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**MHD POWER GENERATION RESEARCH, DEVELOPMENT,
AND ENGINEERING**

Quarterly Progress Report, October—December 1979

Work Performed Under Contract No. AC07-78ET10816

The Montana Energy and MHD Research and Development
Institute, Inc.
Butte, Montana

U. S. DEPARTMENT OF ENERGY

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MHD
POWER GENERATION

RESEARCH, DEVELOPMENT
AND ENGINEERING

Quarterly Progress Report
October to December 1979

THE MONTANA ENERGY AND MHD
RESEARCH AND DEVELOPMENT INSTITUTE, INC.
P. O. Box 3809
Butte, Montana 59701

PREPARED FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Under Contract No. DE-AC07-78-ET-10816

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TABLE OF CONTENTS

REPORT INTRODUCTION.	1
TASK ABSTRACTS.	2
<u>Task Title and Principal Investigator</u>	
MONTANA COLLEGE OF MINERAL SCIENCE AND TECHNOLOGY	
Task A--Characterization of Coal for Open-Cycle MHD Power Generation Systems, F. Diebold.	5
Task B--Compressive Creep and Strength Studies of MHD Preheater Materials, K. Kitto.	12
Task C--Preparation of Coals for Utilization in Direct Coal- Fired MHD Generation, B. Rhodes.	30
Task D--Characterization of Volatile Matter in Coal, D. Beuerman. . .	31
MONTANA ENERGY AND MHD RESEARCH AND DEVELOPMENT INSTITUTE	
Task N--MHD Materials Evaluation, J. J. Rasmussen.	32
MONTANA STATE UNIVERSITY	
Task E--Operability of the Moderate Temperature Slag Flow Facility, H. W. Townes.	40
Task F--Slag-Seed Equilibria and Separations Related to the MHD System, R. Howald.	49
Task G--Thermionic Emission of Coal and Electrode Materials, G. Lapeyre and J. Anderson.	58
Task H1--MHD Instrumentation, Consolidated/Inversion Simulator, and Data Acquisition, R. Johnson.	66
Task H3--Combined MHD-Steam Plant Cycle Analysis and Control, D. A. Rudberg.	72
Task J--Slag Physical Properties: Electrical and Thermal Conductivity, R. Pollina.	89

REPORT INTRODUCTION

During the fall of 1974, a major portion of Montana's scientific community formed a task force to initiate and aggressively pursue a broad-based program of research, development, and engineering in the field of open-cycle magnetohydrodynamics (MHD). This effort was based on the firm belief that MHD technology, although still early in its development and not fully proven as a practical generator of electric power, is the only non-nuclear, central station electric power generation technology with significant potential for greatly improved fuel efficiency and direct operation with coal. MHD also offers lower environmental impact and a reduced pollution signature. Associated with this high efficiency is the reduced consumption of water--a factor of importance to the semi-arid western regions.

This task force was incorporated into the Montana Energy and MHD Research and Development Institute (MERDI). MERDI is a not-for-profit Montana corporation with performing team members drawn from in-house staff and the research faculties of the Montana College of Mineral Science and Technology (MCMST) in Butte and the Montana State University (MSU) in Bozeman.

With the able and generously provided assistance and advice of the MHD research and development staff of the Avco Everett Research Laboratory in Everett, Massachusetts, MERDI formulated a broad-scope research program to address the key technical problems currently recognized for MHD technology at both fundamental and practical levels. In November 1974, a proposal was submitted to the U.S. Energy Research and Development Administration (ERDA), now the U.S. Department of Energy.

ERDA awarded MERDI a contract in March 1975 for a portion of the MHD supporting science and technology tasks submitted in the original proposal. Work was divided among researchers at the performing elements (MCMST and MSU) on the basis of primary specialization and expertise. MCMST was assigned the tasks relating to coal fuel supply, characterization, preparation, and handling as well as MHD materials engineering. MSU tasks are related to science, heat transfer, mechanical engineering, chemistry, and chemical engineering aspects of MHD technology. MERDI assumed responsibility for overall program management, environmental impact assessment of MHD facilities, and site selection studies of future MHD central station power plants.

This report summarizes the work accomplished under these tasks from October 1979 through December 1979 by MERDI, MCMST, and MSU.

