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MHD COAL-FIRED FLOW FACILITY

MASTER

Quarterly Technical Progress Report for the Period July–September 1980

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The University of Tennessee Space Institute
Energy Conversion Division
Tullahoma, Tennessee

U. S. DEPARTMENT OF ENERGY

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Date Submitted - November 1980

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Under Contract No. DE-AC02-79ET10815
Under Contract No. DE-AC01-76ET10757
(Task 1 Only)

ABSTRACT

In this third Quarterly report of 1980 submitted under DOE contracts DE-AC01-76ET10757 (Task 1 only) and DE-AC02-79ET10815, The University of Tennessee Space Institute (UTSI) reports on significant activity, task status, planned research, testing, development, and conclusions for the Magnetohydrodynamics (MHD) Coal-Fired Flow Facility (CFFF) and the Energy Conversion Facility (ECF).

On Task 1, the first phase of the downstream quench system was completed. On Task 2, all three combustor sections were completed, hydro-tested, ASME code stamped, and delivered to UTSI. The nozzle was also delivered. Fabrication of support stands and cooling water manifolds for the combustor and vitiation heater were completed, heat transfer and thermal stress analysis, along with design development, were conducted on the generator and radiant furnace and secondary combustor installation progressed as planned.

Under Task 3 an Elemental Analyzer and Atomic Absorption Spectrophotometer/Graphite Furnace were received and installed, sites were prepared for two air monitoring stations, phytoplankton analysis began, and foliage and soil sampling was conducted using all study plots. Some 288 soil samples were combined to make 72 samples which were analyzed. Also, approval was granted to dispose of MHD flyash and slag at the Franklin County landfill.

Task 4 effort consisted of completing all component test plans, and establishing the capability of displaying experimental data in graphical format.

Under Task 7, a preliminary testing program for critical monitoring of the local current and voltage non-uniformities in the generator electrodes was outlined, electrode metal wear characteristics were documented, boron nitride/refrasil composite interelectrode sealing was improved, and several refractories for downstream MHD applications were evaluated with promising results.

CONTENTS

Abstract	11
Sections	
I. OBJECTIVE AND SCOPE OF WORK	1
II. SUMMARY OF TECHNICAL PROGRESS	4
A. <u>TASK 1 - COMPLETION OF DESIGN AND CONSTRUCTION OF THE CFFF AND FACILITY ACTIVATION</u>	4
1.1 Design and Construction	4
B. <u>TASK 2 - DESIGN AND FABRICATION OF THE 8PPS TEST EQUIPMENT</u>	6
2.1 Primary Combustor	6
2.2 MHD Generator	10
2.3 Downstream Components	16
C. <u>TASK 3 - BASE OPERATIONS FOR THE CFFF AND EC FACILITY</u>	22
D. <u>TASK 4 - 8PPS HIGH SLAG THROUGHPUT TESTING</u>	31
E. <u>TASK 5 - TESTING OF DOE SUPPLIED COMPONENTS</u>	34
F. <u>TASK 6 - MODIFICATIONS TO THE CFFF</u>	34
G. <u>TASK 7 - TECHNOLOGY DEVELOPMENT PROGRAM</u>	34
7.1 Primary Combustor	34
7.2 MHD Power Generator	35
7.3 Downstream Components	55
7.5 Pollution Control	55
7.6 Materials	55
7.7 Diagnostics	64
7.8 Generator Loading	66

III. CONCLUSIONS	67
References	68
Topical Report Status	69

FIGURES

1. Quench System	4
2. Venturi Throat Illustrating the Fluid Injection Nozzles	5
3. Induced Draft Fan with Associated Ducting	7
4. Induced Draft Fan with Cyclone in Background	8
5. Quench Cross Over Duct	9
6. Diagnostic Conductivity Channel	10
7. Heat Flow Schematic in CFFF Capped Electrode Frame	12
8. Peak Capped Electrode Temperature vs. Thermal Conductance of Cap to Frame Bonding Material	13
9. Thermal Stresses in the CFFF Solid Frame	15
10. Stud Installation in Diffuser Section No. 4	16
11. Furnace Inlet Showing Manway and Downcomer Connections	17
12. Fabrication of Low Pressure Water Supply Header	18
13. Diffuser Inlet to Radiant Furnace	18
14. Cutting Prior to Installation of Mandoor into Drum Module	19
15. Completion of Exterior Seal Between the Secondary Combustor and the Ash-Seed Hopper	20
16. Elemental Analyzer	22
17. Atomic Absorption Spectrophotometer/Graphite Furnace	23
18. Boat for Aquatic Sampling	26
19. A Kemmerer Water Bottle Designed for Trace Metals, Insecticide, and Hydrocarbon Sampling	27
20. Hydrolab Sonde Unit which Enables <u>in-situ</u> Measurements of Temperature, pH, Conductivity and Dissolved Oxygen	28

21.	Hydrolab Digital Indicator Unit which Displays Multiple Parameter Readings <u>in-situ</u>	29
22.	CFFF Environmental Monitoring Sites	30
23.	Ballast Resistor to Electrode Connection Scheme	37
24.	Cumulative Current Distribution at Various Loads (Case I) . . .	39
25.	Leadout Current Distributions and Design Point Considerations for Power Take-off (Case II)	40
26.	Comparison Between 2-D Calculation and Experimental Data	41
27.	Current Distribution in the Upstream P.T.O. Region	42
28.	Current and Voltage Distributions in the Upstream P.T.O. Region at Various Primary Loads (Case III)	43
29.	Prediction of Current and Voltage Distributions in the Upstream P.T.O. Region	45
30.	Viscosity of the Slag vs. Temperature	47
31.	Mach Number Contour at N=300	52
32.	U Velocity Vectors at N=300	52
33.	Pressure Contour at N=300	53
34.	Temperature Contour at N=300	53
35.	Potential Contour at N=300	54
36.	Stream Function Contour at N=300	54
37.	Platinum Clad Anode Cap with Exposed Copper Substrate	56
38.	Iridium Clad Anode Cap with Exposed Copper Substrate	57
39.	Cross Section of Platinum Clad Anode Cap	58
40.	Cross Section Copper Anode Cap	59
41.	Cathode Cap Surface Exhibiting Fractured CuO Layer	59
42.	Potassium and Sulfur Rich Deposit on Cathode Surface	60
43.	Oxide Layer on Sidewall Cap in Cathodic Region	60
44.	Vertical Arc Tracks on Sidewall Cap in Anodic Region	61
45.	Pinholes in Sidewall Cap in Anodic Region.	62

TABLES

I. ITAH Materials List	21
II. Resistor Sizes for Power Take-off Schemes	36
III. Test Condition Matrix	48
IV. Radiant Furnace Test Refractories	65

SECTION I

OBJECTIVE AND SCOPE OF WORK

A. Contract No. EX-76-C-01-1760

Under Contract EX-76-C-01-1760, The University of Tennessee Space Institute Energy Conversion Division is to achieve the following goal for Task 1:

- Complete and activate the Coal-Fired Flow Facility

B. Contract No. DE-AC02-79ET10815

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

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

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

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

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

2. Task 3 - Base Operations for the CFFF and the R&D Facility

Perform all operations and maintenance required to maintain the CFFF facility and the R&D Facility in a standby condition. Items included are a) materials and components handling equipment, b) required equipment for installation of components, coal/seed handlings, etc., c) emissions monitoring, and d) instrumentation and sampling devices for continuous monitoring of O₂, CO₂, NO_x, CO, SO₂, H₂S, etc. This Task covers such major services as:

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

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

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

4. Task 5 - Testing of DOE Supplied Components

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

5. Task 6 - Modifications to the CFFF

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

6. Task 7 - Technology Development Program

Develop quantitative performance data pertinent to basic thermal, electrical and gasdynamic design effects in MHD power generation. UTSI is to investigate the contractually specified components and provide recommendations for design, including materials selection and fabrication techniques of advanced components for CFFF verification. This task comprises a continuing effort to improve the technical basis upon which MHD commercialization results throughout the entire plant. The experiments are tracked not only from a standpoint of performance during testing, but also from how these results relate to the fundamental underlying technology. Conceptual designs will be produced, test results evaluated, plans formulated for retesting, and projected work replanned on a basis of data obtained. Theoretical work will be

utilized to aid the design as well as predicting and interpreting experimental results. This task will support the technology needs of the 8 lb/sec facility.

7. Task 8 - Test Integration and Interface

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

8. Task 9 - Program Management

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

SECTION II

SUMMARY OF TECHNICAL PROGRESS

A. TASK 1—COMPLETION OF DESIGN OF CFFF & FACILITY ACTIVATION

1.1 Design and Construction

All of the construction bid packages are completed. Finish-up type construction projects have generally been completed, and the sample preparation and inverter shelters are almost completed and ready for occupancy. The holding pond designs were released, and bids were requested and received. Procurement should be initiated when funds are made available. The High Mass Flow Quench specification was completed and quotes received. The purchase order will be released when funds are made available. Next Quarter, holding pond progress will be reported.

The first phase of the quench system was completed with the venturi, cyclone and transition duct installed in Bay 2 (see Figures 1 and 2).

Figure 1. Quench System

Figure 2. Venturi Throat Area Illustrating the Fluid Injection Nozzles

All connection ducting to the induced draft fan was installed as planned (see Figures 3 and 4). Late delivery of the hydroclones and associated piping prevented system completion by the end of the report period. These items will arrive during the first part of next Quarter. For more detailed clarification, Figure 5 is presented to show the quench crossover duct (90% installed). Next Quarter installation details will continue as planned.

The opacity monitor to be used in the CFFF was received this Quarter. This was the last instrument scheduled for emissions monitoring until a request was received for monitoring water content in the gas in the radiant furnace. A dew point monitor for this use has been specified and is out for bids. The trailer to house the instruments for the CFFF was received and instrumentation racks installed. All of the new instruments for this trailer have been mounted in the racks. The Bendix sampling systems will arrive early next Quarter and will be installed in the van.

