**THE UNIVERSITY OF TENNESSEE
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**DOE/ET/10815-224
DIST. CATEGORY UC-112
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**TECHNICAL PROGRESS REPORT
FOR
THE MAGNETOHYDRODYNAMICS
COAL-FIRED FLOW FACILITY**

**For The Period
July 1, 1993 - September 30, 1993**

December 1993

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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TULLAHOMA, TENNESSEE 37388-8897

COAL FIRED FLOW FACILITY

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COAL-FIRED FLOW FACILITY

PREFACE

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

Previous reports have provided comprehensive data on NO_x and SO_x control, radiant heat transfer, particulate control (baghouse and 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 a multi-task research contract directed toward developing the technology for an MHD steam combined cycle power plant. During the period two tests were conducted in the DOE Coal Fired Flow Facility. Both of these tests were part of the western coal proof-of-concept (POC) test series. The report describes the performance of the tests and provides some preliminary performance data on particulate removal systems during the tests. The performance of ceramic tubes being tested for high temperature air heater application is described. Performance of advanced diagnostics equipment from both UTSI and MSU is summarized. The results of experiments designed to determine the effects of potassium compounds on combustion are included. Plans for analysis of metal tube specimens previously removed from the test train are discussed. Modeling and analysis of previous test data include a deposition model to predict ash deposition on tubes, mass balance results, automated data screening and chemical analyses and the data base containing these analyses. Laboratory tests on sealing ceramic tubes and corrosion analyses of previously tested tubes are reported.

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

- **A quarterly QA audit by the State of Tennessee Division of Laboratory Quality Assurance was completed in September 1993. The results indicated all instrumentation to be operating within EPA operational guidelines.**
- **A western coal long-duration, proof-of-concept (POC) test, LMF5-I, was completed in July 1993 and accomplished 212 hours on coal.**
- **A western coal POC test, LMF5-J, was completed in September 1993. It was terminated after 52 hours on coal due to a loss of coal flow caused by plugging of the coal delivery line to the combustor.**
- **The baghouse was operated for nearly all hours on-coal during the LMF5-I test. The particulate collection efficiency remained very high. Emissions were well under New Source Performance Standard (NSPS) requirements.**
- **The dry ESP removed as much as 99.8% of the particulate at flow conditions higher than the design point during the LMF5-I test.**
- **Compliance tests conducted at the stack showed a mass emission rate of approximately 0.06 lb/MBTU while the wet ESP was processing 10-20% of the gas flow. This is well below the CFFF's operating permit limit of 0.17 lb/MBTU.**
- **Testing of the Busek generator test module in the CFFF during LMF5-J was successfully concluded.**

TABLE OF CONTENTS

SECTIONS

I. OBJECTIVE AND SCOPE OF WORK	1
CFFF PROGRAM GOALS AND SCHEDULE	3
II. SUMMARY OF TECHNICAL PROGRESS.....	5
TASK 3 - BASE OPERATIONS FOR THE CFFF.....	5
FACILITIES OPERATION, MAINTENANCE, AND REPAIR	5
TEST CONTROL AND SUPPORT.....	5
DATA ACQUISITION SYSTEMS.....	7
ENVIRONMENTAL AND ANALYTICAL SERVICES	7
ENVIRONMENTAL MONITORING.....	8
Water Quality	8
Terrestrial Ecology	8
Ambient Air Monitoring.....	8
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
PARTICULATE REMOVAL SYSTEMS	11
Baghouse (BH) Performance	11
Dry Electrostatic Precipitator (ESP) Performance.....	13
Wet Electrostatic Precipitator (ESP) Performance	15
MASS BALANCE AND AUTOMATIC DATA SCREENING	15
CFFF Mass Balance	15
CFFF Data Reduction	15

Data Filtration Programming	16
Chemical Analysis Database	16
Secondary Combustor Seed Variation Experiments	16
Potassium-Sulfur Kinetics Study	17
Ash Deposition Modeling.....	17
 ADVANCED MEASUREMENT SYSTEMS	 18
TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS	25
TASK 6 - MODIFICATIONS/ADDITIONS TO THE CFFF	25
HIGH TEMPERATURE AIR HEATER (HTAH) DEVELOPMENT	25
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.....	6
3. Baghouse Cleaning Cycles at the Start of LMF5-I.....	12
4. Dry ESP Field 1 Operating Parameters During LMF5-I	14
5. Pressure Measurements and Coal Flow at the Instrument Ring	19
6. Typical Insittec Measured Particle Size Distributions.....	20
7. Typical Particle C_v Variations.....	21
8. TS1 and BH/ESP Inlet Particle Size Distributions	22
9. Effects of Induced Agglomeration at the BH/ESP Inlet	23
10. TS1 Line Reversal and SiDA Measurements.....	24
11. Busek Generator Module	26
12. Busek Generator Module Installed in Test Train	26

TABLES

1. CFFF Test Series	10
2. LMF5 Samples from Test Section Tubes after 639 Exposure Hours	11
3. Baghouse Particulate Collection Efficiency During LMF5-I	11
4. Dry ESP Collection Efficiency During LMF5-I.....	13

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 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 with the evaluation of test specimens for tube construction with promising composite materials.

