flow in the cooling jacket of the bypass line will be reduced for the LMF5-H test. Since past evidence has been inconclusive as to the cause of the blockage at the ash/seed tap, the view port to the ash/seed tap was moved to allow more direct observation of the formation of the blockage. Possible mechanisms are large chunks falling from the inlet transition walls or gradual growth from freezing spent seed. The evidence in the past has been inconclusive because the original view port only permitted observation of the relative amount of light penetrating the opening, and not observation of the tap opening itself.

One modification was made to the sootblowing system for the LMF5-H test. The CS7 sootblowers were connected to the high pressure air system for two reasons: first, to improve the cleaning in this region of the SHTM, and second, to permit the incorporation of this section into the automated sootblowing program.

The ash deposition probe was modified to allow for the use of a 2.5 inch diameter tubular deposit surface which can be observed directly and to allow ash deposition growth patterns to be compared with theoretical projections. This is considered a better option than attempting to compare the existing records of the 1.3 inch diameter test surface used for past heat transfer studies and extrapolating that data to a larger diameter commercial sized heat exchanger surface (commercial superheaters use 2", 2-1/2", and 3" diameter tubes).

Coal Flow Control Valve Rollers

In several prior tests, the two metal grooved rollers in the Moulder coal flow control valve exhibited significant wear after several hundred test hours, causing a loss of accurate control of coal flow at low flow rates. The maximum useful life of hardened tool steel rollers has been about 1000 hours. In an effort to increase the life of these rollers, other materials were being investigated. Two materials which show promise are transformation toughened aluminum oxide and tetragonal zirconia

polycrystal. Because of predicted better wear resistance and fracture toughness, tetragonal zirconia polycrystal rollers will be installed for use during the LMF5-H test.

PARTICULATE REMOVAL SYSTEMS

Electrostatic Precipitator (ESP) Performance

Equipment modification and installation were performed on both the dry and wet electrostatic precipitators (ESP).

The high voltage discharge wires in the dry ESP were replaced. ADA, Inc. conducted a series of bench scale tests to evaluate the existing wires and made recommendations for improving collection efficiency. Based on their results, the electric field strength generated by relatively large diameter wires (1/4" dia. round and 5/16" square) produced insufficient current for efficient particle capture. With existing wires, the corona was generated primarily at the ends of each wire. Higher and more effective current was obtained by decreasing wire size in the dry ESP down to approximately 1/8" dia. round. This modification should result in increased current, improving overall unit performance. Air load tests will be used to evaluate operational changes required prior to the LMF5-H test.

Work on the wet ESP centered on completing the installation of the rotary vacuum filter which was satisfactorily checked out during the LMF5-G test. While the filter was fully operational at the end of the LMF5-G test, the structure enclosing the filter and detailed plumbing and wiring were not completed until this quarter.

Baghouse (BH) Performance

During the LMF5-G test, the baghouse cleaning cycles were not as effective when compared with the LMF4 test experience. The bags during the LMF5-G test did not become blinded from particulate, as evidenced by the low residual pressure drops achieved following either a shutdown of a few hours duration or multiple cleaning cycles. Apparently the cleaning procedure is not intense enough to remove the ash layer. Tests were conducted to determine the reverse fan capacity compared with its rated capacity. However, electrical current overloads were experienced and the circuit breaker tripped each time the fan was operated at an ambient temperature of only 40°F. Due to the increased gas density, the electrical current limits were exceeded during these off-line tests. Additional evaluations will be conducted during the LMF5-H test to determine if a higher capacity fan is required to effectively clean the bags.

MASS BALANCE AND AUTOMATIC DATA SCREENING

The principal areas of activity during this period were calculation of CFFF mass balances, including data reduction, data filtration, and maintenance of chemical

database; secondary combustor modeling; potassium-sulfur kinetics studies; and ash deposition modeling.

CFFF Mass Balances

Much of the interest in performing mass balances is for the purposes of determining the disposition of two major constituents of the feed streams, seed material and coal ash. During this quarter, mass balances for alkali metals (mainly seed) and other metallic elements (mainly coal ash) were added to the mass balance program. A single mass balance input file was then prepared, covering the combined group of the LMF4 POC series tests. The program was run and analysis of the output data was started. Preliminary indications are that this mass balance will be significantly better than previous mass balances for individual tests due to:

- Accumulation terms which contribute to non-closure of the balances decrease in importance as the period over which the balance are accomplished is increased.
- Multiple individual chemical analyses for the various feed and product streams were averaged to obtain inputs for the program, thereby lessening the magnitude of error introduced by random analytical errors impacting the result.
- The new balances performed on alkali and non-alkali metals appear to yield improved results.

Work is progressing on a technical paper entitled "Analysis of Material Disposition for Illinois #6 Coal POC Testing at the CFFF" which has been accepted for presentation at the Thirty-First Symposium on Engineering Aspects of Magnetohydrodynamics (SEAM).