B. TASK 2—DESIGN AND FABRICATION OF THE 8 LB/SEC TEST EQUIPMENT

2.1 Primary Combustor

A test of the gas turbine combustor vitiation heater was conducted in the ECF. Unfortunately, problems occurred with the fuel flow control, and the combustor was destroyed. However, two more gas turbine combustors of a more modern and heavy duty design were donated by General Electric. These combustors were received during this Quarter.

The low mass flow (LMF) vitiation heater was delivered this Quarter. It was discovered early in July that the coal access port was incorrectly angled. This problem was resolved by installing an additional access port. The liner had to be removed, requiring new insulation and a code stamp "R." The heater modification is now complete, and assembly of the coal transport tube can now be completed. The UTSI burner will be installed in the vitiation heater.

Fabrication of support stands and cooling water manifolds for the combustor and vitiation heater were completed. Items for the facility interfacing of oxygen, nitrogen and fuel oil have been ordered and some, such as the flow venturies, have been delivered. An additional fuel oil system for the oxidizer plate is presently under design.

All three combustor sections have been completed, hydro-tested, ASME Code stamped and delivered. Some modification was made to the cooling water access tubes to provide for hose connections. The refractory has also been installed in these sections. Curing will take place in October in conjunction with the curing of the radiant furnace refractory.

Machining of the oxidizer plate is approximately 80% complete. This plate should be delivered in early October. Next Quarter, all of the oxygen, nitrogen, cooling water, and fuel oil lines should be installed.

As reported last Quarter the nozzle has been delivered to UTSI. All hydrotesting and other preparations have been accomplished. The component is scheduled for instrumentation and assembly into the test train during the coming Quarter.

Figure 3. Induced Draft Fan with Associated Ducting

Figure 4. Induced Draft Fan with Cyclone in Background

Figure 5. Quench Cross Over Duct (90% Installed)

The components of the diagnostic conductivity channel have been received and portions of the channel have been assembled (see Figure 6). Several insulator systems are being examined in conjunction with channel assembly. In addition, design of the downstream optical diagnostic module has been initiated. Instrumentation planned for this module includes luminosity systems for temperature profiles, line reversal for absolute temperature, and a traversable pitot for pressure profiles and gas sampling. The feasibility of using laser velocimetry in this module is also being evaluated. Results of this work will be reported on next Quarter.

Figure 6. Diagnostic Conductivity Channel

2.2 MHD Generator

The extensive activity conducted this Quarter is discussed under three headings: heat transfer and thermal stress analysis, generator design and fabrication, and diffuser design development and fabrication.

a. Heat Transfer and Thermal Stress Analysis

Analysis of the heat transfer characteristics of the CFFF capped electrode design continued through this Quarter. This study constitutes part of an overall effort to investigate the operating temperatures for the CFFF electrode caps and to evaluate the cooling characteristics of the capped electrode design. Sub-efforts related to this analysis include a thermal bench test being conducted on an assembled capped frame copper model and a thermal stress analysis of the capped electrodes structure.

These studies will provide input as to the final means employed for bonding the cap to the frame in the CFFF generator channel.

A numerical finite element model of the capped electrode design has been developed to study the heat transfer in the assembled structure. This model incorporates composite materials to account for the bonding material between the cap and frame and also to allow the study of stainless steel caps over copper frames. The model is subject to a constant heat flux at the plasma surface boundary. Heat loss between adjacent frames is imposed as a sidewall boundary condition by matching the temperature and heat flux at corresponding points along the opposite sidewalls. (This is in contrast to earlier work reported wherein the sidewalls were assumed to be adiabatic.)

Results of computations performed with the two-dimensional, finite element model indicate that appreciable interframe heat transfer will occur during generator operation. This exchange takes place along the interface of the upstream leg of the cap and its adjacent frame. For cap-to-frame bonding material with a very low thermal diffusivity, the interframe heat transfer dominates. Such a case is illustrated by the results given in Figure 7.

The interframe heat transfer dictates that a steady state thermal distribution will be present in the assembled structure even for a gap material which thermally insulates the cap from its frame. In this situation, all the heat which enters at the cap plasma surface will be dissipated in the cooling passage of the upstream adjacent frame. The maximum temperature for any given cap heat flux is dictated by the ability of the system to transfer heat in this manner.

Results of a series of numerical computations performed on the capped electrode are shown in Figure 8. These represent a parametric study of the peak cap temperature as a function of plasma surface heat flux and gap material conductivity. In the CFFF generator, the maximum heat flux projected is near 350 watts/cm² which occurs in the entrance region of the channel. Based on the prediction of Figure 8 it can be seen that real, "as built," gap conductivities for the CFFF must be limited to greater than .010 watts/cm²-°C. At lower levels, the temperature level of the cap surface exposed to plasma flow will become severe and an increase in the electrochemical erosion rate will occur with the possibility of local melting. Results from the thermal analysis performed thus far indicate that the material selected to bond the cap to the frame must be specified to achieve maximum electrical and thermal conduction. The interframe heat exchange demonstrated by the mathematical model will provide a secondary path for heat to flow. This effect, which was not considered in earlier analyses of the system thermal behavior, will serve to relieve the temperature levels in the cap somewhat. However, the choice of the cap-to-frame bonding material remains a critical item in assuring optimum operating temperature for the design.

A series of calculations was made to evaluate the thermal stress levels in the window frame design generator. These computations were performed on the Control Data Corporation (CDC) computer system using the "ANSYS" program. ANSYS is a general purpose stress and thermal stress

Figure 7. Heat Flow Schematic in CFFF Capped Electrode Frame

Figure 8. Peak Capped Electrode Temperature vs. Thermal Conductance of Cap to Frame Bonding Material

computer program which can be adapted to practically any geometry and boundary condition (both thermal and loading). In the stress analysis performed thus far, a solid copper frame of the CFFF type geometry was evaluated.

The solution for the thermal gradients which are required as input to the stress calculations was also predicted by the ANSYS program. The heat transfer model used in this thermal analysis was that of a solid copper frame with a constant plasma surface heat flux and adiabatic sidewalls. The thermal gradients predicted by ANSYS agreed quite well with those generated using the finite element code developed at UTSI, which has been previously described.

The stress problem posed was that of plane stress. As such, pure two-dimensional stresses are predicted in the cross-section of the electrode. The entire electrode was free to expand in all directions, which restricts the solution.

Results of thermal stress calculations (see Figure 9) using the ANSYS code are for a solid copper frame subject to a surface heat flux of 350 wt/cm.² The thermal displacement of the frame and contours of all three principal stresses are shown with stress contours given in uniform increments around the neutral (zero stress) contour. Maximum and minimum principal stress levels are located on the frame; their magnitude is called out for reference. The overall maximum predicted local thermal stress is about 5500 psi, with this maximum level predicted to be on the upper plasma surface of the frame near its center. All these stress levels computed by ANSYS are well within the yield point of the copper material. Further stress calculations with ANSYS are planned in the future. A solution for the capped electrode considering composite material and modeling of the entire three-dimensional structure will be pursued.

b. Generator Design and Fabrication

During this Quarter, fabrication drawings for the generator were completed. Upon receipt of DOE design approval, the fabrication drawings and materials were delivered to the low bidder, Schmiede Machine Tool Company. Fabrication began during August. Drawings for specially instrumented electrodes were also completed and delivered this Quarter. The support table drawings were finished and have been released for fabrication.

During the next Quarter, fabrication of the generator frames and caps will proceed in parallel so that each module, on completion, can be tested for assembly and inspection at the fabricators and delivered to UTSI for final assembly and testing. The present schedule calls for delivery of all modules by June 1981. Fabrication of the generator assembly table and support stand will be accomplished, as well as procurement of all accessory fittings such as the cooling tubes, insulated screws and washers, and interframe insulating material needed to assemble the channel.

Additional testing in the ECF is scheduled for the coming Quarter to finalize the selection of material used for the electrode cap/frame interframe and the electrode cladding material and its method of application.

c. Diffuser Design, Development, and Fabrication

The fourth section of the diffuser has been delivered to UTSI and the studs to hold refractory installed (see Figure 10). The three upstream sections were completed during this Quarter and will be delivered upon satisfactory completion of hydrostatic testing. The support stand for section four is completed and fabrication drawings for the remaining support stands have been released. The cooling tubes have been specified and ordered for these sections.

During the next Quarter, the refractory lining of section four will be installed and cured. Support stands will be completed for all sections. The cooling tubes will be procured, together with accessory hardware, and final assembly of the diffuser will be accomplished.

As reported last Quarter, the cold flow facility was nearing completion. During this Quarter, the facility has been completed, the diffuser and radiant furnace models have been completed and installed. Pressure instrumentation including a traversing total pressure probe

Figure 9. Thermal Stresses in the CFFF Solid Frame

Figure 10. Stud Installation in Diffuser Section No. 4

and flow visualization apparatus have been installed. A laser velocimeter system will be used for flow mapping in the next Quarter.

The diffuser and radiant furnace are half-scale, which allows matching both Mach and Reynolds numbers for runs of approximately 15 minutes with the pressure available in the blow-down supply tank.

The diffuser flow will be mapped with inlet boundary layers controlled to simulate the flow conditions expected in the LMF full-scale diffuser. If separation problems are encountered, some vortex generator designs will be tested to determine their effectiveness.

The information obtained will be used directly in future diffuser design and in developing a computer code for diffuser design.