- The addition of a wet electrostatic precipitator and rotary drum filter 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 FY93.

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 July through September 1993 period, and FY93.

FIGURE 1. SCHEDULED TASKS

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SECTION II

SUMMARY OF TECHNICAL PROGRESS

This section addresses the technical progress of work conducted during the period July 1 through September 30, 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

During the LMF5-I test, the rotary drum filter support shaft failed at the weld between the shaft and drum stiffeners. The shaft failure caused damage to the drum support bearings and to the gearbox seal and drive chain. New stiffeners were welded to the drum. A collar was welded to the stiffeners and a new shaft was welded to the collar. The bearings were replaced. The gearbox and drive chain were repaired. All repairs were completed prior to the LMF5-J test.

The following additional maintenance items were accomplished.

- The control room and computer room air conditioning system that failed during test LMF5-I was repaired.
- The dry ESP pre-heater was replaced.
- Ash system denseveyors were cleaned and repaired.
- Refractory in the north side of test section no. 1 (TS-1) hopper was removed and replaced.

TEST CONTROL AND SUPPORT

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

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

Documentation of the Busek Company generator channel module instrumentation requirements and drawings showing the physical location of the Busek instrumentation were prepared. The two hundred and fourteen data channels

FIGURE 2. CFFF Integrated MHD Bottoming Cycle Schematic

required for testing the generator module were assigned names and were entered in the Computerized Instrumentation and Data Manual (CID).

DATA ACQUISITION SYSTEMS

A Busek channel electrical power network to simulate generator conditions was designed and installed. The design maximizes use of existing power resistors and wiring already in place as part of the former generator power-take-off. In addition, water flow and electrical measurements needed for Busek testing were installed and calibrated.

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

The following additional electrical maintenance items were accomplished.

- The number 2 diesel pump (fire loop) control and charging circuit were repaired.
- Underground cable was installed to lighting in the coal yard area.
- The vent fan in the test building was repaired.
- Dry ESP preheater controls were repaired.
- The ash removal system control program was modified to speed up the sequencing to increase the throughput of ash from the dry ESP.

ENVIRONMENTAL AND ANALYTICAL SERVICES

Composite samples from fuel, ash, slag, and deposits from the LMF5-I and LMF5-J tests were received and analyzed. In addition, samples were collected and analyzed each month from the designated stream and lake sites.

A round robin coal sample was received from Standard Laboratories and analyzed as an external quality assurance check. This program provides averaged data from more than 200 independent coal laboratories for quality assurance purposes. All results with the exception of heating value were within ASTM limits. Apparently the jacket temperature and the bucket temperature on the bomb calorimeter were not balanced correctly prior to the analysis. Due to budgetary constraints, participation in this QA program has been discontinued indefinitely.

The laboratory will complete analysis of all MHD samples from CFFF tests and distribute the data. Water quality samples will continue to be collected and analyzed as determined by permit requirements and other considerations.

ENVIRONMENTAL MONITORING

Efforts were taken for the orderly shutdown of off-site monitoring facilities.

Water Quality

The routine monitoring and treatment of the holding ponds continued. Monitoring efforts were intensified during the LMF5-J test period due to the increased flow through the ponds while testing.

Terrestrial Ecology

No activity for this area of work was conducted during the quarter.

Ambient Air Monitoring

A quarterly QA audit by the State of Tennessee Division of Laboratory Quality Assurance was completed in September 1993. The results indicated all instrumentation to be operating within EPA operational guidelines.

Groundwater Monitoring

Groundwater level measurements were completed and the input used to estimate groundwater flow. The State of Tennessee, Division of Solid Waste Management was contacted to provide input on the future groundwater monitoring requirements. Representatives from the State are scheduled to visit UTSI in October 1993 to review action necessary to comply with Tennessee permit regulations.

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

TESTING

A western coal long-duration, proof-of-concept (POC) test, LMF5-I, was completed in July 1993 and accomplished 212 hours on coal. The primary objective to operate with 1% potassium in the primary flow, with seed added into the primary combustor as a 47% solution of potassium carbonate, was accomplished. An orderly shutdown was made at this point due to upstream water leaks, slag tap blockages and a burned out dry electrostatic precipitator (ESP) auger motor.

A western coal POC test, LMF5-J, was completed in September 1993. It was terminated after 52 hours on coal due to a loss of coal flow caused by plugging of the coal delivery line to the combustor. However, the primary objectives were accomplished: to operate at a nominal stoichiometry of 0.85 and a nominal secondary stoichiometry of 1.10 with 1% potassium added to the primary combustor as a 47% solution of potassium carbonate; to install in the test train and evaluate a Busek Company generator module prototype and return the module and test data to Busek for evaluation.