CFFF Data Reduction and Data Filtration

CFFF data reduction and filtration schemes are being conducted to support the mass balance and other analytical efforts. Past data reduction problems were related to the use of data channel numbers for identification of desired data, as data channels for a given parameter may change from one test to another. As channel numbers were reassigned, the data requested by the FILTER and PULL computer programs was different than what was intended. The problem was mitigated by changing the program to use parameter name rather than channel number to select data. Work has started on the LMF5 test data collected to date using this new technique.

Chemical Analysis Database

Maintenance of the chemical analysis database also supports the mass balance effort. One use of the database was to prepare information for the MHD

Contractors' Review Meeting. Enhancements were made to the Macintosh PC version of the database to allow calculation of means and standard deviations.

Secondary Combustor Modeling

During this quarter, work continued on the 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 code[1]. Problems with the jet inflow boundary condition were resolved and a two-dimensional non-reactive solution was obtained. A refined grid is needed to improve the solution and reduce memory requirements for the three-dimensional cases. A grid generation program is 50% complete. When improved two-dimensional results are obtained, the reactive flow cases will be started.

Potassium-Sulfur Kinetics Study

Work continued on planning for the study of potassium-sulfur chemical kinetics. A prototype laminar flame burner (Figure 5) was built to assess design, fabrication and experimental issues. Based on this experience and other design studies, a burner design was completed, and shop drawings were being prepared. The burner will consist of a bundle of 0.040" inside diameter tubes. The tubes are arranged so a mixture of air and methane (doped with potassium and/or sulfur compounds if desired) enters through a 1" x 1" square section in the center of the burner. Nitrogen enters through a 1/4" wide section around the perimeter of the burner. The nitrogen blanket is required to prevent mixing of the fuel with outside air. This burner design has been used in several previous flame kinetics studies reported in the literature. Material for the burner, gases, flowmeters, and other equipment needed for the experiment will be procured.

Preliminary concepts for optical instrumentation have been developed. The measurement of $\text{OH}^\bullet$, K and possibly a diatomic sulfur species will be made by measuring absorption of a broadband source. Detailed optical system design was in progress. The experiment will be located in a UTSI laboratory area that already contains an optical table and other required equipment.

The CHEMKIN chemical kinetics computer program[2] has been obtained from Sandia National Laboratories and installed on a Sun Workstation. This program has the capability of including the effects of species, momentum, and energy diffusion processes along with chemical kinetics calculations. The program will be used to evaluate the results of the laminar flame experiment, and also will be used in conjunction with the secondary combustor performance model. This information will help to develop operating guidelines and designs for commercial systems.

FIGURE 5. Prototype Laminar Flame Burner

Ash Deposition Modeling

Work continued on the development of the overall analytical computer model entitled "AshEffects" for evaluating and predicting the effects of fireside ash deposits on superheater tubes. When completed, this model will provide a tool for generating 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. The FuelCalc module of the AshEffects computer program was expanded and upgraded significantly to automate handling of time-dependent values such as as-fired coal moisture, oxygen and nitrogen flow rates, and oil used in the vitiation heater.

Image analysis work was continued for evaluation of important characteristics of ash particles, including determining diameters and quantifying cohesive strengths via measurement of sinter-bond development produced under laboratory conditions. Aerodynamically-sized ash particles were heated for several periods of sintering time with closely controlled time-at-temperature to assess the potential for measurement of a sintering rate parameter (surface tension/viscosity) at the sintering temperatures of interest (where the ash viscosity is greater than 10^{10} poise) for ash-deposition calculations. Initial results were promising.

Calculations were made using the Impact module of AshEffects for the inertial-impaction mechanism of mass transfer. This module assumed fly-ash particles with a density of 2.66 g/cc contacting a superheater tube operating at 1100°F metal temperature in 2200°F flue gas using combinations of flue-gas velocities and outside diameters of the superheater tube (including 20, 60 and 70 feet per second velocities and 3.0, 2.5, 2.0 and 1.5-inch tube diameters). CFFF five-stage cyclone measurements were used to describe the particle-size distribution and flue-gas mass loading (dust loading) of real MHD fly-ash particles. Flue gas composition and viscosity were calculated using appropriate CFFF coal analyses. Two-dimensional deposit shapes were calculated in 0.5-hour increments over an elapsed time of eight hours in most cases. Significant changes in deposit shape were found among the different combinations of design and operational conditions.

Work continued on a computer code for calculating small particle thermophoretic mass transport and vapor condensation on the fireside surface of superheater tubes. After these codes are completed, development of two-dimensional finite-element routines will be developed for description of localized effects. During the next quarter, work will continue with image analysis and development of the code for thermophoresis and vapor condensation.

ADVANCED MEASUREMENT SYSTEMS

Laser Doppler velocimetry (LDV) data acquired by UTSI and Mississippi State University (MSU) in the secondary combustor during the LMF5-F and LMF5-G tests

was analyzed. This preliminary data was acquired in support of the study of secondary combustor flame suppression by potassium described in previous Quarterly Technical Progress Reports[3] [4].