2.3 Downstream Components

Work continued on installation of the radiant furnace as planned. All sectional joints and the various access ports, doors, thermowells and other penetrations were completed. The downcomer piping (Figure 11) was similarly completed and the entire unit filled with water to determine if any of the weldments leaked. Work began on the low pressure water piping (Figure 12) and the refractory installation late in the report period. Figures 13, 14 and 15 show additional salient details on radiant furnace installation. All major equipment and components were on order by the end of the period. Long deliveries of critical materials continued to hamper

Figure 11. Furnace Inlet Showing Manway and Downcomer Connections

the project schedule. Next Quarter, installation of instrumentation and controls will continue as planned. General fabrication of furnace components and support equipment will continue.

Installation of the secondary combustor was completed this Quarter. Leak tests were conducted and repairs were made as necessary. Additional instrumentation ports have been installed as required, but no instrumentation has been installed at this time. An additional angle-iron ledge was added to the secondary combustor to serve as support for the refractory. Refractory installation and curing will take place in October, and instrumentation will be installed. As-built drawings are now being prepared so that documentation of the secondary combustor will remain current.

The intermediate temperature air heater (ITAH) test module preliminary design drawings have been completed and a bid package for the module

Figure 12. Fabrication of Low Pressure Water Supply Header

Figure 13. Diffuser Inlet to Radiant Furnace

Figure 14. Cutting Prior to Installation of Mandoor into Drum Module

Figure 15. Completion of Exterior Seal Between the Secondary Combustor and the Ash-Seed Hopper

fabrication is being prepared. It is anticipated that a purchase order for the fabrication will be issued by November 1, 1980. This is compatible with our desire to have the module installed by the start-up of LMF-1.

It has been difficult to find suppliers of several of the grades of tubing, listed in the previous Quarterly report, as probable test materials. This difficulty can be attributed to both the tube size required (1" x 0.083") and the individual alloys themselves. Therefore, some modifications of the materials list have been made and these are reflected in the revised materials list shown in Table I. Several of the

TABLE I

ITAH Materials List

<u>Material</u>	<u>Size</u>
304 S.S.	1" x .065"
316 S.S.	1" x .049"
321 S.S.	1" x .083"
E-Brite 26-1	1" x .083"
Inconel 600	1" x .065"
Croloy 2-1/4	3/4 IPS Schedule 40*
Croloy 9	3/4 IPS Schedule 40*
310 S.S.	3/4 IPS Schedule 40*
446 S.S.	3/4 IPS Schedule 40*
Chromic Oxide plasma sprayed 316	
Nickel Aluminide plasma sprayed 316	
Magnesia Alumina plasma sprayed 316	

* 1.050" x .113"

alloys have been dropped from the list and the tube size requirements have been varied. Regarding the latter, it was necessary to obtain some of the grades in the heavier walled pipe sizes in order to have those grades available to test. All of the materials contained in the list are either already purchased or are presently being bid and these will be the initial test materials for the LMF-1 test sequence. Vendors are now being sought to bend the tubes/pipes and to plasma spray the necessary pieces.

In a related activity, it was decided to install refractory in the ash/seed hopper in order to ensure adequately high gas temperatures for the air heater module. This refractory lining will consist of approximately 1-1/2" of A.P. Green's Greencrete ARC.

Next Quarter activities will consist of receiving and evaluating bid packages for the component fabrication. Tube materials will be received during the Quarter. Operation of the test component is anticipated during the second Quarter of FY81.

C. TASK 3—BASE OPERATIONS FOR CFF & E C FACILITY

Because of the diverse though related activity conducted under this task during the Quarter, activities are reported under the following headings: Engineering and Laboratory Services, Air Monitoring, Aquatic Monitoring and Terrestrial Monitoring.

a. Engineering and Laboratory Services

Work progressed in Engineering Services at the manpower level of effort. The primary activities were planning and budgeting work for the next fiscal year.

A standard laboratory procedures manual has been completed with the method of analyses given for coal, slag, ash samples, etc., and training of new employees in the chemical laboratory in the analysis of water and waste-water has been performed this Quarter. With the arrival and installation of the Elemental Analyzer, analysis of samples for carbon, hydrogen, and nitrogen is being performed (see Figure 16). The coal preparation laboratory is in the final stage of completion.

Figure 16. Elemental Analyzer

With the arrival and installation of the Atomic Absorption Spectrophotometer/Graphite Furnace (see Figure 17), trace metal analysis in samples now can and will be performed. Trace metal will be analyzed in a variety of samples, e.g., coal, slag, ash, water and wastewater, soil and air filters.

Figure 17. Atomic Absorption Spectrophotometer/Graphite Furnace

A gas chromatograph has been ordered which will aid in the identification and quantification of gases and organic compounds. We now have methods for the analysis of organic compounds in stack gases, air, water, sediment, animal tissue, etc. Next Quarter polynuclear and other organic compounds will be analyzed using gas chromatography - mass spectrometry.

Analytical work on water was performed, concentrating in particular on precision and accuracy. A new technician was trained to do water testing, and a file system was set up for keeping records of test data, including the calculations done on each test. Coal analysis was begun on the Perkin Elmer 240B, but there is not yet enough data to specify limits. By the end of October there should be enough data to start reporting results and writing specifications.

After the completion of the testing in Cell I, the Thermo Electron sample conditioner was completely reworked. New water traps were installed in the refrigerated bath and the conditioner made into a dual stream conditioner. All lines and connections from the probes to the instruments were checked and air leaks repaired. For the Cell III testing, a switchable manifold was fabricated and installed to allow switching the sampling stream to any one of the three points along the gas stream. During the initial shake-down runs in Cell III, the rebuilt system performed better than in the past.

b. Air Monitoring

During this Quarter, the sites were prepared for the installation and operation of two air monitoring stations, one at the major impact site and the other at a site for gathering baseline data. The unit for use at the major impact area was set up, calibrated and is presently in full operation. This was accomplished in conjunction with personnel from the

Montana Energy and MHD Research and Development Institute, Inc. (MERDI). A technician was employed by UTSI and trained for assisting in the operation of these monitors. The second station is to be used for the acquisition of baseline data and is now being prepared for operation and should be functional within two weeks.

For the purpose of analyzing data from the two stations, a Cromemco Z2H Computer was installed. The hardware installation is complete with some minor additions pending and the software is being designed and implemented by personnel at UTSI. On-line capability with UTSI's computing center has been initiated as well as affiliation with United Computing Systems, Inc., for use of Cyber and Cray computer systems. A series of training sessions in Atlanta, Georgia, was attended by environmental monitoring personnel on United Computing Systems services.

There has been work done on air pollution modeling in affiliation with Tennessee Air Pollution Control Technical Services. This effort is aimed at acquiring our own software for dispersion modeling. This work will continue.

During the Quarter, one chemist became acquainted with high volume instrumentation and procedure. Additional knowledge will be acquired next Quarter. A high volume air quality simulated run (24 hour) was made on July 11th following EPA procedure. A preliminary high volume sampling method (adoptable to ECD samplers) is in the final stages of completion.

A NASA and Army Pollution Abatement Program (APAP) literature search was performed in mid-September. Both searches were conducted in the Hi-volume and filter sampling areas. In addition to the above areas, the air pollution problems of MHD were searched out and papers and reports from symposiums and conferences were obtained. Next Quarter, high volume sampling and literature review will continue.

With regard to air pollution, negotiations with the Tennessee Air Pollution Control Division (TAPCD) concerning air pollution permits for ECF test cells number 1 and 3 were started. A baghouse or other air pollution control device may have to be added to meet the State emission requirement. The need for the design of the baghouse are presently under investigation. Confirmation of air pollution operating permit issuance for the CFFF cryogenic system boiler has been given by the TAPCD. We originally agreed to limit operation to under 800 hours per year per suggestion of TAPCD, to conserve this area's increment. Nevertheless, negotiations are underway to expand allowed operation to an almost continuous basis. An air pollution source operation permit was submitted to TAPCD for the 200 HP oil fired steam boiler recently delivered to the ECF. We expected the operation to be limited by permit to under 200 hours per year to conserve the increment, but TAPCD has issued a construction permit with no operational time limitations.

The Franklin County Landfill Authority has formally agreed to dispose of flyash and slag generated by Energy Conversion Division (ECD) facilities.

ECD will be responsible for transporting these wastes, but disposal charges by the county authority will only amount to a very reasonable \$1.25 per cubic yard of uncompacted waste. ECD facilities were surveyed for potential and existing hazardous wastes. Notification as a generator of hazardous wastes was forwarded to the Chicago Operations Office.

Next Quarter, the following will occur:

- 1 Continue permit negotiations with TAPCD for operating permits for the ECF Cells 1 and 3, and the 200 HP steam generator. Pollution control devices will be considered but, in addition, the possibility of variances for small R&D air pollution sources such as Cells 1 and 3 will also be considered.
- 2 Continue negotiation activities directed to securing the necessary operating permits for the CFFF. The CFFF is now under construction permits and is not eligible for operating permits until operation is ready to commence.
- 3 Install and operate a third air pollution and meteorological monitoring station tentatively scheduled to be supplied by MERDI.
- 4 Continue data acquisition program from the two existing air pollution and meteorological monitoring stations to establish baseline levels for this area.
- 5 Assist the Franklin County Landfill Authority in any engineering or analysis work required to dispose of solid waste (flyash and slag) generated by the CFFF.

On the MERDI project (both air and terrestrial monitoring) permits for electrical installation were received and electrical connections were made. The air monitoring trailers were then moved and set in their designated areas. Electrical hook-up was made and instruments were turned on. With MERDI's help, we then calibrated both the metering and analyzing equipment. The impact trailer was put into full operation with routine checks made for assurance of stability. Data collection and hi-volume air sampling was begun. The filter samples were changed out every three days with a variation from co-located to inhalable domes.