TASK ABSTRACTS

MONTANA COLLEGE OF MINERAL SCIENCE AND TECHNOLOGY

Task A--Characterization of Coal for Open-Cycle MHD Power Generation Systems

The research to establish a set of coherent analytical procedures for the rapid, accurate, and precise analysis of coal has involved application of a number of instrumental techniques. The coal properties investigated are Btu, proximate and ultimate values, major metal concentrations, minor metal concentrations, and minor non-metal concentrations. A scheme for the analysis of these coal properties has been designed. This scheme incorporates those sample preparation and analytical techniques to improve upon or maintain the accuracy and precision of the ASTM procedures. Those areas requiring additional work have been identified and a time frame for their completion has been established.

This work has incorporated the investigation of an alternate sample preparation technique designed to reduce the loss in Btu of the coal sample and to increase the efficiency of the process. In the inductively coupled emission spectroscopy (ICPES), analysis of metals in the coal element interferences have been identified and a correction procedure is being designed. The precision of the automated combustion train analysis of C-H-N has been improved and efforts are in progress to compare this data with ASTM generated data. Routine analysis of tibble samples is scheduled to begin within the next quarter to establish the time variation in coal properties.

Task B--Compressive Creep and Strength Studies of MHD Preheater Materials

During the past quarter, isothermal compressive creep testing continued on a fusion cast spinel (Corhart X-317) and a castable spinel (Norton LS-812). Initial test results on X-317 have been encouraging under isothermal (1173 K or below) low compressive load conditions (2.8 MPa). For example, a slagged X-317 sample showed only a small deformation of 0.00008m from a pore collapse after 950 hours at 1773 K and 2.8 MPa. LS-813 had a secondary creep rate of 0.0004%/hour after 1350 hours at 1400 K and 5.5 MPa.

Hot compressive strength measurements were made on Corhart X-317, Corhart RFG (pristine and preheater slagged) and Carborundum Monofrax E over the temperature range of 1273 K to a high strength value (7120 MPa) to 1673 K followed by a drop off to 88 MPa at 1773 K. Porous interior samples of X-317 had a lower range--80 MPa to 35 MPa over the same temperature range. Monofrax E showed a steady decline in strength, from ~ 115 MPa to 35 MPa over the range, while pristine RFG showed a drastic decline after 1573 K; 80 MPa to 35 MPa. Hot compressive strength tests also were performed on slagged RFG from four regions of the MSU core 1.

Task C--Preparation of Coals for Utilization in Direct Coal-Fired MHD Generation

Further testing on the one-square-foot fluid bed drying unit was carried out during this quarter. The small spray dryer was received. The annual review was presented in Bozeman for all MHD research projects.

Task D--Characterization of Volatile Matter in Coal

This task is working with Task C to solve the organic elution problems by coordinating the operating conditions of their dryers with the analysis of their waste gases.

THE MONTANA ENERGY AND MHD RESEARCH AND DEVELOPMENT INSTITUTE

Task N--MHD Materials Evaluation

Corhart X-317 bricks tested for up to 1170 hours at Fluidyne Engineering Company showed less corrosion than the X-317 tested for 200 hours at Montana State University. The difference in the results is apparently due to the difference in base/acid ratio of the slags used in the two tests. The Fluidyne slag/seed was basic with a ratio of about 18 while the same slag without the seed at Montana State was acidic at 0.67. The basic refractory with a ratio of about 56 would be expected to be more corrosion/erosion resistant in the Fluidyne tests.

MONTANA STATE UNIVERSITY

Task E--Operability of the Moderate Temperature Slag Flow Facility (MTSFF)

The second core in the moderate temperature slag flow facility (MTSFF) was operated with slag injection for a total of 950 hours. Several successful slag meltouts were made. A 200-hour materials test run was made for the selection of a new material for the third core.

Task F--Slag-Seed Equilibria and Separations Related to the MHD System

Potassium equilibrium vapor pressures were measured over composition ranges approximating several typical compounds in four-component model slag systems. Methods are being developed for thermodynamic analysis of these systems.

Task G--Thermionic Emission of Coal Slag and Electrode Materials

The apparatus for measuring slag thermionic emission under potassium vapor has been constructed and assembled except for the ovens and the potassium source. The thermionic emission part of the apparatus has been tested by measuring the emission of an iridium sample in vacuum. X-ray photoemission spectra were taken from samples of iron-containing slag, as well as Fe_2O_3 , Fe_3O_4 , and metallic iron, in the beginning of an effort to establish a procedure for routinely determining the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio. Existing literature

describes the method as well as the data reduction routines necessary to extract the desired ratio. The data so far indicate that the value for the ratio cannot be estimated by inspection or extracted by hand methods. Rather, computer methods on digitized data must be used.