The LDV results were compared with CFFF secondary combustor cold flow model results obtained in 1982[5] to assess how adequately the cold flow mixing results apply to the full scale combustor. The LDV measurements were made at penetration no. 2404 below the contraction section of the secondary combustor, and at an $x/L=1.96$, $y/L=0$ and $z/L=0.545$, for $L=0.628$ m (24.75 in.), which is the half width of the secondary combustor after refractory loss. Coordinates are pictured in Figure 6, and correspond to coordinates used in the cold flow model study. For data comparisons, the model data for a $z/L=0$ was used since the data in both situations corresponds with flow aligned with an air injector rather than with the edge of, or between, injectors. A linear interpolation of model data for $x/L=1.675$ and 2.375 gives a $\bar{U}/V = 3.6$ and a $u'/V = 1.6$. For a measured LMF5-G test bulk combustion gas flow of 2.97 kg/s ($V=8$ m/s), the LDV measured essentially the same $\bar{U}/V = 3.7$ but a lower $u'/V = 0.63$. The lower u' value indicates possible modifications of the mixing due to the chemical reactions and associated density effects, or possible damping of the vortex shedding observed in the model, perhaps due to Reynolds number effects, or an effect of flow variations with z . It has not been possible to evaluate the LDV data for shedding frequencies, or for z variations. Future measurements with a more sensitive forward scatter system are planned during the LMF5-H test.

The CFFF laser velocimeter (LV) and MSU LDV are being configured to make these shedding frequency measurements. The UTSI LV set-up area also is being used to conduct the experiment to obtain kinetic data for a K-S system. A CH_4 laminar flame burner and K and OH^- absorption diagnostics have been assembled in this area as a joint Advanced Measurements and Process Engineering task. This effort has been described in detail in the "Downstream Component Systems" section of Task 4 of this report.

MSU data reports for the LMF5-F and LMF5-G test were used in the LMF test train performance evaluations. The multiple color pyrometer (MCP) measurements of radiant furnace wall temperatures and emissivities were used to assess the radiant component of wall heat flux measured by the UTSI heat flux probes monitored by each MCP. The MCP measurements and previous visible/infrared emission spectrometer (VIES) measurements of high temperature air heater (HTAH) tube samples were used to help predict potential HTAH performance and to plan for future HTAH experiments. (See "Modifications to the CFFF" section of Task 6 of this report.) The VIES slagged HTAH tube spectral emission curve, from 0.35 to 4.8 μm for the LMF4 test conditions, was provided for evaluation of enhanced radiant heat transfer and fouling avoidance concepts, and a section of clean tube was sent to MSU to measure the clean tube spectral emission curve. The potassium emission/absorption system (PE/AS) measured peak 2500K gas temperatures at the instrument ring in the aerodynamic duct using spatial signal separation rather than temporal separation. The PE/AS also measured potassium number densities and calculated conductivities, typically from 4

FIGURE 6. Coordinates for Secondary Combustor Flow Studies

to 8 mhos/m. Coherent anti-Stokes Raman spectroscopy (CARS) was employed at the instrument ring to study the effects of potassium addition on the CARS measurements. When K_2/S was less than 1.7, the CARS spectra showed only minor nonresonant background from particle induced laser breakdown, but at the POC condition ($K_2/S = 4.2$) significant nonresonant background was measured. This nonresonant background must be considered in the CARS data reduction. Finally, two-color laser transmissometer (TCLT) measurements of dry ESP particle loadings showed, again, a significant increase in particle number densities with K_2/S ratios at or above 1.65.

The MSU TCLT measurements were acquired in conjunction with the Insitec, Inc. in-situ probe for measurements of dry ESP particle number densities and changes in loading with time. Insitec's PCSV instrument[6] was modified to allow particle sizing down to 0.2 μm , but at the high K_2/S POC conditions. The PCSV instrument was limited to sizing particles above 0.5 μm by the large number of particles of smaller size encountered. When the baghouse or dry ESP is fully functional, the PCSV instrument generally measures the cleaned gas particle size distribution down to nearly 0.2 μm . The UTSI sample extraction/dilution system (SEDS) should measure particles down to 0.1 μm when proper operation of the SEDS dilution settings are established for the LMF POC conditions. The PCSV instrument measures particles as large as 15 μm and should complement the SEDS measurements which only measures up to 3 μm particles. As shown in Figure 7, the Insitec volume concentration (loading) measurements showed sporadic increases, as did the SEDS. These loading increases present considerable difficulty in setting operational parameters for the SEDS. The loading increases could not be correlated with sootblowing sequences, and better time correlation will be attempted during the LMF5-H test to resolve the source of the loading increases. The Insitec particle size distributions are being used by MSU to improve the Sauter mean particle diameter measurements from the TCLT data and additional TCLT measurements are planned in conjunction with Insitec measurements during continuing LMF5 testing.