The base site, due to a faulty air conditioner unit, was unable to begin operation. A compressor was purchased and the bad compressor was replaced. This trailer also had a bad printer, which was shipped to Campbell Scientific Company for repair. The repair has been finished and the printer is now fully operational. A regular maintenance check is made at both trailers with various calibration checks performed. The base site should be ready to begin operation early next Quarter.

c. Aquatic Monitoring

Based on analytical results from previous Quarters, a limited aquatic monitoring program was enacted during this Quarter and will continue for the duration of the pilot plant operation. This program consists of expanding the number of sampling sites, reducing sampling frequency and including field analyses in the water quality assessment data base.

Arrival of the boat (Figure 18) and necessary field equipment (Figures 19-21) now makes site monitoring possible. Field data for this Quarter have been gathered from additional sites as well as existing sites (Figure 22).

Figure 18. Boat for Aquatic Sampling

During the latter part of the Quarter, preliminary phytoplankton analysis was begun. Collection sites for biological samples were correlated with previous existing sampling stations. An investigation of the methodology for phytoplankton analysis outlined by Millipore Corporation was made. Other methods of algae analysis, such as the Wisconsin Plankton Net/Sedgwick Rafter method, are under consideration. Comparison was also made of plankton preservatives to determine the best preservative to use for the duration of the study. Surveys of the phytoplankton population will be conducted to depict any trends and variations in the algal population. Progress will be reported next Quarter.

Figure 19. A Kemmerer Water Bottle, Designed for Trace Metals, Insecticide, and Hydrocarbon Sampling

Figure 20. The Hydrolab Sonde Unit Which Enables in-situ Measurements of Temperature, pH, Conductivity and Dissolved Oxygen

Figure 21. The Hydrolab Digital Indicator Unit which Displays Multiple Parameter Readings in-situ

Figure 22. CFFF Environmental Monitoring Sites

Identifications will be determined to the lowest possible taxon by the principal analyst who will compare his results with those of the project phycologist.

A quality control program has been approved for water analysis during this quarter. Recommendations for internal quality control as well as external quality control checks have been made. Chemical analyses on water samples from Woods Reservoir will be conducted by an outside agency to assure quality control in the area of water chemistry. Quality assurance for biological sampling will be provided by an expert phycologist from an independent agency. Progress will be reported next Quarter.

d. Terrestrial Monitoring

The terrestrial environmental monitoring program has accomplished the sampling of foliage and soil from all study plots. Separate foliage samples were taken for red oaks, white oaks, dogwoods and hickories. Foliage was obtained from all forty-eight study plots. A total of 1,440 leaves was collected from 889 hardwood trees and 3,825 pine needle bundles were collected from 399 pine trees. The foliage was grouped into 72 samples which were sent to MERDI for chemical analysis. Soil samples were obtained from forty-eight study plots at three depths to sample the A, B and C soil horizons. A total of 288 soil samples were combined to make 72 samples which were sent to MERDI for chemical analyses.

Chemical analysis on the leaves will be based on a total analysis using an acid extraction method. For the soil samples, biologically available analyses will be obtained by using an organic extraction method. A MERDI chemist has informed us that funding limitations will necessitate eliminating the test for Cr from the original list of elements and compounds. The revised list consists of F1, NO₃, SO₄, Cl, PO₄, Hg, K, Cd, Pb, and As.

For growth analysis, eight plots of .05 hectare have been established in each of the six main study areas. All trees equal to or greater than 5 cm have been marked with a numbered aluminum tag and the diameter measured and recorded. A total of 1,288 trees were tagged. Steel posts have been set for marking the beginning of each study area. Three wood poles have been set to enable the collection of rainwater samples.

D. TASK 4—EIGHT LB/SEC HIGH SLAG THROUGHPUT TEST

The final drafts of component test plans for all the components contained in the LMF-1 and LMF-2 test series were completed and distributed to DOE. Comments were received from DOE on the Overall Test Plan. The revised version was submitted to DOE. The Component Test Plans are general in nature and do not contain the specific detail required for operation in the Coal-Fired Flow Facility. Therefore, preparation of a detailed test plan for implementation of the LMF-1 test series in the CFFF was initiated. The detailed test plan will contain specific information on test objectives, flow train configuration, test conditions and duration,

instrumentation and control requirements, and data processing requirements for the LMF-1 test series. The specific information will be provided for all components installed in the LMF-1 test train. A draft of the test plan will be circulated for review at UTSI near the middle of the next Quarter.

Design was initiated on an optical flange to be installed in the coal-fired combustor during LMF-1. The flange will provide access to the combustor flow field for making luminosity and line reversal temperature measurements. Flange design will be completed by the end of next Quarter. Purchase requisitions have been released to acquire the additional electronic components required for the luminosity and line reversal systems.

For the LMF testing, codes are being developed to expedite the reduction of data and its formatting for comparison with theoretical calculations. The auxiliary information needed to perform this task is stored in a central location and is set up before testing. This facilitates the tracing of errors or the validation of results. Access to the data will be improved and it is hoped that the codes developed will solve many of the major problems that have existed in data reduction.

In the analysis of experimental data, one major obstacle is the organization of information into subsets for distinct, fixed operating conditions. Another obstacle is the identification and elimination of anomalous data. Since the analysis of MHD system performance involves examining the large volume of data which accompanies extended test times and large numbers of parameters, it is expedient to develop software to aid in the perusal of this data.

The capability to display data in graphical format is desirable since it enables the observer to interpret relationships between points and obtain a broad view of the experimental behavior quickly. Three programs, 1) SETUP, 2) DATATRIEVE, and 3) DISPLAY, have been recently developed for the UTSI central computer system to provide this capability. These programs are and shall continue to be in a state of expansion and refinement. Present versions of these programs are operational and are being used interactively in the reduction and analysis of UTSI ECF data taken during past generator test series. A description of the function and capabilities of each program is given in the following discussions.

The SETUP program reads raw test data from a disk, averages it and then reformats it for use by other programs. It also performs selected

calculations which include a statistical analysis of data over any input time interval and the computation of selected performance parameters. Histograms of each dataset can be produced to give an overall view of the range of test conditions encountered during the given test.

The DATATRIEVE program is a DEC utility program which was originally designed for business applications. It has been adapted quite successfully to the task of reduction and analysis of test data. Using this program interactively one can easily isolate data at any desired set of test conditions. This is accomplished by issuing a command to the program whereby limits are set on selected parameters: e.g., B-Field between 1.4 and 1.6 Tesla and total mass flow between 3.8 and 4.0 lb/sec. Upon establishing the particular set of test conditions to be analyzed, the program stores all these data on disk for use by the program DISPLAY. DATATRIEVE also has the capability of producing listings of all or selected data on an as-needed basis. This feature eliminates the need for a comprehensive listing subroutine. The version of DATATRIEVE now in use can access the more important MHD generator test parameters. These include flow parameters, heat loss parameters, and the generator electrical parameters.

The DISPLAY program is designed to produce plots of the data selected by the DATATRIEVE program. These plots include time-histories, axial distributions, histograms, and cross-plots. For a time-history plot, either all data at every time point or the average of these over the entire time interval can be plotted. Axial distribution plots for the MHD flow train can be produced for either the entire flow train or for any individual component. The cross plotting routine allows the user to compare and correlate selected variables: e.g., thermal input versus power output, load voltage versus load current.

Along with the plotting routines, the program has several other features which can be used in the analysis and presentation of test data. In particular, these include the ability to produce listings of selected data, either in chronological order or averaged. It also has the ability to construct input data files which can be passed to other programs.

An extended version of all three programs discussed will be available during the coming Quarter. This new version will include an expansion to allow keying on many more parameters. A routine for the display program is in development which will produce three-dimensional plots of variables, such as voltage distribution versus time.

In the analysis of unsteady phenomena most of the broadband data acquisition system has been installed, although delivery has been delayed on the tape search system, which will allow the broadband data to be correlated to general performance data in the CFFF. Digitization equipment has been ordered so that the broadband data can be analyzed using the digital analysis codes which are being developed in Task 7.7.1, Diagnostic Support R&D.

Mie scattering calculations have been completed to establish an optical setup for laser velocimeter measurements utilizing system component flanges. Progress will be reported next Quarter on continuing activity toward maximizing generator output and lifetime.

E. TASK 5—TESTING OF DOE SUPPLIED COMPONENTS

There is no activity to report.

F. TASK 6—MODIFICATIONS TO THE CFFF

There is no activity to report.

G. TASK 7—TECHNOLOGY DEVELOPMENT PROGRAM

7.1 Primary Combustor

Shakedown testing of a combustor model has been performed in the water tunnel in the Cold Flow Test Facility. Various system water leaks were found and repaired. The techniques of flow visualization, by injection of dyes or generation of hydrogen gas bubbles in the flow, are being developed. The laser vector velocity measuring system remains unfinished until some electronic, solid state, integrated circuit chips are received. These components were ordered early in this fiscal year, but demand for them has kept the suppliers backordered.

Calculations are being made of axisymmetric, recirculating flows in combustors. The present model of combustor aerodynamics is for isothermal flow. A parametric study of the effects of oxidizer injection characteristics has been performed. The changes in the internal velocity field, including the recirculation zones, have been obtained. Work in progress is designed to extend the model to hot flow.

Two topical reports are being prepared. One describes the math-modeling effort that has been done this year and the other report describes the experimental facility and testing performed. Both reports are expected to be complete in a draft form early next Quarter.

Preliminary design concepts for a large, multiport combustor were formulated this Quarter. The expected heat flux, the length and diameter for a preliminary design were determined by analysis. With this information, a shell design was conceived that is relatively less expensive to fabricate than the wrapped tube design currently used. Oxidant injector configurations will be developed by cold flow modeling techniques.

A mock-up of the Cell I combustor coal injector has been fabricated and installed in a drum test module. The drum module supports an array of sampling probes that span the interior. This experimental apparatus is being used to quantify the performance of the UTSI coal injector configurations. The individual sampling probes are located to collect pulverized coal samples at selected distances from the coal injectors. Individual samples are collected, weighed and analyzed for particle size distribution and coal/seed distribution.