Task H1--MHD Instrumentation, Consolidation/Inversion Simulator, and Data Acquisition

The dynamic combustor-nozzle-channel-diffuser computer model program is now operational. Modifications to increase the stability of the integration routine for the case of severe compression shock conditions are being undertaken to increase the applicability of the program. Test runs are proceeding on the original program in parallel with the modification work.

The forced commutated inverter system has been successfully run without notch filtering. Notch filtering is being incorporated for harmonic suppression. Speed constraints of the Z80 microprocessor being used for commutation of the silicon-controlled rectifier has necessitated the inclusion of three of these processors.

Task H3--Combined MHD-Steam Plant Cycle Analysis and Control

Combined-cycle MHD-steam power systems are being modeled by digital computer simulations. Methods to provide efficient control of such systems are being investigated by using the simulations to ensure stable modes of response and to obtain coordinated control of many interdependent subsystems. Dynamic component models have been developed, as has a multi-input, multi-output model of the combustor-nozzle-channel-diffuser. First-principle dynamic models of plant components are being embedded in the latest simulation. Final assembly of the various subsystems composing the combined power system model is near completion. This model will form the basis upon which various coordinated control policies for combined cycle plants will be tested and evaluated. A technical report on the combined cycle dynamic model is expected by June 1980.

Task J--Slag Physical Properties: Electrical Conductivity and Thermal Expansion

The experimental phase of the electrical conductivity work in Rosebud coal slag seeded with potassium carbonate has been completed. Results are presented in the report for those measurements from 700 to 1450°C from zero to 30 percent weight equivalent K₂O seed concentration in the slag; also, some results from the computer modeling studies of the electrical conductivity data are presented. During this quarter, the electrical conductivity and leakage resistance of a hypothetical slag layer on a water-cooled electrode wall were calculated as well as the voltage drop through such a slag layer as a function of wall temperature and the field gradient through the slag layer. These latter calculations are for a diffuse mode with electrically compatible electrodes. The report also presents information on how this data could be useful in current channel design.

TASK A
Characterization of Coal for Open-Cycle MHD Power Generation Systems
F. Diebold

I. OBJECTIVE AND SCOPE OF WORK

The objective of this program is to investigate experimental techniques for their incorporation into a coherent and efficient analytical scheme for the rapid generation of accurate and precise concentration data of the following properties in coal:

- A. Btu, percent moisture, volatile matter, fixed carbon, ash, and S, H, C, O, N, Cl, F, and P content;
- B. Major metals: Al, Ca, Fe, K, Mg, Na, Si, and Ti; and
- C. Minor metals: Ag, As, B, Ba, Be, Cd, Co, Cr, Cs, Cu, Ga, Hg, Hf, Li, Mn, Ni, Pb, Rb, Sb, Se, Sn, Sr, U, V, Zn, and Zr.

Another objective is to characterize the western United States standard MHD coal with respect to the above parameters. These data are to represent the time variation in Rosebud seam properties as the coal is processed through a typical power plant coal feeding system.

II. SUMMARY AND IMPACT

The work in analytical method development that has taken place over the last few years has been integrated into a general analytical scheme that maintains the accuracy and precision of the ASTM procedures. The important point is that our integrated set of procedures includes sample preparation procedures and instrumental techniques that, in some cases, improve accuracy. The efficiency of this set of procedures is such that the small commercial laboratory can, with a marked reduction in man-hours, analyze a relatively large number of samples. This is a critical point since a large number of coal samples need to be analyzed to support MHD research development. The importance of such analytical data is described by Gorbaty, et al., 1979. Eventually, field instrumentation must be developed to provide short-time measurement of the items in A. and B. above. Short time is considered to be approximately 1/2 hour. Since the MHD channel response is rapid and the coal handling system slow, this amount of time would allow analysis plus a feed forward signal to the system for anticipatory response.

Another important development that is directly related to our analytical method development work is the recent activity of the ASTM D-05 committee responsible for the adoption of coal analytical techniques. Strong consideration is being given to the formation of a new section which will consider the adoption of relatively rapid coal analysis techniques. Obviously, this provides an open avenue for us to make the necessary input.

III. DETAILED DESCRIPTION

A. Formulation of Analytical Scheme

1. Work Accomplished

The various components of the analytical method development work have been integrated into a general coal analytical scheme. This scheme is portrayed in Figure 1, which incorporates notations where additional work is required. These areas requiring additional work are listed in Table 1, which also incorporates a proposed time schedule for their completion.