Efforts continued to establish appropriate SEDS operational performance setting and evaluate measurement uncertainties for variable dilution rates and instrument sampling rates. As shown in Figure 8, the Particle Measuring Systems, Inc. (PMS) size distribution monitor was found to be sensitive to sample flow settings. It also was found to bias the small particle size counts at higher LMF sample flows. The effectiveness of the SEDS dilution ratio settings, and the cause of the SEDS plugging experienced during the LMF5-F and LMF5-G tests, were still being studied. A new sample orifice is being designed to address the plugging problem, and one of the PMS monitors is being recalibrated for a lower sample flow rate.

CG-2309

FIGURE 7. Typical Particle Volume Concentration Upstream of the ESP6

FIGURE 8. Sensitivity of PMS Instrument to Sample Flow

Plans for the LMF5-H test include the flow train operational diagnostics, including the diffuser, furnace and test section 1 (TS1) line reversal systems. Additionally, the TS1 line reversal operation on potassium emission will be evaluated to determine if greater sensitivity can be obtained at lower TS1 gas temperatures. Instrumentation, including helium bleed dynamic pressure transducers and luminosity probes, will be used to evaluate coal flow stability (and elimination of bistable flow) with the rebuilt Moulder valve. MSU will provide MCP instruments to monitor both UTSI furnace heat flux probes for assessing the radiation contributions and gas side surface temperatures and emissivities on the new HTAH test tube. MSU or UTSI will install an LDV system to complete the secondary combustor mixing studies, and MSU may install their PE/AS instrument at the instrument ring to again measure conductivities in the aerodynamic duct.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

No activity was planned or carried out during the quarter.

No activity is currently planned for FY93.

TASK 6 - MODIFICATIONS TO THE CFFF

TEST FACILITY MODIFICATIONS/ADDITIONS

High Temperature Air Heater (HTAH) Development

Activities this quarter centered around materials analysis, heat transfer enhancement studies and preparation for the LMF5-H test.

Material Analysis

A paper entitled "Evaluation of a Candidate Material for a Coal-Fired Magnetohydrodynamic (MHD) High Temperature Recuperative Air Heater" was presented at the 17th Annual Conference & Exhibition on Composites and Advanced Ceramics. A copy of the paper is included in Appendix A. The paper concluded that the Lanxide DIMOX(TM) composite material that was tested for 107 hours in a 1650°C MHD exhaust gas stream showed no evidence of corrosion or chemical attack. It did, however, increase in porosity.

Microscopic observations of the unexposed (but heated) and exposed material illustrated the change in porosity compared to the as-received sample. The porosity increased from as-received to the unexposed and further to the exposed samples. The Weibull number for unexposed and exposed samples showed a decrease in the value indicating a higher probability of failure which is in accordance with observations for the change in porosity. Mechanical testing of both samples, however, showed comparable fracture strength in tension (unexposed: 258 MPa and exposed 265 MPa) as well as compression (unexposed: 283 MPa and exposed 266 MPa).

Even though the increase in porosity is an indication of a higher probability of failure, it would not (at least in this case) have a significant influence on the mechanical strength of the samples. In order to realize the effect of change in porosity on mechanical strength of the material, it is essential to establish a limiting porosity value after exposure to various temperatures for several exposure durations.

The preliminary results reported on in Appendix A are based on a very limited number of test samples and parameters which warrant caution in deriving definite conclusions at this time. Extensive additional studies are required to quantify the impact of the increased porosity.

Work next quarter will include testing of a two-inch OD Lanxide DIMOX(TM) bayonet style tube during the LMF5-H test. A videotape will be made of the slag formation as it accumulates on the tube and Mississippi State University will provide optical instrumentation for measuring the tube temperature. Material samples from the Hague International Company, the Babcock & Wilcox Company, and Composite Ceramics Incorporated will also be exposed in the radiant furnace during the LMF5-H test. An analysis of DIMOX(TM) samples that were exposed to a more severe environment than that reported in the conference paper is also planned.

Heat Transfer Enhancement

Techniques for heat transfer enhancement of candidate HTAH tubes were developed. These efforts concentrated on ways to induce swirl flow with vanes. Full characterization of a vane swirler is scheduled for next quarter.

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

Dr. Joel Muehlhauser, Dr. James Chapman, Mr. Norm Johanson and Mr. Richard Attig attended the DOE/PETC MHD Contractors' Review Meeting held in Pittsburgh, Pennsylvania during February 2-4, 1993.

Twelve abstracts for technical papers to be presented at the Thirty-First Symposium on Engineering Aspects of MHD (SEAM) were sent to DOE for review/approval.

TASK 9 - CFFF PROGRAM MANAGEMENT

MANAGEMENT AND ADMINISTRATIVE SUPPORT

MHD Monthly Contract Status Reports for January, February and March 1993 were issued to DOE/CH.

The FINAL Quarterly Technical Progress Reports for January-March 1992, April-June 1992, and July-September 1992 were issued.

The draft issue of the October-December 1992 Quarterly Technical Progress Report was issued to DOE/CH.

A proposal for extending the MHD contract period from April 1, 1993 through March 31, 1994 was submitted to DOE/CH.

The annual Government real and personal property inventories reports were issued to DOE/CH.