Table 1 shows the CFFF testing completed through September 1993. This completes the testing program for FY93.

DOWNSTREAM COMPONENT SYSTEMS

The information reported this quarter is primarily based on data obtained during the LMF5-I test. The LMF5-J test was also completed this quarter but most of this test data was not analyzed in time for the publication of this quarterly report.

Superheater Test Module (SHTM) Gas-side Tube Corrosion Studies

Following the LMF5-G test in October 1992, sections were cut from selected superheater/intermediate temperature air heater test section tubes to conduct corrosion evaluations of those alloys after 639 test exposure hours. Each extracted section was replaced with virgin material of the same alloy. Table 2 gives the location and tube alloy of each section extracted. These sections were further reduced in length and were cut into quadrants, one quadrant centered on the upstream or leading edge, one on the trailing edge, etc. The quadrant samples were individually encapsulated in plastic mounting material, sectioned perpendicular to the tube axis, ground and polished. The location of each polished section was precisely where pre-exposure ultrasonic wall thickness measurements were made. Microscopic measurement of remaining wall thickness and also of corrosion scale thickness and subsurface penetration depth were in process, but no quantitative results were available. However, there was no thinning or any sign of corrosion evident from unmagnified observation of the polished sections. Scales under magnification were found to be thin, like those from Illinois #6 coal tests after 500 hours, and of similar thickness to the steam-side scales. Corrosion evaluation of the 639-hour tube samples will continue along with compilation and reporting of results.

The LMF5-J test concluded LMF5 POC western coal testing and corrosion exposure of the test section tubes. Final accumulated exposure time will be about 1000 hours. Following the LMF5-J test, samples were cut from tubes at the locations where pre-exposure ultrasonic wall thickness measurements were made. The type of corrosion evaluation performed will depend upon the budgeted time and personnel available. More accurate remaining wall thickness measurements can be made from polished sections, in addition to the ability to obtain scale thickness and penetration depth data, and to examine scale composition and morphology. Since half or more of the effective wall loss for austenitic alloys may be due to subsurface penetration,

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).)

microscopic examination of polished sections is the only way to obtain accurate and really meaningful results. However, the time required to accomplish this would be much greater than for simply glass bead blasting of the samples to remove exterior and interior scales and making wall measurements by micrometer.

Table 2. LMF5 Samples from Test Section Tubes after 639 Exposure Hours

<u>Tube</u>	<u>Pass</u>	<u>Location</u>	<u>Material</u>
TS1-1	2	Bottom	316
TS1-2	2	Bottom	253MA
TS1-3	2	Bottom	347H
TS1-4	2	Bottom	304H
TS1-5	2	Bottom	310
TS2-1	2	Bottom	316
TS2-2	2	Bottom	253MA
TS2-3	2	Bottom	347H
TS2-4	2	Bottom	304H
TS2-5	2	Bottom	310
TS3-5	1	Middle	T9
TS3-6	1	Middle	T22
TS3-7	3	Middle	T11
TS3-8	1	Middle	304H
TS3-8	4	Bottom	SA192

PARTICULATE REMOVAL SYSTEMS

Baghouse (BH) Performance

The baghouse was operated for nearly all hours on-coal during the LMF5-I test. The particulate collection efficiency remained very high as measured by isokinetic particulate samples (see Table 3). Emissions were well under New Source Performance Standard (NSPS) requirements. As with all tests using high K_2/S ratios on western coal, the reverse air using sonic horn assist was ineffective in removing collected ash from the bag surface. It was observed, once again, that the very first cleaning cycle of the test was extremely long (nearly 3 hours), with all remaining cycles averaging less than 45 minutes (see Figure 3). Apparently, during the intervals between LMF5 tests, the ash fell from the bags which proved that the bags were not blinded, but rather the cleaning method was ineffective.

Table 3. Baghouse Particulate Collection Efficiency During LMF5-I

Date	Gas Flow ACFM	Particulate Emissions lb/MBTU	Collection Efficiency %
7-11-93	5500	0.0057	99.91
7-14-93	5340	0.0036	99.97
7-17-93	5010	0.0092	99.87

FIGURE 3. Baghouse Cleaning Cycles at the Start of LMF5-I

In an attempt to improve the length of time between cleaning cycles an alternate cleaning procedure was attempted. During the reverse air operation on a particular compartment, the reverse air poppet dampers were cycled from open-to-shut at intervals of approximately 10 seconds during the 2-minute cleaning period. This marginally improved the length of time between cleaning cycles by approximately 5 to 10 minutes. By cycling the poppet damper, the bags were inflated/deflated several times which proved to be more effective than the conventional method of cleaning. Higher reverse air flow may be required to provide the necessary cleaning for proper operation. This can only be accomplished by installing a higher capacity reverse air blower.