2. Discussion

The philosophy behind our effort in analytical method development has been to set up an integrated series of more rapid procedures for the Btu, proximate, non-metal and metal analysis of coal that would be relatively efficient while maintaining the accuracy and precision of the ASTM procedures. The contribution of this work to MHD research and development will be realized when this scheme is adopted by the commercial analytical laboratories. The point is that these laboratories, not the university laboratories, have and will be generating the multitude of data important for the characterization of the large number of samples required to be supportive of MHD research, development, and use. The problem is that these laboratories are required to follow the relatively time-consuming and costly ASTM procedures. Thus, the mechanism by which we can make a contribution will be through the appropriate ASTM committee recommending such relatively rapid instrumental methods for use by analytical laboratories.

An additional aspect of our research is that we have endeavored to investigate those instrumental procedures which would not only be appropriate for multi-elemental analysis but would be within the capital and operational cost limitations of the usually small commercial analytical laboratories.

B. Laboratory Sample Preparation

An alternative to our previously established laboratory sample preparation procedure has been under investigation. This involves a comparison of different grinding systems and their influence upon coal properties. The grinding systems we are investigating are those suggested by Reilby and Hicks (1979). This alteration to our laboratory sample preparation procedure is being considered in order to reduce the amount of possibly high Btu dust loss and the relatively large amount of time consumed during sample preparation.

C. Procedures for Metal Analysis

The element interferences have been identified and the standards prepared for the routine ICPEs metal analysis. It is important to note that the analysis of the Rosebud tippie samples for the major metals is critical to our real-time analysis effort (i.e., the generation of appropriate equations for calculating the ash content of the Rosebud seam coal). Since the concentrations of some minor elements have an effect on the major element data, it is also important to analyze for these minor elements. In addition, knowledge of the time variation of these minor elements that are on the EPA toxicity list will be critical for designing environmental control devices.

D. Procedures for Non-metal Analysis

The use of smaller particle size coal samples, smaller sample mass, and new gas valves has significantly improved the precision of the PE 240 automated combustion train analysis of C, H, and N. This improvement will allow us to obtain a reliable comparison with the data generated by the ASTM procedures. This study will take place within the next few weeks, and the routine analysis of the tippie samples can then be started.

The relatively longer time effort projected for establishing the anion chromatographic analysis of F, Cl, S, and P (Table 1) will not have a serious impact on the routine analysis of the tippie samples. Our earlier work has shown F, Cl, and P to be of relatively low concentration in the Rosebud coal. Western Energy Company data sheets for these tippie samples will carry information concerning total sulfur content.

E. Coal Property Determination

The tippie samples from the sampling tower in the yard of Western Energy at Colstrip are still being received. The sampling station for the burner samples was moved from the Corrette Plant in Billings to the units at Colstrip. These samples have recently been taken, and we should receive splits within the next month. The location of the sampling stations is illustrated in Figure 2. The acquisition of these burner samples will give us the set of samples needed to initiate our program for determining the time variation in properties. The Btu, ash, moisture, and sulfur data generated by Western Energy will be related to the C, H, N, and major and minor element data generated in our laboratory.

TABLE 1

Additional Method Development Work

ACTIVITY

Sample Preparation

Investigation of Btu difference due
to different grinding steps (1 month)

Sample Storage

Continual monitoring of sample properties
in storage system (1 year)

Air Drying Step

Verification of equilibrium constants
expressing residual moisture in coal
as function of relative humidity of
atmosphere (long term)*

Determination of properties of water
(ΔH & S) within coal. (long term)*

Proximate Analysis

Establishment of alternative moisture
analysis system that will improve
accuracy and indicate loss of volatiles
other than H_2O . (2 months)

Anions

Comparison of automated combustion train
and ASTM for C-H-N. (1 month)

Establishment of anion chromatographic
system for F, Cl, P & S analysis (6 Months)

Metals

Establishment of automatic spectral inter-
ference system for ICPEs analysis of metals (1 month)

*Long Term: The minor amount of effort that will be expended throughout
this current year in this activity means that additional work
will be required.

Figure 1

General Analytical Scheme

Figure 2. Western Energy Coal Feeding System - Colstrip, MT.

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2. Reilby, J. E., Hicks, O. G., "Slurry Injection Atomic Absorption Spectrometry for Analysis of Whole Coal," Analytical Chemistry, Vol. 51, No. 12, pp. 1905-1915, 1979.