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GLOSSARY

AH	• Air Heater
ASTM	• American Society for Testing and Materials
BGC	• Bendix Gas Chromatograph
BH	• Baghouse, particulate capturing device using a fabric type filter bag
B&W	• Babcock & Wilcox
CARS	• Coherent anti-Stokes Raman spectroscopy
OFFF	• Coal Fired Flow Facility
CS(n)	• Cooling Section where n = number of section
ODIF	• 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
E	• Emissivity or velocity fraction
ECF	• Energy Conversion Facility
EFM	• Electric Field Meters
EPR	• 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/BR	• 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
RF1	• Radiant Furnace #1 Position
SCA	• Specific Collection Area for ESP
SCI	• Secondary Combustor Inlet
SCO	• Secondary Combustor Outlet
SCR	• Silicon Controlled Rectifier
SEDS	• Sample Extraction/Dilution System
SER	• Site Environmental Report
SEM	• Scanning Electron Microscope
SHTM	• Superheater Test Module
SLR	• Sodium Line Reversal
Sootblower	• Device for removing particulate collection on heat transfer surface
T/C	• Thermocouple
TCLT	• Two Color Laser Transmissometer
TGA	• Thermogravimetric Analyzer
TS(n)	• Test Section, where n = number of section
TTIRC	• Technology Transfer Integration and Review Committee
Upstream	• That part of the Flow Train from the vitiation heater to the exit of the diffuser
UTSI	• The University of Tennessee Space Institute
VES	• Visible/Infrared Emission Spectrometer
WSDAAS	• Wide Band Data Acquisition and Analysis System

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APPENDIX A

EVALUATION OF A CANDIDATE MATERIAL FOR A COAL-FIRED MAGNETOHYDRODYNAMIC (MHD) HIGH TEMPERATURE RECUPERATIVE AIR HEATER

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INTRODUCTION

The need for greater efficiency in electricity producing plants has driven the development of magnetohydrodynamics (MHD). An MHD cycle would be added to steam turbine facilities so that the MHD cycle would be the first or topping cycle and the steam turbine cycle would be the last or bottoming cycle. With commercial MHD electric power plants it will be possible to increase the efficiency of the electricity producing process. The University of Tennessee Space Institute has a proof of concept (POC) magnetohydrodynamic coal fired flow facility in order to test the concept in a working environment.

In order to achieve the desired efficiency in the MHD cycle, one of two procedures must be employed. The first is to inject pure oxygen during combustion in order to achieve higher combustion temperatures which will yield better conversion efficiencies. The other is to preheat the combustor air through the use of high temperature air heaters (HTAH).

A recuperative air heater heats the combustor air directly by passing it through tubes which are in the exhaust gas flow before sending it into the combustor. The procedure of passing air through the furnace requires a material for the tubes which will withstand the high temperatures and corrosive environment of the furnace and should have a high heat transfer coefficient. All of the necessary properties seem to exist in ceramic materials, so ceramics have begun to be studied for high temperature air heaters as well as other high temperature applications. The present project outlines one such effort to evaluate the performance of a ceramic composite tube in a coal fired MHD facility in order to determine any changes in the tube material after exposure to high temperature and a highly corrosive environment.

A recuperative high temperature air heater (HTAH) would be positioned in the radiant furnace, because the radiant furnace provides conditions comparable to an actual MHD facility and is adequate for testing HTAH materials [1]. The temperature conditions in the furnace range from approximately 1600°C to 1890°C, and velocities of approximately 12 m/s to 100 m/s have been measured depending on the location in the furnace [1].

The evaluated tube was placed in the furnace in a reducing environment with approximately 14 m/s velocity, 1650°C gas temperature, and 1230°C tube temperature [2]. The potassium seed in the coal used to ionize the exhaust gas significantly increased the corrosive

nature of the slag. The tube was in direct contact with the high velocity slag at high temperature for approximately 107 hours.

The material which was evaluated in this study was a tubular component of silicon carbide particulate reinforced alumina ($\text{SiC}_p/\text{Al}_2\text{O}_3$) made via Lanxide Corporation's DIMOXTM directed metal oxidation process and purchased from Du Pont Lanxide Composites Inc. The composition of the composite in volume percent was approximately 45% SiC, 45% Al_2O_3 and 10% aluminum alloy. The 10% residual metal is due to the synthesis method of producing the composite.

PROCEDURE

The tube was evaluated to determine any physical or chemical changes in the material due to exposure to the furnace. The evaluation included mechanical testing of exposed and unexposed samples, optical and scanning electron microscopy, and microprobe analysis of as-received, unexposed, and exposed samples. As-received samples were samples in the same condition as when they had been received from the manufacturer. Unexposed samples were samples which were involved in the furnace test but which were not in direct contact with the slag and furnace environment. The unexposed section was the part of the tube which was inserted in the wall of the furnace in order to hold the tube in the furnace, so the temperature of the unexposed section was lower than that of the exposed section. Exposed samples were samples which had been in the furnace directly exposed to the slag and furnace environment during testing.