Dry Electrostatic Precipitator (ESP) Performance

The dry ESP removed as much as 99.8% of the particulate at flow conditions, higher than the design point during the LMF5-I test. By replacing the discharge wires with smaller diameter wires prior to the LMF5-H test, the efficiency of the dry ESP has been exceptional. During the LMF5-I test, four separate particulate emission tests were performed (see Table 4). The test on July 9, 1993 was conducted with very little seed flow. The remaining tests were conducted at higher flow and lower specific collection areas (SCA) than the design condition of 6300 cfm (475 SCA). Emissions were under NSPS requirements, except for the test on 7-14-93, when the flow was 40% greater than design.

Table 4. Dry ESP Collection Efficiency During LMF5-I

Date	Outlet Gr/DSCF	Outlet Flow lb/MBTU	ACFM	SCA	Collection Efficiency, %
7-09-93	0.0196	0.0236	6,750	445	99.1
7-10-93	0.0109	0.0116	7,620	394	99.8
7-14-93	0.1473	0.1828	10,580	284	98.2
7-17-93	0.0217	0.0250	7,680	390	99.6

The only problem experienced with the dry ESP was ash bridging in field 1, resulting in shorting out of the field. Apparently, due to the increased ash throughput from increased flow and collection efficiency, the automatic ash handling system cannot handle the dust at the rate the ESP is removing it from the gas stream. Once it forms a bridge in the hopper, the auger merely tunnels through the ash. The ash accumulates and eventually touches the wire rack and shorts it out. During the LMF5-I test, shorting occurred approximately every 24 hours (see Figure 4). Restoring the ESP to its proper operation required shutting down and manually removing the ash. Steps have been taken to speed up the automatic ash handling routine to prevent shorting from occurring.

FIGURE 4. Dry ESP Field 1 Operating Parameters During LMF5-I

Wet Electrostatic Precipitator (ESP) Performance

The wet ESP was used sparingly during the LMF5-I test, consisting of startups, shutdowns, BH cleaning cycles, etc. No collection efficiency results are available as the one mass loading measurement conducted was invalidated. However, the collection efficiency was probably not above 90%, based on stack opacity during periods when significant portions of the gas flow were directed through the wet ESP. **Compliance tests conducted at the stack showed a mass emission rate of approximately 0.06 lb/MBTU while the wet ESP was processing 10-20 % of the gas flow. This is well below the CFFF's operating permit limit of 0.17 lb/MBTU.**

As with previous tests, potassium sulfate crystalline deposits were formed in the electrical section of the wet ESP. Since the recycled filtered solution is saturated with potassium sulfate, further evaporation in the wet ESP results in precipitation of crystals which attach to discharge electrodes and shorted-out the honeycomb sections. These deposits degrade the collection efficiency of the wet ESP. To eliminate these effects it may be necessary to limit the concentration of potassium salts (carbonate and sulfate) to below their saturation point. This, however, would require significant blowdown rates which add to the testing cost because of disposal costs for the blowdown solution.

MASS BALANCE AND AUTOMATIC DATA SCREENING

CFFF Mass Balance

Work continued on modifications to the mass balance program, collection of data used by the program, and completion of CFFF mass balances. A major program addition, adding ability to the program to accept carbonate analyses for various feed and product streams, was completed. In checking the output after this addition, most streams appeared fine, but the inorganics balances seemed to be "adversely affected" by the modifications. The errors associated with the inorganics balances were then found and corrected. The revised mass balance program outputs were then thoroughly checked for accuracy and the program now appears to be functioning properly. To perform this work, protection schemes for the various program parts were changed to permit others to modify the program codes.

A technical paper discussing recent mass balance results was presented at the Thirty-First Symposium on Engineering Aspects of MHD (SEAM).

CFFF Data Reduction

Process condition (filtered and reduced) data files from the LMF5-A-G tests were corrected. Reduced test data from the LMF5-H and LMF5-I tests were generated using the PULL computer program. The time required to manipulate large data files continues to be the main impediment to our rapid reduction of test data.

Data Filtration Programming

Work has resumed on expanding existing data filtration capabilities. The previous work done on a "generic" algorithm, and programmed in LISP is under review, to be followed by translating needed portions of that program into the "C" computer language, and then testing and implementation.

Chemical Analysis Database

Additional chemical analytical results were completed. The CHEMUPDATE computer program was run to type and transfer the 91 new chemical analyses provided to the computer chemical analysis database. A new computer program to output only updated records was written and successfully tested. It was used to create a computer file of the updated chemical analysis results.

Also a number of recent chemical analyses have been extended (i.e., additional chemical analyses were obtained for a sample after original analyses were completed). A number of these "new results" were manually added to the chemical analysis database. If time and resources are available, this problem will be further addressed.