TASK B
Compressive Creep and Strength Studies of MHD Preheater Materials
K. Kitto

I. OBJECTIVE AND SCOPE OF WORK

The primary objective of this task is to characterize the properties of potential MHD materials which directly aid in engineering design work and those which are directly applicable in current and future test rig materials selection. Property tests include the following:

- High-temperature compressive creep
- High-temperature compressive strength
- High-temperature creep/strength during and after temperature cycling simulating preheater conditions
- Thermal cycling/materials investigations

The above tests can be performed under the following simulated preheater conditions: a) temperatures to 1973 K, b) atmospheres, oxidizing or simulating combustion, c) forces indicative of brick positions, d) cycling of temperatures, e) times to 1500 hours and beyond, and f) materials in their pristine or slagged preheater tested state.

Test samples include such commercial materials as magnesia/magnesia-alumina spinels, magnesia-aluminas, alumina/magnesia-aluminas, chrome-aluminas, aluminas, etc., insulating castables, and innovative laboratory materials. These samples are tested in the task first as pristine materials (for materials ranking) and then after being exposed in experimental preheater rigs (for endurance evaluation).

Before and after testing, ceramics are subjected to several microstructural tests which include a) simple metallography, b) SEM with EDAX examinations, and c) X-ray analysis for phase change detection. Fracture toughness studies on post-creep samples and thermally cycled specimens are to be made by MERDI's Applied Research Division.

II. SUMMARY OF PROGRESS TO DATE

A. Test Equipment

The three air atmosphere creep frames and the microprocessor data acquisition system (described in detail in a previous report)¹ were operative during the quarter and a great deal of information was generated. Construction on the rig to test large samples continued as did construction on the frame for the "Astro" furnace. Emphasis has been placed on completing the brick rig first with the Astro frame construction moved to a later part of the program.

B. Testing

Also during the quarter, several long-term creep tests were completed. Tests have concentrated on a core material, a magnesia/magnesia alumina spinel (Corhart X-317), and an insulating material, a spinal castable (Norton LS-812). X-317 has been designated as a potential core material, while LS-812 is being tested as a support dome material and a valve lining material.

High-temperature compressive strength tests were performed on a number of important pristine and preheater tested materials. Results from this test program have aided design work in two ways: first, as a source of basic engineering parameters and, second, as a source for understanding destruction mechanisms in the preheater as they relate to materials.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

A. Equipment

In addition to the creep frames and other furnaces "on-line," progress has been made on the construction of three additional frames and furnaces. Table 1 lists the planned creep system. A priority schedule for completion of the frames was discussed with Fluidyne and various materials tasks in Montana. Although both frames are important to the overall program, a need to test larger samples (for study and comparison) of these relatively inhomogeneous materials was expressed. Also during the quarter, a separate thermal cycling furnace was completed. The ultimate goal is a high stress design model without catastrophic crack propagation. This difficult and important study will require much effort and time to produce proper results.

B. Tests and Results

1. Work Accomplished

During the past quarter, several creep tests, compressive strength tests, and microstructural examinations were carried out. Creep testing has concentrated on Corhart X-317 and a spinel castable Norton LS-812. Corhart X-317 is a potential core material that has shown some success in the Fluidyne test rig, while LS-812 has potential as support dome material or valve lining material. Compressive strength testing has concentrated on various potential core materials, but measurements have also been made on LS-812.

2. Discussion

Detailed descriptions of past theoretical creep studies¹ and a literature survey⁵ were presented in previous reports. Since the task is concerned with gathering engineering design type data on multiphase, complex commercial ceramics, complex theoretical creep models cannot be developed with ease. However, these models are not necessary for the engineering goals of MHD ceramics if an activation energy is calculated and a creep mechanism is approximated. An approximate activation energy

and an approximated creep mechanism can be made on the commercial refractories. For example, as described in a previous report,⁵ if one deformation mechanism is rate controlling, then steady-state creep could be described by the following:

$$\dot{\epsilon} = A(\sigma/G)^N e^{-Q/RT} \quad \text{or}$$

$$\dot{\epsilon} = A\sigma^n \exp\left(\frac{-\Delta H}{RT}\right) \quad (\text{if stress is not normalized})$$

The activation number may be calculated by several methods, but in complex refractories with inhomogeneous structures, it is usually calculated by taking the slope of an Arrhenius plot. In this method, creep rate $\dot{\epsilon}$ is plotted versus reciprocal temperature for a constant stress. In addition to plotting for a constant stress value, a constant deformation value may be chosen.

The value of the exponent, n , in the above equation is indicative of the deformation mechanism^{1,5} for plastic strain. This stress exponent can be found by plotting the natural log of steady-state creep versus the natural log of (σ/G) . Also, the activation energy could be calculated by

$$Q = \frac{R/n (\dot{\epsilon}_1/\dot{\epsilon}_2)}{1/T_2 - 1/T_1}$$

if A and G were constant. During the next quarter, we will try to see how our results tie into these equations. Hopefully, a rough estimate of an activation energy and a deformation mechanism can be made.