The strength of ceramic materials, unlike metals, is limited by the size of inherent flaws such as porosity, inclusions, microcracks, etc. In addition, stressed ceramic components fail according to the weakest link theory, which states that the failure stress is determined by the weakest point, which is the most critical flaw [3,4]. As a result, strengths tend to vary and require statistical description. For this purpose, the Weibull statistical method was chosen. Weibull statistical analysis is based on the weakest link theory and has been used extensively to determine the probability of failure of ceramics under load. The probability of failure in a ceramic can be related to the strength of a specimen through determination of the Weibull number which is estimated using the experimental strength values obtained from mechanical testing.

The tube was cut so that the part of the tube which was outside the furnace and the part of the tube which was inside the furnace and exposed to the furnace conditions were separated. These parts were then further sectioned into rings approximately 10 mm in width ($\pm 2\text{mm}$), and each ring was marked in order to identify the top of the tube while in the furnace. Six of these rings from both the exposed and unexposed sections were selected for testing under uniaxial tension and compression to determine their mechanical properties. An Instron testing machine was used to perform both the compression and tensile tests. In order to achieve uniform line contact during the uniaxial tensile testing, two steel pins (6mm diameter and at least 70mm long) were positioned diametrically opposite on the inside surface of the ring. These pins were attached to a moving cross-head and a load cell by holding fixtures. The ring was positioned so that the top of the ring corresponded to the top of the tube while it was in the furnace. This was done in order to determine the effect of the tube orientation in the furnace on fracture origin during testing. The compression testing sample was placed between two diametrically opposite flat plates which were connected to the moving cross-head and load cell. This arrangement also provided uniform line contacts between the sample and the plates.

Each ring was loaded under either uniaxial tension or compression at a strain rate of $2.07 \times 10^{-4} \text{ s}^{-1}$. Load-elongation curves were recorded on an x-y recorder using the output from the extensometer. These plots were then used to construct stress-strain curves. A ring modulus and fracture strength were then obtained from the stress-strain curves. The ring modulus obtained was calculated as stress over strain, or the Young's modulus, for a circular ring configuration. This information was further used to calculate the Weibull number.

Optical and scanning electron microscopy for studying porosity, residual aluminum, and element distribution was performed on as-received, unexposed, and exposed samples. Each sample was metallographically prepared by polishing with a series of grit papers. The final polishing was done with a $3 \mu\text{m}$ diamond paste.

Quantitative elemental analysis was performed using a Cameca MBX microprobe with a light element detector for x-ray analysis using energy dispersive spectroscopy (EDS). The distribution of elements in the material was also studied quantitatively on the microprobe using wavelength dispersive spectroscopy (WDS) techniques.

Scanning electron microscope pictures were taken at 800x to measure the area fraction of porosity by the point count method. The pores were traced onto a transparency sheet which was overlaid with a calibrated grid [5]. The point count method was also employed to determine the volume percentage of residual metal in the material samples using optical micrographs.

DISCUSSION

Mechanical Testing

The parameters obtained from the mechanical testing were the compressive and tensile strengths. The mechanical testing performed was not designed to produce an absolute measure of these parameters but rather to detect any difference in the parameters between the unexposed and the exposed material due to the large temperature difference between these two sections. These parameters were then used to calculate the ring modulus, strain, and Weibull number.

The mechanical tests performed to evaluate the reliability of the material were conducted on a small number (six) of samples. Also, the unavailability of as-received material in the tubular shape forced the evaluation of the unexposed material against the exposed material. Therefore, the statistical analysis conducted on a relatively small number of unexposed and exposed samples does not truly reflect absolute values for the samples and is a qualitative indication of the changes in properties of the material after exposure to the high temperature furnace atmosphere. Also, the magnitude of the error in the results is relatively high, therefore the results must be viewed cautiously.

An estimate of the Weibull number was needed since it was not known for the material after exposure to high temperatures. There are several methods of estimating the Weibull number for a brittle material. Among these are the least squares method, the method of maximum likelihood, and the method of moments. The least squares method was chosen for this estimate due to the ease of calculation and because the probable high error resulting from the small number of test specimens made a more precise estimate insignificant.

The equation for stress, σ , is given by

$$\sigma = \frac{P}{b\pi r_o} Q, \quad (1)$$

where P is the load in pounds, b is the width in inches, r_o is the outer radius, and Q is the stress magnification factor for a circular ring which is non-dimensional [6].

The probability of failure, P_f , is given by

$$P_f = 1 - \exp\left[-V\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m\right], \quad (2)$$

where m is the Weibull number, V is the volume of the material, σ is the failure stress, σ_0 is a characteristic stress, and σ_u is the stress below which there is no probability of failure [3,7]. The parameter σ_u was taken to be zero, and the average of the stress values for a given test was used for σ_0 . Then, this equation can be put in the form

$$y = \ln\ln\left(\frac{1}{1-P_f}\right) = \ln\frac{V}{\sigma_0^m} + m\ln\sigma. \quad (3)$$

The graph of y versus $\ln\sigma$ is a straight line of slope m [7].