By varying the azimuthal orientation of the probe rake, a complete coal flux survey can be made for any arbitrarily selected axial distance from the coal injector plane. At the present stage of development, problems still exist in removing the coal not sampled. The drum module is being modified and testing will resume. The data will be used to improve and further develop coal injector technology for MHD applications.

Heat flux distribution along the test train from TP-40A runs was analyzed. Design of the heat flux probe assembly for CFFF tests was completed and fabrication initiated. A technical paper entitled "Heat Transfer as a Diagnostic Tool in the Development of Direct Coal-Fired MHD Combustors" was presented at the ASME-AIChE National Heat Transfer Conference in Orlando, Florida. A revised manuscript of the topical report on heat transfer study was completed and reviewed. A test plan was developed to study the MHD combustor performance at constant mass flow rate and variable pressure. A successful experimental run was made and the data are being analyzed. The testing will continue in the next Quarter.

A survey was initiated to determine the status of development of various diagnostic techniques applicable to hostile combustor environments. Candidate systems include, but are not limited to, laser velocimetry (LV), laser holography, line reversal, laser-Raman spectroscopy (LARS) and coherent Anti-Stokes Raman spectroscopy (CARS). The LV system can potentially provide information on flow velocity, turbulent fluctuations and shear stress in the combustor flow. The line reversal system will provide temperature information while the LARS and CARS systems can potentially provide specie concentration information in addition to static temperature data. The survey will include an in-depth review of the diagnostic development currently in progress at Mississippi State as well as various DOD and NASA installations. When completed, the survey will provide a basis for selection of the diagnostic approach to be used in coal-fired combustor development in the ECF. The survey will continue next Quarter.

7.2 MHD Generator

During the past Quarter, the MHD generator efforts supported included the following: 1) analysis of power take-off (PTO) performance from recent generator testing, under test plan 40A, 2) definition of a testing program to investigate local electrical conditions at generator electrodes for the purpose of defining controls, and 3) a continuation of the development of analytical capabilities in the support of power train design and analysis of performance. Details concerning these three efforts are discussed below.

a. Continuing MHD Generator Testing

During the Third Quarter, preparation of a test report on the results of the TP-40A generator test series began. The report, scheduled for completion during the coming Quarter, is intended to provide the data base for further in-depth analyses and to provide some preliminary data analysis for combustor performance, generator performance, materials evaluation, and PTO scheme performance. Two papers based on the experimental results and analysis were accepted for the AIAA 19th Aerospace Sciences meeting to be held next January in St. Louis. Of these areas of investigation, highlights of the last item are presented herein.

Three different PTO schemes were investigated during the TP-40A series. The first (Case I) was comprised of ballast resistors connected directly between adjacent electrodes in the PTO regions as shown in Figure 23. The ballast resistors used in this scheme were sized in an attempt to minimize the Hall current in the take-off regions. Resistor sizing was based upon analytical predictions for complete Faraday operation of the 60° diagonal conducting wall (DCW) ECF generator as computed using the DESIGN3 computer code in conjunction with the NASA SP-273 chemical equilibrium code.¹ The resistance values used during testing are tabulated in Table II.

TABLE II

Resistor Sizes for Power Take-off Schemes

Case I	Case II	Case III
TP-40A-01 thru 12	TP-40A-3 thru 16	TP-40A-17
R ₁ ^A 0.02	R _{NOZ} 8.54	R _{NOZ} 5.25
R ₂ 0.04	R ₁ 8.19	R ₁ 5.25
R ₃ 0.06	R ₂ 7.76	R ₂ 5.25
R ₄ 0.08	R ₃ 7.18	R ₃ 5.25
R ₅ 0.10	R ₄ 6.44	R ₄ 5.25
R ₆ 0.12	R ₅ 5.48	R ₅ 5.25
R ₇ 0.14	R ₆ 4.30	R ₆ 5.25
R ₈ 0.15	R ₇ 2.88	R ₇ 5.25
R ₉ 0.16	R ₈ 1.49	R ₈ 5.25
	R ₉ 0.15	R ₉ 5.25
R ₆₉ 0.08	R ₆₉ 0.15	R ₆₉ 1.0
R ₇₀ 0.06	R ₇₀ 0.29	R ₇₀ 1.0
R ₇₁ 0.05	R ₇₁ 1.21	R ₇₁ 1.0
R ₇₂ 0.04	R ₇₂ 1.39	R ₇₂ 1.0
	R _{DIFF} 1.54	R _{DIFF} 1.0

* Resistances in ohms

(a) Case I

(b) Case II and III

Figure 23. Ballast Resistor to Electrode Connection Scheme

The second PTO scheme (Case II) used for the TP-40A tests consisted of series-connected current consolidating circuits to each individual take-off electrode. These circuits included ballast resistors in series with diodes. The resistor values were set to produce equalized current from all electrodes consistent with the recent analysis by Pan and Doss.² The ballast resistors for the experiments conducted were sized in an attempt to achieve a near equal distribution of lead-out current from each PTO electrode.

The third PTO scheme (Case III) used in the test series was identical in layout to that of the second scheme. Diodes and equal ballast resistors in the current collecting regions were used. The resistance values for the PTO schemes II and III are also tabulated in Table II and identified with the corresponding tests.

Resistors for implementation of the first PTO scheme were sized for a primary load of 12 ohms. Experimentally, the cumulative current distributions shown in Figure 24 for generator primary loads of 12, 8, 4, and zero ohms were obtained. As the primary load decreases, the load current increases and the latter electrodes absorb more current until the cumulative value matches the load current at the ninth PTO collector.

More detail concerning the design criteria for the PTO can be found in the TP40A test report which will be issued next Quarter. As discussed there, all the schemes were designed for a constant voltage operation across the primary load. Figure 25a presents the current leadout data from run TP-40A-13 at two different primary loads. In Figure 25b, the design point and actual operating points are shown on generator load line curves.

The resistors were sized for a terminal voltage of 1072 volts. Based on the load line calculated with a dimensionless voltage drop, Δ , of 0.3, this terminal voltage corresponds to a 16 ohm load with current of 67 amps as indicated by the darkened circle. In Figure 25b the V-I characteristics for the DESIGN3 predictions are plotted (curve A). Also included in the figure is the experimental load line from the TP-40A-13 test data (curve B). Operating conditions did not achieve the desired levels, due to low coal flow and a higher N/O ratio than that specified for design point operation. Since the performance was off-design, the ballast resistor sizing would actually correspond to a design for primary load conditions of about 35 amps and 31 ohms (darkened triangle on figure) at 1072 volts. The ballasting thus does not give the desired results.

Referring again to Figure 25a, the experimental data for the 16 ohm primary load indicates that the average current in the first seven PTO electrodes was indeed about 3.5 amps (± 0.8 amps). The current in the last three electrodes increases, reaching a high value of 12 amps at the

Figure 24. Cumulative Current Distribution at Various Loads (Case I)

Figure 25. Leadout Current Distributions and Design Point Considerations for Power Take-Off (Case II)

last electrode. The total current flowing through the primary load was 46.7 amps. This same trend is also evident from data collected during operation at the 4 ohm primary load which is also plotted in Figure 25a. At these conditions the total current was 67 amps.

The resistors were sized based on a given terminal voltage; however, the generator operates at a fixed external load. Consequently, as the load lines shift, the terminal voltage used to determine the resistors would result in a different load. Operating at fixed load thus leads to off-design conditions for the PTO system. Changing load along a loadline will cause the lead-out current distribution to be non-linear, increasing toward the active generator section (see Figure 25a) as load decreases, and decreasing as load increases. Shifting load lines will cause the current levels to shift.

This case was also analyzed using a 2-D electrodynamic code.⁴ Figure 26 presents a comparison of the predicted leadout current distribution to experimental data from run TP-40A-16. Agreement is shown to be very good.

Figure 26. Comparison between 2-D Calculation and Experimental Data (Current Distribution on PTO Electrodes)

Figure 27a is a plot of the current distribution in the entrance region of the Channel, whereas Figure 27b presents a detail of the distribution over the first few PTO electrodes. As can be seen, the electrodynamic is shown to be at least two-dimensional in character.

(a)

(b)

Figure 27. Current Distribution in the Upstream P.T.O. Region

Figure 28, a through d, presents plots of the cumulative leadout current distributions in the upstream power take-off region for constant resistors (Case III). The figures correspond to primary load resistances of 16, 8, 4 and zero ohms respectively. Included in each of the figures is the corresponding electrode voltage distribution. The dashed lines in Figures 28a and 28d show the variation of the individual electrode currents.

Since the nozzle and first electrode are both at zero potential (the nozzle is grounded), it is evident that these electrodes are shorted

Figure 28. Current and Voltage Distributions in the Upstream P.T.O. Region at Various Primary Loads (Case III)

together. This is substantiated, as shown in Figures 28a and 28d, by the fact that these two electrodes were carrying the same amount of current.

In their analysis of the U-25 Channel power take-off, Pan and Doss² discuss a case that is similar to those presented in Figure 28. In Figure 29 their predictions for the current and voltage behavior using equal resistors and diodes are presented. If the load current, I , is greater than the local short circuit current, I_s , then field reversal occurs, accompanied by an increasing leadout current distribution which is evident in Figure 29.

The data presented in Figure 28 indicate that the same phenomenon is apparently occurring. The steep jump in voltage at the second electrode cannot be accounted for at present, although it is evident that the field does reverse downstream of this point.

b. Electrode Control

Efforts towards better understanding of the physical process involving interelectrode breakdown, constricted current leakages through the plasma (arcs) and other electrochemical instabilities are being continued. The investigation, as reported in the last Quarterly report, involves an improved segmented electrode design to monitor the current distribution in the electrode frame and an electrical control system network.