Typical temperature and compressive stress conditions in an MHD preheater (according to Fluidyne) are given in Table 2. The values range from 0.2 MPa to 1.0 MPa at 1900 K to 2000 K in the upper dome region and 1.0 MPa to 5.0 MPa at 1300 K to 1500 K in the support dome regions. Note that the stress values given refer only to the stress due to the weight of the bricks and that the stresses induced by the thermal cycling are not included. For instance (according to Fluidyne),⁶ the maximum stress from thermal cycling will occur in the bottom matrix brick at the beginning of the air phase. This maximum thermal stress is estimated to be approximately 26 MPa. Given these conditions, we plan to initiate creep testing with thermal cycling immediately after initial isostatic, isothermal creep characterization is completed.*

During the past quarter, isothermal creep testing has continued on Corhart X-317 and Norton LS-812 spinel castable. A summary of the

*The cycling rate including heat transport considerations will be planned with Fluidyne in an upcoming meeting.

creep runs and results is given in Table 4. As shown in that table, initial runs on the core material, X-317, are very encouraging. For example, a test on a slagged sample X-317 (taken after 420 hours in the Fluidyne rig) showed only a small amount of deformation (0.00008m) due to the collapse of a small pore upon testing at loads to 2.8 MPa at 1773 K for approximately 950 hours. A test condition listing and a plot of this test are given in Table 5 and Figure 1.

The results of the initial creep testing program on Norton LS-812 spinel castable are also given in Table 4. This material is being considered for the dome support region of the preheater and is currently being tested as a valve lining material at Fluidyne. Because it is a castable, a complex design of the support dome region could easily be fabricated from the LS-812. Results of a creep test under dome support conditions are given in Table 6 and Figure 2. The secondary creep rate is 0.0004%/hour.

A quick comparison of Figures 1 and 2 shows the radical difference in behavior of the two materials. The dense fused cast X-317 experiences a period of thermal expansion after equilibrium, before any deformation occurs,¹ while the porous castable experiences almost immediate deformation after equilibrium. This permanent thermal expansion after equilibrium is thought to be typical of fused cast materials.⁷

The results of the hot compressive strength tests of various core materials are given in Figure 3. The plot (compressive strength versus temperature) shows the drop off of compressive strength of the material with an increase in temperature. Refer to Table 3 for the compositions, manufacturing methods, and cold compressive strengths for the materials.

Corhart RFG is a rebonded fused grain magnesite-chrome* material that has been used in the first two cores of MSU's indirect-fired preheater program. Although it is obviously not a serious candidate material, the study of the pristine material and the material after being exposed to actual preheater test conditions is important. Insights can be gained into the mechanisms of destruction in various regions of the preheater. Once these factors are known, a better understanding of preheater design can be utilized. The results of the pristine test (Figure 3) show that this material exhibits almost no loss of strength to 1573 K and a severe loss of strength at temperatures greater than 1573 K. This could be attributed to a silicate phase losing strength at high temperatures; this behavior is typical of a material containing a silicate phase. Another problem with RFG is the oxidation of FeO to Fe₂O₃ or Fe₃O₄ in an oxidizing atmosphere at high temperatures. Since the lattice parameter changes upon oxidation, stresses could be set up within the material and contribute to its poor mechanical performance.

*See Table 3.

Monofrax E is a fused cast, high chrome spinel material that has undergone short materials tests at MSU and Fluidyne. The compressive strength of this material drops off quite readily with temperature. However, in a recent materials test at MSU, Monofrax E was found to exhibit a poor resistance to thermal cycling and fracturing seemed to be a problem. In a report by the Carborundum Company² on these materials, cycling of the material after exposed fractures were filled with slag was presented as a problem that could affect the performance of the material. This material, then, should be a prime candidate for thermal cycling study.

Corhart X-317 is a fused cast magnesia/magnesia-alumina material that has performed well as a core material in initial tests at Fluidyne. Because of a quality control problem this refractory has a greater amount of macro- and micro-porosity than is expected of a fusion cast product. The compressive strength test results are a good indication of why quality specifications need to be placed upon a refractory for satisfactory operations. However, a compromise must be made in regard to porosity. Although lower porosity usually leads to better strength, load resistance and corrosion resistance, pores act as crack stoppers in thermal shock. This thermal cycling resistance (crack initiation without propagation) may well be one of the larger factors in preheater design. However, the large amount of porosity in X-317 is a quality control problem at this time.