The least squares method uses this linear model to obtain an estimate for m which is given by

$$m = \frac{\sum y_i \ln\sigma_i - (1/n) \sum y_i \sum \ln\sigma_i}{\sum (\ln\sigma_i)^2 - (1/n) (\sum \ln\sigma_i)^2}, \quad (4)$$

where n is the number of samples tested and y_i is given by

$$y_i = \ln\ln\left[\frac{1}{1-[i/(n+1)]}\right]. \quad (5)$$

The stress values, σ_i , must be ordered so that $\sigma_1 \leq \sigma_2 \leq \dots \leq \sigma_n$. Then the expected value of $P_f(\sigma_i)$ is $i/(n+1)$.

The estimate of the Weibull number obtained for the tension testing was 19.39 for the unexposed material and 7.02 for the exposed material. For the compression testing the estimate was 8.69 for the unexposed material and 5.41 for the exposed material.

A smaller number for the Weibull number represents a larger scatter in the data and therefore a higher probability of failure. In both the tension and compression testing, the Weibull number is less with the exposed material than for the unexposed material. This seems to indicate that the probability of failure of the material after exposure in the furnace is higher.

Equation 1 was used for both the tensile and compressive strengths. This was possible because the only difference between these two tests is that the load was assumed negative for tensile testing and positive for the compressive testing.

The equation for Q is given by

$$Q(\psi, r) = 2A_0 - B_0\left(\frac{r}{r_0}\right)^{-2} + \sum_{n=2,4,6} [2A_n(n+1)(n+2)\left(\frac{r}{r_0}\right)^n + 2n(n-1)B_n\left(\frac{r}{r_0}\right)^{n-2} + 2n(n+1)C_n\left(\frac{r}{r_0}\right)^{n-2} + 2(n-1)(n-2)D_n\left(\frac{r}{r_0}\right)^{n-2}] n \cos(n\psi) \quad (6)$$

where

$$A_0 = \frac{1}{2(1-x^2)}, \quad (7)$$

$$B_0 = -\frac{x^2}{1-x^2}, \quad (8)$$

$$A_n = \frac{1}{2R_n} \left(\frac{1-x^{2n}}{n} - \frac{1-x^{2n+2}}{n+1} \right), \quad (9)$$

$$B_n = \frac{1}{2R_n} \left(\frac{1-x^{2n}}{n} - \frac{1-x^{2n+2}}{n-1} \right), \quad (10)$$

$$C_n = \frac{x^n}{2R_n} \left(-\frac{1-x^{2n}}{n} + \frac{1-x^{2n+2}}{n+1} x^2 \right), \quad (11)$$

$$D_n = \frac{x^n}{2R_n} \left(-\frac{1-x^{2n}}{n} x^2 + \frac{1-x^{2n+2}}{n-1} \right), \quad (12)$$

$$R_n = (1-x^{2n})^2 - n^2 x^{2n+2} (1-x^2)^2, \quad (13)$$

ψ is the angle from the vertical axis, r_o is the outer radius of the ring, r_i is the inner radius of the ring, r is the radius of interest, and x is the ratio r_i/r_o [6]. The equation for stress breaks down as r approaches r_o . Therefore, the values used for the stress magnification factor were calculated at $r=r_i$. The tests were uniaxial diametrical loading of a ring, therefore the inside diameter was used as the original dimension for the calculation of the strain.

A summary of the parameters obtained may be seen in Table 1. The change in the Weibull number is significant for both tension and compression. However, the change in the ring modulus and strength is much more prevalent in the compression testing than in the tension testing.

Table 1. Summary of parameters from mechanical testing.

Tension	Ring Modulus (GPa)	Fracture Strength (MPa)
Unexposed	-23.92	257.9
Exposed	-25.59	264.8
Compression		
Unexposed	53.63	283.5
Exposed	36.16	266.2

Microscopy

The results of the EDS on all three materials confirmed that the major elements present were silicon and aluminum. Even though the micro-probe is equipped with a light element detector for energy dispersive x-ray analysis (EDS), in many instances, sample self-absorption effects significantly reduced the intensity of oxygen and carbon peaks. No other element was detected in a quantity sufficient to indicate anything out of the ordinary in any of the materials.

When the micro-probe was utilized for the WDS analysis and properly calibrated, detection of carbon was possible, although oxygen was still out of the precision range. Using WDS, x-ray maps of silicon, aluminum, and carbon were produced for each of the materials.

The slag was also evaluated in the micro-probe, although not to the extent of the ceramic material. Two types of slag were evaluated. One was a hard greenish material and the other a yellowish material which broke into a coarse powder very easily. The major elements in both slag types detected using EDS analysis were potassium (K), silicon (Si), aluminum (Al) and calcium (Ca). When the yellowish slag was evaluated, a broad peak extending over a wide range of eV values (~10-19) was seen. Such a broad peak is an indication of either extremely fine grains or a near amorphous structure comprised of various elements.