Secondary Combustor Seed Variation Experiments

During the LMF5-I test, seed variation experiments were conducted to determine the effect of seed on secondary combustor performance. During these experiments, fuel and oxidizer inputs were adjusted to maintain an approximately constant secondary combustor inlet gas temperature, while the primary stoichiometry was adjusted to nominal values of 0.80, 0.85, and 0.90. Final stoichiometry was maintained at about 1.05 for all cases by adjusting the secondary air flow to maintain 2% O₂ at the secondary combustor outlet (SCO) sampling location. Seed flow was varied in discrete steps from zero to the normal flow rate corresponding to 1% K in the plasma, or until a loss of flame was observed in the secondary combustor.

Three sets of experiments were conducted. During the first set, the measured secondary combustor inlet (SCI) gas temperature was approximately 1530-1550°F (actual inlet gas temperature was estimated at 1630-1650°F). At 1530-1550°F measured inlet gas temperature, seed flow corresponding to a K₂/S ratio of about 2.3 resulted in more than 1% CO remaining in the flue gas at the SCO for the nominal 0.90 primary stoichiometry case. (The actual primary stoichiometry estimated from the SCI CO concentration was 4 to 5 percent higher than the nominal value for all cases due to air leakage into the furnace.) Higher seed flow was required to produce the same effect at lower primary stoichiometries, but in both the 0.80 and 0.85 nominal primary stoichiometry cases seed flow corresponding to a K₂/S ratio of about 3.3 resulted in more than 1% CO remaining in the flue gas at the SCO. The results indicate that the effect of potassium on combustion is greatest when the concentration of reactants is lowest and the concentration of potassium is highest, as expected for kinetically-based flame inhibition.

The experiments were repeated when the measured SCI gas temperature was approximately 1770-1800°F, and again when the measured temperature was approximately 1970-1990°F. No effect of seed concentration was observed during these experiments, indicating that the gas temperature was high enough to overcome the retarding effect of potassium on the flame reactions. Similar experiments were carried out during the LMF5-J test with similar results. The data from the LMF5-J test experiments will be analyzed and reported.

Potassium-Sulfur Kinetics Study

An experiment was designed to measure the effect of K and S on a methane (CH_4) flame in a laminar flat flame burner. Flame temperature will be measured using potassium line reversal and K and OH concentrations will be measured using flame spectroscopy. Reaction rates determined from the experiment will be used to model secondary combustor performance. The flat flame burner was fabricated and checked out. The equipment was setup to make flame temperature and OH absorption measurements.

Initial measurements of flame temperature were made using potassium line reversal. Flame temperatures were initially far lower than anticipated (about 1500 K). It was determined that heat transfer to the burner face was greater than expected. This effect was offset by increasing the burner flow rate, after which a flame temperature of about 1800 K was obtained. In order to increase the flame temperature further, the flow metering system must be modified to increase CH_4 flow. The burner will also be water cooled as a precaution. With these two modifications, it should be possible to achieve flame temperatures up to 2000 K.

Design of the optical system for the OH absorption measurements was completed. It was determined that a spatial resolution of 0.5 mm was possible. Such a configuration was set up, using a focused asymmetric lens system, and the desired spatial resolution was obtained. The flame was scanned for OH rotational transitions and good lines were found between 3100 and 3110 angstroms. However, the lines were less resolved than desired. The spectrometer's internal alignment was probably not correct. A realignment of the spectrometer is planned. According to the spectrometer specifications, it should be possible to obtain a spectral resolution of 0.1 angstrom, which should be sufficient to resolve the individual lines. In spite of the spectral resolution problem, the OH decay in the flame was qualitatively investigated by setting the spectrometer on an absorption peak and moving the burner vertically downward. The resulting OH decay profile was evident and the trend was as expected.

Setup of the experiment is in progress and detailed measurements will begin if testing is resumed.

Ash Deposition Modeling

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 will 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 deposition model. An initial (simplified) calculation of heat transfer with the finite element code was successfully carried out.

Other work involved evaluating fire-side deposits as they formed on a rotatable superheater ash deposition probe in the LMF5-I test during an eight-hour period following sootblowing. Dimensions of deposit thickness and width were obtained using computer image-analysis measurements of videotaped images. After the LMF5-I test, thickness measurements were made in-place and samples of deposits remaining on selected areas of several tubes in test sections 1, 2, and 3, were taken. Photographs were made of several deposits. A concept for a new tool and procedure to aid in measuring on-tube porosity of powdery superheater tube deposits after the LMF5-J test was developed. The results of image analysis will be reported.

The AshEffects computer model was used to make deposition calculations of velocity effects on inertial impaction of fly ash on a 2.5" O.D. superheater tube in 10 feet/second intervals for flue-gas velocities from 20 to 70 feet/second. The results of the modeling effort show how significantly deposit thickness patterns in an MHD test section can be influenced by local variations in velocity. This helps to explain and better understand the general observations after the LMF5-I test. The final report will examine this phenomenon in more detail.