Figure 3, however, shows the excellent hot compressive strength of X-317. The dense X-317 taken from the skin of the brick shows little decrease in strength up to 1673 K. In excess of 1673 K, the strength drops somewhat but X-317 is still much stronger than the other materials tested. In fact, only the most porous samples of X-317 are needed on the recent batches of X-317 to determine possible mechanical variations. Preheater slagged samples will also be run when the samples are obtained.

Norton LS-812 is a calcium aluminate bonded fused grain spinel. The material itself was another piece of the bricks that were cast and fired at Fluidyne. The results of the hot strength tests are given in Table 7. Note that the numbers are very much a function of casting methods; of course, the castable's strength is much lower than those of the dense core materials, but it seems sufficient for some regions. However, the load bearing capacity at high temperatures (>1700 K) for long times is questionable at the present time. Again, different materials appear to be appropriate in different regions of the preheater.

A study was made of the hot compressive strengths of Corhart RFG that was removed from the first core of the MSU facility at the end of run #6.* This material was then sectioned and sent to various groups within the community for a range of microstructural examinations and tests.

*A detailed history is given in MSU Task E reports.

Figure 4 is a plot of the compressive strengths versus distance from the top (hot) of the core for four different testing temperatures. As this figure shows, the behavior of a preheater tested refractory is different from the pristine material and is also different for samples taken from different regions of the preheater.

In recent microstructural reports^{3,4} on this same material, destruction modes within the core are described. Referring again to Figure 4, sample "2-2" (0.1m from the top of the bed) showed little compressive strength at temperatures in excess of 1473 K. Sample "5-2" showed a similar drop but not as severe. Sample "14-2" showed a great increase in strength at 1373 K and 1473 K (>160 MPa, > pristine material), followed by a drastic drop off in strength at temperatures > 1473 K. Sample "23-2" also exhibited high strength at 1373 K and 1473 K (but not as large as "14-2") but followed with only a moderate decline in strength at 1573 K and 1673 K.

Possible explanations for this behavior can be found by close examination of the microstructure of the samples. In a recent report by Bates,⁴ the following data was reported:

- 2-2: No remaining original RFG, continuous phase vitreous or crystalline $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$
- 5-2: Interior to be a mixture of MgO , $2\text{MgO} \cdot \text{SiO}_2$, $\text{Mg}(\text{Al}, \text{Cr}, \text{Fe})_2\text{O}_4$ spinel, Al/Cr/Fe ratios 3/3/2
- 14-2: Slag penetration of the entire sample: RFG original structure as islands in the reaction products of $2\text{MgO} \cdot \text{SiO}_2$ and particles of Mg rich $\text{Mg}(\text{Cr}, \text{Al}_2)\text{O}_4$ spinel and $\text{Mg}(\text{Cr}_{0.2}\text{Al}_{0.8})_2\text{O}_4$
- 23-2: Remaining original RFG structure surrounded by Mg rich $\text{Mg}(\text{Al}, \text{Cr})_2\text{O}_4$ and MgO phases, surrounded by $2\text{MgO} \cdot \text{SiO}_2$ and Mg rich $\text{MgO} \cdot 2\text{CaO} \cdot 2\text{SiO}_2$

A similar study was done by Youngblood and Sun³ with similar results. Results from that study show the open porosity of "2-1" to be ~ 5%, "5-1" to be ~ 2.8%, "14-1" to be ~ 1.8%, "23-1" to be 4.2% with pristine RFG ~ $12.5\% \pm 0.7\%$. A similar plot is given for bulk density.

For example, sample "14-2" had the smallest amount of open porosity which indicates a filling of the original open porosity with the greatest amount of slag, while a study of the interior microstructure shows $2\text{MgO} \cdot \text{SiO}_2$ with regions of original RFG, etc. These facts could account for "14-2's" remarkable strength below 1473 K and its drastic fall off above 1473 K, according to the behavior of that silicate phase. Similar behavior is shown by sample "23-2"; however, it does not have the strength of "14-2" at high temperatures (> 1473 K) but shows greater strength at higher temperatures (> 1473 K). The higher amount of residual RFG in the structure could account for this.

Sample "2-2" had the greatest amount of degradation in the preheater leaving no residual RFG. The remaining new interior structure $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ showed little strength with temperatures in excess of 1473 K. Finally, sample "5-2" which has an interior mixture of MgO , $2\text{MgO} \cdot \text{SiO}_2$ and $\text{Mg}(\text{Al},\text{Cr},\text{Fe})_2\text{O}_4$ spinel showed little strength above 1473 K compared with samples with different microstructures. More study could be necessary if exact mechanisms are to be found.