The slag had accumulated to varying thicknesses on the tube surface, and it appeared to adhere mechanically, since very little force was required to remove it from the tube. Once removed, the surface of the tube was visually inspected and appeared virtually identical to the unexposed surface indicating that no reaction had taken place between the slag and the tube. In addition, the dimensions of the tube had not changed significantly from the unexposed to the exposed sections. The micro-probe analysis also showed no depth of penetration of the slag and no new elements on the surface. Therefore, it can be concluded that no reaction occurred between the slag and the material of the tube under the given conditions of temperature and furnace atmosphere.

The assumption was made that the porosity was isotropic throughout the material. This assumption seemed to be acceptable for the unexposed and exposed samples. However, the as-received porosity seemed to vary from quite evident to almost none. The material was examined in several places and the porosity appeared to be fairly uniform, so measurements were taken with one photograph for each sample of the materials. The results of these measurements showed that the porosity in the as-received material varied from less than 1 volume % in some areas to greater than 3 volume %. The porosity of the unexposed material increased to approximately 18 volume %, and the porosity of the exposed material increased even further to approximately 23 volume %.

This indicates that the porosity of the material increases when exposed to high temperatures. There are several possible explanations for this occurrence. First, as the temperature of the material increases, more of the aluminum alloy is likely to oxidize. As this happens, porosity will increase since the density of alumina (3980 kg/m^3) is higher than that of aluminum (2699 kg/m^3) [8,9,10]. Also, as the temperature reaches higher than the melting point of aluminum ($\approx 660^\circ\text{C}$), it is possible for aluminum to move through the material by capillary action. Through this process, the aluminum can reach a surface of the tube and either drip off or boil off depending on the temperature of the environment.

The post exposure measurement of aluminum alloy content indicated that it was lower in the exposed material than in the unexposed or as-received. The unexposed was very close to the as-received. This seems to indicate that the temperature of the unexposed section of the tube was not high enough to cause loss of aluminum. A plot showing the aluminum content and porosity content can be seen in Figure 1.

Another possibility for the increase in porosity is a process called coalescing whereby the existing pores begin to grow together forming larger pores. This theory is supported by the fact that the calculated mean pore size was $2.96 \mu\text{m}^2$ in the as-received sample and $7.57 \mu\text{m}^2$ in the exposed material. The other possibility is that the material is actually deteriorating chemically. Silicon has a strong affinity towards oxygen thereby forming a thin layer of silicon dioxide (SiO_2) on the surface of the silicon carbide. When exposed to high temperatures, such a SiO_2 layer could react with Al_2O_3 forming a low melting eutectic (1587°C). This low melting

eutectic could in turn initiate any one or all of the previously mentioned mechanisms and result in the formation of pores.

A high possibility is a combination of processes. If the as-received material started with 2 volume % porosity and 10 volume % residual metal, then if all the aluminum alloy were removed leaving pores, that would yield a maximum porosity of 12 volume %, which is below the 23 volume % measured in the exposed material. Also, because there is still residual metal in the exposed material, the porosity cannot be caused solely by the oxidation or vitrification of aluminum. Therefore, it is highly likely that the combination of two or more of these processes worked in the formation of the porosity.

Furthermore, scanning electron micrographs of fracture surfaces of the rings tested in tension in compression for both the unexposed and exposed conditions were evaluated. Overall fracture in all samples appears brittle (coarse surface) in nature as expected for ceramic materials. However, the surface does show striations in some regions indicating a localized ductile nature. This ductile nature may be due to the presence of residual aluminum in the composite. As previously mentioned, the variation of residual aluminum due to high temperature exposure is not substantial as is the case for porosity. This fact may be a possible reason for having small values of the Weibull number (m) for the exposed sample as compared to the unexposed, and strength values remaining the same within a small reasonable range respectively.

CONCLUSION

The analysis of the silicon carbide/alumina material used for high temperature air heater tubes can be summarized with the following results. First, the mechanical testing did not show a significant change in the strength of the material after exposure, and the orientation of the tube in the furnace did not affect fracture origin. However, the Weibull number decreased from the unexposed to the exposed material indicating a higher probability of failure and a wider spread of the data. The data found from the mechanical testing should be used with caution due to the extremely small test size. Second, the measurements of the tube indicated little or no corrosion or erosion by the slag. Next, the surface analysis showed that there was no reaction with the slag, and the major elements found in the samples were consistent with the as-received material. Finally, microscopic examination revealed an increase in porosity associated with the exposure temperatures. When the porosity was measured, it showed as-received approximately 2 volume %, unexposed approximately 18 volume %, and exposed approximately 23 volume % porosity. Also, the aluminum alloy measurements showed as-received as 6.33 volume %, unexposed as 6.02 volume %, and exposed as 3.78 volume %. Thus,

Figure 1. Plot of aluminum and porosity content.

based on the analysis performed on this material in this study, it appears that the material is very promising for use in high temperature air heaters. It seems to have high strength characteristics as well as good resistance to corrosion and erosion. However, further research is necessary to determine the material properties after extended exposure to higher temperatures. The porosity needs to be evaluated after exposure to various temperatures for various exposure times to determine if there is a limiting porosity value, or if the material will eventually deteriorate completely.

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