A preliminary test plan for the detailed examination of the local current and voltage non-uniformities in the generator electrodes has been prepared. Since the physical processes involved are very complex, the testing program has been carefully planned to systematically study the various phenomena leading to or caused by local electrical non-uniformities. The first phase of the investigation will be devoted to increasing the understanding of the basic physics involved and taking the first steps towards conceptual design of a local control system for generator electrodes.

Experimental investigations at UTSI and AVCO Everett Research Laboratory indicate that non-uniform interelectrode voltages and, hence, non-uniform current distributions can develop. These are a result of local conditions and may wander around between adjacent electrodes. If uncontrolled, the magnitude of voltage imbalance may grow in time causing a local overload, arcing, and material damage. Although in early stages the non-uniformities do not affect the overall performance of the generator, local shorting and uneven distribution of current in the channel do reduce the life of generator components.

For the proposed initial testing the current and interelectrode voltage distribution will be monitored using three electrodes specially designed for this purpose. Each electrode has ten segments insulated from each other and the electrode frame. Utilizing a resistor, current, and voltage measuring network, the current flowing in each segment and the intersegment voltages will be recorded for different electrode segmentation configurations. For the planned testing three different slag carry-over

ϕ = potential (volt)
 i_n = individual electrode current

Figure 29. Prediction of Current and Voltage
 Distributions in the Upstream P.T.O. Region
 (U-25 Channel)

conditions will be simulated by the following gas compositions while maintaining the same stoichiometry and seed fraction:

	Coal + Seed	Kerosene	N ₂	O ₂
I.	1.068 lbs/sec	0.095 lbs/sec	0.390 lbs/sec	1.996 lbs/sec
II.	0.851 lbs/sec	0.248 lbs/sec	0.400 lbs/sec	2.051 lbs/sec
III.	0.671 lbs/sec	0.376 lbs/sec	0.407 lbs/sec	2.096 lbs/sec

This variation in plasma constituents will cause some variation in the resultant slag viscosity. This variation can be examined using theoretical calculations based on the following formula:

$$\log_{10} \eta = \frac{10^7 M}{(T-150)^2} + C$$

where η is viscosity (poises)

T is temperature (°C)

$$M = 0.01043 (S_iO_2) + 0.01003 (Al_2O_3) - 0.29629$$

$$C = -0.01542 (S_iO_2) - 0.03881 (Al_2O_3) - 0.01617 (Fe_2O_3) - \\ 0.00891 (CaO) - 0.01293 (MgO) + 1.04678$$

All oxides are expressed as weight percentages.

This correlation, as proposed by W. Capps⁵, shows that a range of slag viscosities may be achieved (see Figure 30). The information contained in Figure 30 was obtained using the weight percents of oxides as calculated by the modified NASA 273 program for the three gas mixtures given above.

The sequel of steps for the proposed tests is listed in the test condition Matrix, Table III. During the first three tests, the effects of the three gas compositions on overall generator performance and local non-uniformities will be investigated. One of these mixtures will be selected as the standard for further tests.

The emissions from the plasma will be scanned through a spectrometer in the ultraviolet and near-infrared regions. The emission spectrum will be utilized to determine the wavelengths of optical filters (~10 Å wide) suitable for cinephotography. In addition an electric field (with magnetic field turned off) will be applied to photograph the arc formation under high (simulated) applied fields. An outline of the test details is given in Table III.

Design and construction of the following diagnostic systems and special instrumentation are in progress:

- 1 Special copper caps for segmented electrodes, insulated by boron nitride (BN) grade A 1/32" thick plates. (A bench test to

Figure 30. Viscosity of the Slag vs. Temperature

TABLE III

Test Condition Matrix

<u>Run No. & Duration</u>	<u>Electrode Configuration</u>	<u>Inter-Segment and Inter-Electrode Connection</u>	<u>Applied Electric Field (volts)</u>	<u>Generator Load (Ohms)</u>	<u>Movie Picture</u>
1	I	Open	0 - 200V	4.0	Scan the Ultra-violet and Infrared Region
2	III			8.0	
3	V			16.0	
4	V	All Segments of #42 Connected by R=0.1, 1.1, 5.1, 10.1, $\infty \Omega$	0 - 200V	16.0 and Short Circuit	5 Sec. Shots at 500 fr./sec Speed
5	V	Open	0 - 200V	16.0 and Short Circuit	2 Sec. Shots in Ultraviolet Region at 3000 fr./sec
6	Repeat Run #5 If Movie Pictures Are Not Of Satisfactory Quality				
7	V	Connect Segments TEI-0184-06 & TEI-0185-06 by 0.1 Ω Resistance	0 - 200V	16.0 and Short Circuit	10 Sec. Shots Infrared Region at 500 fr./sec

ELECTRODE CONFIGURATION CHOICE

I

II

III

IV

V

confirm the survivability of the caps in the hot plasma environment (~2000 K) will be conducted during the coming Quarter prior to finalizing the design.)

- 2 Broadband (~10 kHz) acoustic pressure probe designed for high magnetic field environment.
- 3 Microprocessor-based data acquisition system for recording signals with a frequency response of ~ 100 kHz.
- 4 Optical port for fast cinephotographing the time history of arc formations and for observing the slag flow. A variable speed (500 frames/sec-3000 frames/sec) movie camera will be used for these purposes.

During the coming Quarter, the design of the segmented electrodes and the special instrumentation will be completed. Following fabrication and instrumentation buildup during the First Quarter of 1981, testing is planned for the Second Quarter of 1981.

c. Advanced Analysis

An analytical study based on a quasi-one dimensional model of the generator transients is in progress. Events such as sudden opening of the fuel valve, inverter load variations shutdown, and turn-on sequels will be simulated by square pulse changes in relevant parameters. The analysis will be directed towards investigation of possible interelectrode breakdown, material damage, and possible overload (mechanical stress) of generator elements during these transients.

Also, two-dimensional parametric study in the plane perpendicular to the direction of the flow is underway and will be capable of mapping the current distribution in the electrodes with slag under various velocity profiles, with random potential distribution along the channel, and such other phenomena as affect the generator performance. The experimental data made available by the investigations described above will be fed into the program and a quasi-three dimensional model of the non-uniformities will be made.

Concerned with analytical developments for an MHD generator, modifications to existing quasi-one-dimensional programs have been made. There are three different programs currently used for these calculations:

- 1 DESIGN3 - An on-design/off-design generator performance or design program capable of handling Faraday or diagonal conducting wall generators.
- 2 DE3SBALU - A simplified version of 'DESIGN3', performing only diagonal conducting wall generator calculations.
- 3 VDROD - A generator program with the unique ability to handle experimental voltage distribution inputs.

For DESIGN3, primary changes have occurred in the calculations and printout of several new parameters. Various interaction parameters, along with heat loss, short circuit current, and Faraday load current, are probably of most significance.

For DE3SBALU, major changes have been made in the structure of the input format. Most of the input is now set up using a NAMELIST. In particular, this should facilitate new users when operating in edit mode. Along with input changes, the output has also changed in an identical manner as described above for the 'DESIGN3' program.

The most extensive modifications were made to the VDROD program. As in 'DESIGN3', this program now also calculates interaction parameters and provides additional output. Its capability has also been expanded to handle a variable generator channel geometry input and an option on loading in which one can input a table of initial points for each load section and the value of the load current for each section. The most recent modification has been in the addition of variations along the axial direction in effective wall temperatures. This is accomplished by a table of effective wall temperatures and reference axial locations in which one may choose a constant or linear wall temperature variation between reference locations.

In addition, modifications have been implemented in the NASA SP273 program to output results in more convenient units and format. The JANAF files have been updated to include recently published data. The version now in use omits AlO_2 since results including these ions are not consistent with experimental results from conductivity testing.

Besides the NASA SP273 modifications is the continuation of MHD CHANT work described in the last quarterly report. During the Third Quarter the VNAP program (from Los Alamos Scientific Labs) was adapted for the University of Tennessee (UT) computer system and modified by addition of the electromagnetic equations in quasi-two dimensional form.

The work of this Quarter consisted of:

- 1) Modifying the effect of variation of channel width by adding one term into the continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{1}{W(x)} u \frac{\partial W(x)}{\partial x} = 0$$

where $W(x)$ is the width of the channel.

- 2) Introducing the calculation of the boundary layer thickness (δ) gives the following:

Displacement thickness:

$$\delta^* = \int_0^{\delta} \left(1 - \frac{\rho u}{\rho_{\infty} u_{\infty}}\right) dy$$

Momentum Thickness:

$$\theta = \int_0^{\infty} \frac{\rho u}{\rho_{\infty} u_{\infty}} \left(1 - \frac{u}{u_{\infty}}\right) dy$$

Energy-dissipation thickness:

$$\delta_3 = \int_0^{\delta} \frac{\rho u}{\rho_{\infty} u_{\infty}} \left[1 - \left(\frac{u}{u_{\infty}}\right)^2\right] dy$$

- 3) Coupling the boundary layer and mass flow rate by

$\dot{m} = (W(x) - \delta^*) \int_0^h \rho u dy$ where δ^* denotes the sum of cathode and anode displacement thickness.

- 4) Improving the thermodynamic and transport properties for combustion presents a real gas option in our two-dimensional unsteady program. Two different methods can be employed for the calculation of the necessary thermodynamic properties. The simplest method is to assume a perfect gas model as described in the previous Quarterly report. For situations in which the perfect gas model is not valid, the equation of state becomes $p = \rho Z T$ where $Z = Z(p, T)$ is obtained by a table look-up of tabulated data generated by the NASA SP-273 program. In a similar fashion the remaining thermodynamic properties are also generated by the same program running in a TP (temperature and pressure specified) mode using a special output that tabulates the data in a disk data set and then found directly by a linear four point interpolation for functions of two variables.