Work was started on measuring sintered bond strength (via cold crushing strength) of ash particles after sintering in a laboratory furnace for a controlled time/temperature period. A standardized test procedure was developed. Heating and cooling curves, and accuracy of isothermal set-points of the test furnace were measured. Initial measurements were completed successfully using ash specimens sintered at 1700°F. All five specimens were within approximately +/- 1.5 standard deviations of the average cold crushing strength.

ADVANCED MEASUREMENT SYSTEMS

The LMF5-I and LMF5-J tests were supported with a number of diagnostics systems including the UTSI diffuser, furnace and test section 1 (TS1) line reversal systems, the particle sample extraction/dilution system (SEDS); Insitac, Inc.'s particle probes; and Mississippi State University's (MSU) multicolor pyrometers (MCPs), silicon diode array (SiDA) pyrometer system, two color laser transmissometer (TCLT) particle loading diagnostic, and laser Doppler velocimeter (LDV). The non-UTSI provided diagnostics were employed during the LMF5-I test. Although the Insitac, Inc. probes were brought to the CFFF for LMF5-J as well, delays in test initiation prevented application during the LMF5-J test. Although no diagnostics were employed at the instrument ring between aerodynamic replacement duct modules CD-1 and CD-2 for

either test, the ring was installed for the LMF5-I test with a pressure port assembly to determine if flow choking occurred at the ring as suspected from earlier MSU LDV and potassium emission absorption measurements^{1,2}. Periodic pulse purging was used to remove slag build up, but slag blocked the port before pressure readings were taken at the start of the LMF5-I test. The pressure port was cleaned just prior to re-ignition on July 13, and pressure data was obtained for about 20 minutes after the POC thermal input conditions were established. After this period slag accumulation in the pressure port obscured accurate pressure readings. The good pressure measurements are shown in Figure 5, along with continued measurements as the port plugged. Measured pressure was 2.24 Atm, the expected pressure for choked conditions. A 1.7 Atm pressure would be expected for supersonic flow at the instrument ring to throat area ratio. Thus, these measurements confirm the choked flow hypothesis.

FIGURE 5. Pressure Measurements and Coal Flow at the Instrument Ring

UTSI, Insitec, Inc., and MSU successfully applied their different particle diagnostics during the LMF5-I test. MSU installed their TCLT at the particle removal systems inlet ducting as well as at the dry ESP outlet ducting for comparisons with measurements made during earlier LMF5 tests. The TCLT results indicate that for the LMF5-I test at POC conditions the particle loading entering the particle cleanup systems was essentially unchanged from earlier LMF5 POC loadings, but that the dry ESP was not performing quite as well as during the LMF5-H test. The UTSI SEDS system again could not be properly operated at the particle removal systems inlet ducting because the extraction tubing plugged rapidly whenever it was used. The plugging originated upstream of the orifice, and post test evaluations showed the sample extraction pump to be too small to continuously extract a representative sample from the sub-atmospheric flue ducting. Attempts to configure improved sample extraction for the LMF5-J test were unsuccessful, although the speed of plugging was decreased. Due to the inadequate capacity of the sample pump, the dilution pump

was providing most of the sample extraction as well as the dilution flow. Funding limitations prevented correcting this problem.

Insitec, Inc. measured both particle size distributions ($dN/d\ln D$ vs. D) and volume concentrations (C_v) vs. time in the inlet ducting to the particle removal systems and in the dry ESP outlet ducting. Insitec also measured particle size distributions in the baghouse (BH) outlet ducting and at the entrance to TS1, and measured volume concentrations in the wet ESP outlet ducting. Typical particle removal systems inlet and outlet measurements are provided in Figures 6 and 7. Multiplying C_v by particle density provides particle mass loadings for the $10\ \mu\text{m}$ and smaller particles monitored by the Insitec "TESS" C_v probe. From these measurements, efficiencies for the dry ESP and BH were determined to be near 99.8% and 99.98%, respectively. Appropriate measurements could not be made for the wet ESP since it was not functioning properly when C_v measurements were made during both the LMF5-I and LMF5-J tests.