The electrical transport properties are either obtained from empirical relations developed by Nichols (see the previous Quarterly report), or from tabular interpolation in tables of electrical conductivity and electron mobility generated by a subroutine developed by the chief scientist of UTSI in the same NASA SP-273 program. This modified NASA SP-273 program is run with variations of temperature and pressure to generate tables as a function of these two variables. These data are also tabulated in a disk data set for input to the two-dimensional unsteady program.

- 5) Numerical calculation: Some preliminary calculation results (after sufficient iterations to reach stable conditions) are depicted in Figures 31-36 for the 45° generator planned for LMF testing in the CFFF. Note that the calculation begins at the nozzle and proceeds through the MHD channel because of the special feature of the VNAP program which permits the inlet condition of the nozzle to be specified. The working fluid used in the calculation is a combustion product of Illinois No. 6 coal with 69% oxygen, 31% nitrogen and no preheat. The electrical problem is still approximated by an infinitely fine segmentation.

Generator analysis will continue next Quarter.

MACH NUMBER CONTOUR

Figure 31

U VELOCITY VECTORS

Figure 32

PRESSURE CONTOUR

Figure 33

TEMPERATURE CONTOUR

Figure 34

POTENTIAL CONTOUR

Figure 35

STREAM FUNCTION CONTOUR

Figure 36

7.3 Downstream Components

A letter report of the results from chemical analysis of samples taken in the initial test series was written and given limited circulation for review during this Quarter. Corrections to this report are being made based on the comments received, and the report will be distributed within UTSI for final comments. This project is behind schedule, but no impact is expected on the CFFF schedule. Because of reductions in projected expenditures for 1981, further work on this project is expected to be delayed until 1982.

A low level of effort was expended to monitor the testing of potential refractory materials for the radiant furnace utilizing ECF combustors. This is a small task. Results of this testing are reported on under Task 7, Materials, of this report.

7.5 Pollution Control

A study of electrostatic precipitators and fabric filters with and without agglomeration pretreatment has been completed. The draft report has been written and is being typed. A recommendation has been made to utilize, for the LMF test train, the electrostatic precipitator which will be provided under the Babcock and Wilcox Heat Recovery/Seed Recovery contract and to test a slip stream fabric filter.

7.6 Materials

Information in this section is discussed under the following headings: Electrode Metals, Interelectrode Insulators, Combustor Refractory, Metals Corrosion, Refractory and Ceramic Materials, and Miscellaneous Materials.

a. Electrode Metals

Extensive microscopic study of electrode caps after tests in TP-40A has revealed the following general wear phenomena:

- 1 Particle abrasion is evident in areas or on materials which show relatively low wear rates, e.g., platinum clad anodes or copper cathodes.
- 2 Copper caps exhibit oxide layers with a thicker and highly fractured outer layer of CuO over a much thinner adherent Cu_2O layer. These oxide layers are usually continuous on cathodes or cathodic regions of sidewalls, but highly disrupted on anodes or anodic regions of sidewalls.
- 3 The greatest electrode material loss is seen on copper anodes or anodic regions of copper sidewalls where arc tracks are visible; the oxide layer is highly disrupted, and the surface topography is highly uneven (sometimes exhibiting pinholes or large voids). In no case is the evidence of melting obvious.
- 4 There is no apparent difference in wear rates between electrolytic tough pitch (110) and oxygen free (101) copper. Likewise, neither copper alloy shows evidence of sulfur attack on a significant scale.

Subsequent to TP-40A-17, a possible correlation was found between electrode current and copper weight loss for materials in Module 1 of the ECF generator. Considering the observations noted previously, this correlation suggests that the material loss mechanism is more strongly influenced by electrical considerations than geometry, location, or other factors. The approach of a recently published study⁶ on deterioration of ceramic electrodes in MHD environments at the ceramic-metal interface may be applied to the UTSI case considering the ceramic "electrode" to be the oxide layer overlying the copper anode. Considering this model, the oxide layer may become an ionic conductor with counter diffusion of oxygen toward the metal substrate and copper ions toward the plasma. This model would suggest that "electrochemical corrosion" in anodic regions is essentially an injection of copper ions into the plasma which is more dependent on electrical or charge transport phenomena than on chemical phenomena.

The implications of such theory are that it allows those metals to be considered for electrode application which would develop a tightly adherent oxide layer whose ionic and/or semiconducting characteristics could be specifically altered for a given charge transport situation in an MHD generator. For this reason a series of tests with various nickel and cobalt base superalloys and stainless steels is now being considered.

Subsequent to TP-40A, it was possible to further document wear characteristics of noble metal clad electrodes. It has been previously reported that platinum clad anode caps seemingly wore primarily by particle abrasion. In recent studies it was possible to observe platinum clad anode caps in the final stage of wear. An example is shown in Figure 37 where the platinum cladding is worn through exposing the copper substrate and

TP40A-12, Module 5, Anode 41

20X

Figure 37. Platinum Clad Anode Cap with Exposed Copper Substrate

copper-gold brazing alloy. Particle abrasion marks are seen in this photomicrograph. In fact, particle abrasion seems to be the predominant wear mechanism in the early stage of wear, suggesting the following stages of wear for platinum-clad electrodes under UTSI conditions:

- 1 Early stage characterized by surface abrasions and deformation of the leading edge.
- 2 Later stage (next) with materials removal, where small areas of platinum are removed possibly by peeling off from the substrate after the platinum has been penetrated by abrasion in localized areas.

An iridium-clad electrode was included in TP-40A to determine if the superior hardness of iridium compared to platinum would yield lower wear rates in the abrasive environment. Unfortunately the iridium was very rapidly removed by peeling back from the leading edge, leaving only globular masses of the metal toward the trailing edge (Figure 38). It is thought that the iridium was significantly cold-worked during bending the cladding around the leading edge of the anode cap prior to brazing. This

TP40A-12, Module 5, Anode 1

20X

Figure 38. Iridium Clad Anode Cap with Exposed Copper Substrate

led to the accelerated wear and early penetration of the iridium cladding on the leading edge. Further tests are planned with a platinum-iridium alloy.

The experiment with the iridium-clad cap raised questions on the effect of braze quality (as well as cold-working prior to brazing) in the tests with platinum-clad caps. A cross-section photomicrograph of Anode 8

after TP-40A-17 is shown in Figure 39 after four hours and 36 minutes of service. This photomicrograph shows clearly that an incomplete braze was obtained around the leading edge. Despite this fact, there was no deterioration of the platinum-cladding on the leading edge or any evidence

Plasma
Direction

TP40A-17, Module 1, Anode 8

32X

Figure 39. Cross Section of Platinum Clad Anode Cap

of significant melting. With respect to the copper substrate, there is some evidence of copper attack just below the leading edge, and there is a coalescence of oxides in the grain-boundaries of the 110 copper. These oxides were not seen in the adjacent 101 copper caps (Figure 40), confirming that their presence is not related to attack by oxygen (or sulfur) in the plasma. In summary, the platinum-cladding performed adequately despite the incomplete braze on the leading edge.

The TP-40A copper cathode caps exhibited essentially no weight loss throughout the test plan. Cathodes did exhibit fairly continuous CuO layers (Figure 41) as well as highly fractured deposits rich in potassium and sulfur (Figure 42). The color of these deposits suggests the presence of mixed copper sulfates and hydroxides. It is significant that any reaction of the copper cap seems restricted to the immediate electrode surface.

Cathodic regions of copper sidewall caps exhibit essentially the same features as for the cathode caps i.e., continuous oxide layers with salt deposits (Figure 43). In the anodic region of the sidewall caps the situation is quite different (Figure 44). Here the oxide layer is disrupted by vertical arc tracks and other features leading to a very uneven topography. In some areas pinholes develop (Figure 45) which apparently precede the formation of larger holes in the anodic region.

Plasma
Direction

TP40A-17, Module 1, Anode 7

32X

Figure 40. Cross Section of Copper Anode Cap

TP40A-12, Module 5, Cathode 40

20X

**Figure 41. Cathode Cap Surface Exhibiting Fractured
CuO Layer**

TP40A-12, Module 5, Cathode 41

20X

Figure 42. Potassium and Sulfur Rich Deposit on Cathode Surface

TP40A-12, Module 5, Cap 40L-High

20X

Figure 43. Oxide Layer on Sidewall Cap in Cathodic Region

TP40A-12, Module 5, Cap 42R-Low

20X

Figure 44. Vertical Arc Tracks on Sidewall Cap in Anodic Region

TP40A-12, Module 5, Cap 42L-Low

20X

Figure 45. Pinholes in Sidewall Cap in Anodic Region

These features are evidence of the severe electrochemical attack in these anodic areas which most likely occurs by the same mechanism as discussed previously for the anode caps.

b. Interelectrode Insulators

Interelectrode insulators included in TP-40A included 1/16" thick boron nitride (BN) plates and composites of Irish Refrasil impregnated with BN coating. Subsequent to the testing the following observations were made:

- 1 BN plates were fractured by clamping forces during module assembly. After service these cracks were penetrated to an extent by potassium and silicon rich species, yet no shorting of electrodes resulted.
- 2 The BN/Refrasil composite performed satisfactorily. Slag adhered to exposed edges of fabric. Potassium infiltration into the weave near the exposed edge did not lead to shorting.