FIGURE 6. Typical Insitec Measured Particle Size Distributions

Insitec's measurements of particle loadings at the TS1 inlet were far lower than at the BH/ESP inlet ducting, and this allowed their optical "PCSV" probe to measure particle size distributions down to $0.31\ \mu\text{m}$. Most of the mass was concentrated in particles less than $6.3\ \mu\text{m}$, so additional time to determine larger particle loadings was not taken to diminish overheating possibilities for the probe in the 1550K (2330°F) TS1 inlet gas environment. Figure 8 shows measured particle size distributions at TS1 compared to a typical distribution measured at the BH/ESP inlet ducting, and show that the TS1 distributions are about two orders of magnitude lower in loadings for a given particle size.

a. BH/ESP Inlet

b. Dry ESP Outlet

FIGURE 7. Typical Particle C_v Variations

FIGURE 8. TS1 and BH/ESP Inlet Particle Size Distributions

The MSU LDV fiber optic system was installed at line of sight penetrations downstream of the secondary combustor just below the air manifold. At the combustor center the forward scatter collection system provided axial (x) and cross-stream (y) gas velocity component signals for acquisition by both the MSU and UTSI frequency domain laser velocimeter (LV) processors. Both processors had no difficulty processing the collected signals at sufficiently high rates to allow determination of any recirculation zone oscillation frequencies as were predicted by the UTSI cold flow studies of secondary combustor mixing^{3,4}. Weak flow oscillation frequencies were detected in the 5-10 Hz range where the flow oscillations were expected from the cold flow model data. A cursory comparison of mean axial velocity and turbulence intensity showed good agreement for the two different processing systems, both giving a mean axial velocity of about 31 m/s and standard deviation of 7 m/s. This results in a $U/V = 3.4$ and $u'/V = 0.8$ versus cold flow predictions of 3.6 and 1.4, respectively, where V is the bulk jet injection velocity, U is the axial velocity, and u' is the axial velocity standard deviation. This data was acquired in support of the secondary combustor modeling for evaluation of flame suppression by potassium^{5,6}.

Experiments were conducted to test particle agglomeration enhancement techniques being developed at UTSI during both the LMF5-I and LMF5-J test. A 5-stage cyclone measurement of the particle size distribution and loading was made in the BH/ESP inlet ducting during these tests which was aimed at enhancing agglomeration of submicron particles. The resulting particle size distribution, Figure 9, shows significant agglomeration as predicted⁷.

FIGURE 9. Effects of Induced Agglomeration at the BH/ESP Inlet

Previous comparisons of the MSU SiDA probe at the TS1 inlet transition with the TS1 inlet line reversal showed excellent agreement, but the temperature difference between the gas and wall surface was only about 20K (35°F), and was not as high as expected. This was attributed to problems with the line reversal system alignment and the separation distance of the two instruments. To confirm this hypothesis, the comparison was repeated with the line reversal and SiDA systems operating without problems. As shown in Figure 10, the two systems again showed exceptional agreement in measured temperature level oscillations, with the line reversal showing about an 80K (150°F) higher level. A difference of about 100K (180°F) was anticipated. This is obtained by adding half the difference shown between the inlet thermocouple, located near the SiDA monitoring station, and the middle TS1 thermocouple to correct for the cooling of the gas going from the SiDA probe in the inlet transition to the line reversal location at TS1.

FIGURE 10. TS1 Line Reversal and SiDA Measurements

In addition to the above test diagnostics for the LMF5-I test, MSU employed both their multi-color pyrometers (MCPs) and the SiDA pyrometer system to support the high temperature air heater (HTAH) studies and furnace heat transfer studies. Insitec provided support during both the LMF5-I test and before the LMF5-J test to evaluate uncertainties of the SEDS system. In both cases significant data was acquired and was made available for reporting in these subject areas.

TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS

Modifications to the CFFF Low Mass Flow (LMF) test train for installation of the Busek Company's MHD generator test module in place of circular duct (CD-1) in the upstream test train were completed (Figure 11 and 12). Major modifications to the LMF test train that were required to support this effort included the redesign and fabrication of the nozzle and aerodynamic ducting as needed to geometrically mate with the rectangular Busek test module. Transition rings were fabricated and installed in CD-2. The new nozzle was required to maintain a smooth transition from the circular combustor cone to the rectangular channel. The 10 new rings in CD-2 provide a smooth transition from the rectangular channel to the circular duct configuration. Additional efforts for this task included modifying the CFFF upstream cooling water circuits to facilitate installation of the module and the design and assembly of an electrical power circuit to provide power to the module.

Testing of the Busek generator test module in the CFFF during LMF5-J was successfully concluded. This testing was in fulfillment of a DOE Phase II SBIR grant to Busek Company entitled "Ceramic/Metal Elements for MHD Side walls." The module was removed from the CFFF test train, crated and will be returned to the Busek Company early in October 1993.

TASK 6 - MODIFICATIONS/ADDITIONS TO THE CFFF

HIGH TEMPERATURE AIR HEATER (HTAH) DEVELOPMENT

Evaluation of tube materials for a high temperature air heater were conducted in four areas during the quarter:

- Materials Exposure Tests
- Sealing Techniques Tests
- Corrosion Analysis
- Heat Transfer Studies

Materials Exposure Tests

Two composite two-inch OD ceramic tubes manufactured by Lanxide Corp were tested during the LMF5-I test in the 3500°F and 2900°F zones of the radiant furnace. The electric preheater that had been used in the past to preheat air into the test HTAH tubes lost some of its heating elements. To prevent thermally shocking the test tubes from insufficiently preheated air, it was decided to forego the collection of heat transfer data. The tubes were pressurized to test sealing techniques (see next section). Both tubes cracked prior to pressurization, most likely due to problems incurred while trying to get a tight seal at one mounting port and securing the other end of the tube in the opposite mounting port. Any misalignment would produce a large bending stress.