Continued efforts are being made to improve the BN/Refrasil composite by improving its gas sealing characteristics. The approach being taken is to incorporate a non-charring high dielectric elastomer in the composition. This will continue next Quarter.

c. Combustor Refractory

The silicon carbide castable (Carbofrax 11LI) material continued to perform adequately during TP-40A. Microscopic examinations have shown wear

to be primarily by slag attack on the calcium aluminate binder leading to erosion of the SiC aggregate. Other wear mechanisms undoubtedly are operable, such as localized oxidation of the aggregate. It is anticipated that considerations on long duration linings in bonded SiC and other materials will be made in the next reporting period.

d. Metals Corrosion

After some initial limited metallographic analysis on the metal coupons from the Cell III downstream corrosion probes, this activity was delayed due to both the difficulty in metallographically preparing the coupons for scale examination and characterization and the higher priority given to other activities during the Quarter. The difficulty in preparing the pieces for examination is compounded by the fact that due to the very short run times on these coupons, the scale thicknesses range from very thin to virtually nonexistent. However, analysis of the coupons is planned for the coming Quarter, and results from this analysis should be included in the next quarterly report. The metallographic preparation of the corrosion specimens will be enhanced by the use of a Buehler electrolytic etching and polishing system that was purchased and received during the Quarter.

The major activity in the downstream metals subtask during the Quarter was the preparation of a test scheme involving corrosion probe exposure of materials ranging from carbon steels to heat-resistant stainless steels in two different locations in the CFFF. The two locations chosen were the drum module and the secondary combustor, simulating boiler tube and superheater tube environments respectively. The simulated boiler tube probe will have a metal surface control temperature of 700K (427°C) while the superheater probe will have a corresponding control temperature of 865K (593°C). At the present it is believed that the same probes used in Cell III of the EC facility can be used in the CFFF with only minor modifications.

The long-term corrosion probe testing anticipated in the CFFF will provide us with valuable information as to the relevant corrosion mechanisms and will enable us to specify materials for downstream MHD applications.

e. Refractory and Ceramic Materials

Four refractories were installed on studs in the exit area of the exhaust duct and left for the duration of TP-40A:

- 1 Ruby Plastic, a phosphate-bonded chrome alumina refractory, showed low slag penetration accomplished apparently by forming a well adhering reaction layer in which the reaction kinetics were quite slow. Some cracking was evident, but it still had good strength and little spalling tendency.
- 2 HW 10-61, which is a phosphate-bonded MgO ramming material, showed only moderate slag penetration and little attack on the MgO aggregate. It showed good spall resistance.

3 X-3337E, which is a calcium aluminate bonded spinel castable material, showed almost no slag attack but had low spall resistance and low strength. It is believed that the thermal cycling during the test plan contributed greatly to its degradation.

4 Greencrete ARC, a calcium aluminate-bonded chrome ore base castable material, had a very high workability on mixing and was difficult to apply. It did not perform well in this test, but it is probable that its performance was related to the mixing and forming difficulties.

In order to develop alternate and improved refractories for downstream MHD components, a refractory test program draft was completed. This testing program is intended to determine wear and corrosion rates of commercial refractories, to generate information to compare with that of other DOE programs, to determine the basis for future refractory recommendations, and to determine wear mechanisms of downstream refractories. The specific types of refractories to be tested initially in the radiant furnace refractory test doors are listed in Table IV.

f. Miscellaneous Materials

A test apparatus for relative ranking of electrode-to-frame "gap conductivity" sealing materials was constructed during this reporting period. The following materials will be included in the test program:

1 Copper-glycerin mixture currently used in the ECF generator.

2 Silver paints.

3 Copper pastes and heat sink compounds.

4 Graphitic compositions.

5 High conductivity, metal-filled epoxies.

Activities to develop procedures for brazing stainless steel cladding onto copper electrode caps were initiated. A brazing furnace with inert/reducing muffle capability has been ordered. Brazing alloys have been obtained for this experimentation. Next Quarter experimentation will be performed to determine brazing requirements for testing stainless steels and super alloys as candidate materials for cap oxidation protection. Further, the brazing furnace is to be delivered and is to be used for cap cladding.

7.7 Diagnostics

The feasibility study of digital broadband data analysis techniques has produced several codes which are being installed in the VAX computer system at UTSI. These codes have been validated using broadband data recorded during the TP-40A tests in the ECF.

Four triaxial accelerometers have been ordered for vibration studies of the LMF CFFF Channel, and mounting points beneath the cooling water tubes are being located.

TABLE IV

Radiant Furnace Test Refractories

	<u>Primary & Secondary Furnace</u>	<u>Drum Module</u>	<u>Secondary Combustor</u>
Shaped Refractories	1) Fused Cast: Corhart X-317, C-104; carborundum monofrax A, E, K-3 2) Sintered: Harbison Walker Ruby; 90% Al_2O_3 ; SiC; 85% Al_2O_3 ; 60% magnesia chrome 3) Magnesia carbon	1) Bubbled Al_2O_3 : North American NA33 2) IFB for conditions 3) Periclase 4) Harbison Walker Ruby	1) Harbison Walker Ruby 2) North American NA33
Monolithic Refractories	1) Castables: Spirel-Norton LS 812; 90% tubular Al_2O_3 ; bonded chrome ore-AP Green Greencrete ARC 2) Plastics: Al_2O_3 chrome; plastic chrome ore: crushed fused materials; sintered magnesia-chrome; 90% Al_2O_3 ; 85% Al_2O_3 ; 90% Al_2O_3 with graphite	1) Fiber refractory with and without insul- ating castable 2) Light and heavy cast- able, 1645K (2500°F) and 1810K (2800°F) limits 3) Bubbled Al_2O_3 castable 4) 1480K (2200°F) insulating castable 5) 60% and 70% Al_2O_3 castable 6) 60% Al_2O_3 castable with graphite	1) Light and heavy castable 1645K and 1810K limit 2) Spinel castable 3) Plastic chrome ore 4) Materials which perform well in drum module

Next Quarter, layout of the instrumented electrodes for slag layer arcing studies will be initiated and completed. Preliminary drawings should be available.

In advanced diagnostics an AC plasma conductivity instrument was tested in the final TP-40A tests in the ECF. The system has been modified to improve signal-to-noise levels, and design of a switching network to interface it to the generator has been completed. Further checkout is scheduled for the upcoming ECF electrode material test series.

A coal-flow volume fraction meter has been received from Auburn Instruments, Inc. Experiments are being designed to calibrate and evaluate this meter for use as part of the coal delivery instrumentation.

Development of the laser velocimeter (LV) system has been delayed due to delays in receiving critical system components. Portions of the system are complete and arrangements have been made to temporarily use components belonging to the UTSI Gas Diagnostics Division to provide a complete system to measure fluid and plasma velocities. Plans have been initiated to use the sodium line reversal system and other diagnostics being developed at Mississippi State University for the MHD research program.

7.8 Generator Loading

Essential equipment for the Electrical Engineering Laboratory has been identified and purchased with most having been delivered. The inverter building at the CFFF was erected, and completion of power and lighting is pending. Personnel with inverter experience have been hired and more emphasis is planned for next Quarter on developing specifications for the CFFF inverter system.

The circuit configuration for the CFFF resistive power take-off has been specified and work is continuing on establishing criteria for the operating limits. The resistive power take-off design is planned for completion next Quarter. Preliminary investigations are continuing on methods of controllable power take-off.

During the quarter the three control algorithms formulated for the 1000 MW_e MHD/steam plant were implemented on a computer simulation and compared. Since all methods -- proportional integral, and derivative (PID), optimal, and direct digital -- gave satisfactory response to a step load change, the latter, producing a deadbeat performance, was selected as the one most easily implemented using a microcomputer; it only involves quantities that are easily measured and requires no iteration. A topical report is being prepared on this work.

SECTION III CONCLUSIONS

Under Task 2, all test hardware for the first experimental series (LMF-1) has been fabricated. This includes the vitiation heater/combustor, nozzle, conductivity channel, diffuser, radiant slagging furnace and secondary combustor. Installation is well underway. To implement the experiment (Task 4), component test plans have been prepared and sent to DOE for comments. The revised Overall Test Plan incorporating DOE comments was re-submitted. An integrated flow train test plan for the LMF-1 test has been initiated which will contain details of the experiments, including instrumentation hook-ups, data requirements, test conditions, etc.

A variety of activities has been carried out under Task 7. The Cold Flow Facility for aerodynamic simulation has been largely completed. Detailed analysis has begun on the results obtained from TP-40A. Other accomplishments during this Quarter include evaluation and recommendation of electrode and insulating materials, particulate collections and multi-dimensional analysis.

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TOPICAL REPORT STATUS
(July-September, 1980)

1. Submitted for DOE Approval

"Downstream Component Corrosion in Coal-Fired MHD Power Plants,"
FE-10815-48 was sent out in draft form 8-21-80.

2. Issued

"Evaluation of a Coriolis Mass Flow Meter," FE-10815-45 was sent out in
final form 8-18-80.

"Interelectrode Insulator Development for the UTSI Generator,"
FE-10815-44 was sent out in final form 8-18-80.

Cooper, J. "Investigation of Minytrema Melanops Mortality in Woods
Reservoir Near the CFFF," FE-10815-49, was sent out in final form 9-19-80.

3. Projected for Next Quarter

Pendleton, J. D., "Light Scattering Calculations for Evaluation of the
Particle Sizing Techniques of Laser Interferometry."

Roy, G. D. and Attig, R. C., "Development and Heat Transfer Analysis of
Direct Coal-Fired MHD Combustors."

Schulz, R. J., Ghosh, A. and Attig, R. C., "Cold Flow Modeling of
Pulverized Coal Combustors for Magnetohydrodynamic Channel
Applications."

Schulz, R. J., Lee, J. J. and Attig, R. C., "Mathematical Modeling and
Predictions of Flow in Pulverized Coal Combustors for MHD
Applications."

Winkleman, B. C., "Application of a Modified Line Reversal Temperature
Measurement System to Coal-Fired MHD Plasmas."

Wang, H. H., "A Study of Seed Recovery and Particulate Emissions
Control of the Coal Fired Open Cycle Magnetohydrodynamic Steam Power
Plant (CFFF)."

White, M. K., "Downstream Component Corrosion in Coal Fired MHD Power
Plants." Final Form.