FIGURE 11. Busek Generator Module

FIGURE 12. Busek Generator Module Installed in Test Train

Although the tubes were cracked, most of the material was intact after the 212 hours of exposure to the coal exhaust gases. In addition to the two tubes, a small piece of a tube that was exposed during the LMF5-C,D,E,F,G & H tests (a total of 1151 hours) was recovered. This tube will be analyzed.

During the LMF5-J test, seven of the Lanxide tubes were tested for 52 coal-on hours. Five of the tubes were exclusively materials tests and two were sealing tests (see next section). Of the five materials tested, one was in the oxidizing zone below the secondary combustor. The others were in various temperature zones under reducing conditions within the radiant furnace which ranged from 3500°F down to 2000°F. Special attention was paid to avoiding thermal shock and misalignment problems. All of the tubes withstood the test with no noticeable degradation. These tubes will also be analyzed.

Sealing Techniques Tests

One sealing concept tested during the LMF5-I test involved the machining of a modified acme thread on the open end of the Lanxide tube. This was the second try of this technique, but the machining again included a sharp right angle at the inside shoulder at the base of the threads. Although misalignment may have caused the tube failure, the stress riser at the shoulder caused a crack at that point.

The two sealing techniques evaluated during the LMF5-J test were compression fittings where a portion of the stainless steel ferrule was replaced by a hollow graphite cone. The fittings were attached to the open end of the closed end tubes. A groove was ground into the tube so that a stainless steel ring would prevent the tube from slipping through the graphite. The tubes were pressurized to as high as 220 psig. Both tubes leaked on the order of cubic centimeters per hour and the seals reached temperatures of around 700°F. This method shows promise and it will be further refined.

Corrosion Analysis

The corrosion analysis capability was greatly increased by the incorporation of computer scanning of the microphotographs. This made it possible to quantify the porosity and constituents of many test samples and provides better insight into corrosion rates and effects.

Future plans call for laser plasma vapor deposition coating of the Lanxide material with tungsten, tantalum and titanium coatings to evaluate their effectiveness in corrosion protection.

Heat Transfer Studies

A computer code was modified to predict the effects of heat transfer enhancement devices. The code will be used along with a lab test of a swirl-inducing scheme in a three-inch OD, 48-inch long heated tube. The lab apparatus will simulate

the HTAH temperature environment and will be used to compare the effectiveness of various heat transfer enhancing schemes.

TASK 7 - MHD TECHNOLOGY DEVELOPMENT PROGRAM

No activity was planned or carried out this quarter.

TASK 8 - TECHNICAL SUPPORT AND INTERFACE ACTIVITIES

No activity was planned or carried out this quarter.

TASK 9 - CFFF PROGRAM MANAGEMENT

MANAGEMENT AND ADMINISTRATIVE SUPPORT

The September 1993 Monthly Contract Status Report was issued to DOE/CH.

Revision No. 2 to the FY93 Management Plan was issued to incorporate project 5.2.4 covering the residual costs for the Busek generator module materials test.

A Safety, Health and Environmental Quality Assurance Policy Manual was developed and issued.

A status report of UTSI's corrective actions taken to the DOE Environmental Audit of the CFFF was prepared and sent to DOE.

The development of the FY94 MHD Management Plan with cost projections was continued.

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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
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
ϵ	- Emissivity or velocity fraction
ECF	- Energy Conversion Facility
EFM	- Electric Field Meters
EPRI	- Electrical Power Research Institute
ESP	- Electrostatic Precipitator
EDX	- Energy Dispersive X-ray
Flow Train	- Test facility including all components from the vitiation heater to the stack
GC	- Gas Chromatograph
GC/MS	- Gas Chromatograph/Mass Spectrometer
GIS	- Geographic Information System
HPT	- High Pressure Test
HR/SR	- Heat Recovery/Seed Recovery
HTAH	- High Temperature Air Heater
HVT	- High Velocity Thermocouple
ICAP	- Inductively Coupled Argon Plasma
IMPS	- Intrusive Multi-Probe System
IT	- Inlet Transition
ITAH	- Intermediate Temperature Air Heater
ITC	- Integrated Topping Cycle
LDV	- Laser Doppler Velocimeter
LMF(n)	- Low Mass Flow Test, where n = number of test
LPS	- Light Pipe Sensor
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
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
WBDAAS	- Wide Band Data Acquisition and Analysis System

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