Studies like these must be made on preheater tested ceramics if insights are to be gained into the mechanisms of destruction within the preheater rigs themselves. Again, different materials may be suited for different preheater regions.

IV. WORK FORECAST

During the next quarter, the following sub-tasks will be continued:

- A. Creep testing on commercial refractories and castables.
- B. Construction on the "brick size" test rig and the "Astro" furnace rig with priority given to the brick rig.
- C. Creep testing with thermal cycling considerations
 - 1. Samples cycled prior to testing
 - 2. Samples cycled during testing.
- D. Engineering design materials testing
 - 1. High-temperature compressive strength
 - 2. Thermal cycling effect studies.
- E. Microstructural examinations.

TABLE 1

Experimental Creep System at Montana
College of Mineral Science and Technology

	Air Atmosphere (small)	Air Atmosphere (large)	Air Atmosphere ("Astro")
Number of frames	3	1	1
Maximum Temperature	1973 K	1923 K	2023K
Source	MoSi ₂	MoSi ₂	Graphite
Load Cell	50 kg 100 kg 500 kg	1750 kg	50 kg
Sample Size	2.5cm x 2.5cm x 10cm [1" x 1" x 4"]	13cm cube [5" cube]	1.3cm x 5cm cylinder [0.5" x 2" cylinder]
Temp. Cycle capability	Yes	Yes	Yes
Atmosphere Cycle Capability	Major Modification	Major Modification	Yes
Status	all 3 operating simultaneously	under construction	Under construction
Controls	microprocessor	microprocessor	microprocessor
Data Retrieval	automatic	automatic	automatic

TABLE 2

Temperature and Compressive Stress
Conditions in a MHD Preheater
(Fluidyne)

LOCATION	COMPRESSIVE STRESS		TEMPERATURE IN K
	MPa	PSI	
UPPER DOME	0.2-1.0	29-145	1900-2000 (Hot Face)
UPPER MATRIX	0.1-0.5	14-72	1900-2000
MIDDLE	0.2-0.8	29-116	1500-1800
LOWER MATRIX	0.2-1.0	29-145	1300-1500
SUPPORT DOME	1.0-5.0	145-725	1300-1500
VALVE LINING	0.2-1.0	29-145	1900-2000 (Hot Face)

TABLE 3

Compositions and properties of the materials used in the testing program.

Manufacture Method	Monofrax E Fused Cast	X-317 Fused Cast	RFG Rebonded Fused Grain	LS-812 Calcium aluminate bonded fused grain
% Al ₂ O ₃	4.7	31	8.0	Unknown
% MgO		67	55-60	Unknown
% Cr ₂ O ₃	79.7		20	Unknown
% SiO ₂	1.3	0.5	2.5	Unknown
% Fe ₂ O ₃	6.1	0.8	11(FeO)	Unknown
% CaO		0.5		
Cold Compressive Strength MPa	137.9*	92.6-178.7	64.8**	16.8

* Manufacturers

** Measured

TABLE 4

Summary of creep results on X-317 and LS-812

Material	Temperature K	Load MPa	Secondary creep rate %/hr
X-317 (Corhart)	1573	0.34	no creep (275 hrs.) ***
	1623	0.34	no creep (504 hrs.) ***
	1623	0.52	no creep (300 hrs.) ***
	1673	0.52	no creep (450 hrs.) ***
	1773*	0.83	no creep (528 hrs.) ***
	1823*	0.83	no creep (192 hrs.) ***
	1923*	0.83	no creep (150 hrs.) ***
	1773**	2.80	no creep (950 hrs.) ***
	1773	6.90	0.0014%/hr
	1773	4.70	0.0006%/hr.
	1663	15.0	calculation
LS-812 (Norton)	1400	5.50	0.0004%/hr.
	1700	1.00	calculation
	1700	1.00	calculation (exp. check)
LS-812 Batch #2	1700	0.45	in progress
	1400	4.60	in progress

* one sample

** taken from a 420 hour run at Fluidyne

*** thermal expansion after equilibrium - not exceeding 1.25%.

TABLE 5

Experimental conditions and
comments for a creep test on
Preheater tested X-317* whose graphical
Presentation is given in Figure 1

SAMPLE:	Corhart X-317, Batch #2, taken near the skin of the brick. *Taken from a 420 hour run at the Fluidyne Corporation.
TEMPERATURE:	1773 K (middle matrix)
LOAD:	2.4 MPa for 300 hours 2.8 MPa for 300-950 hours
COMMENTS:	The small amount of deformation at 150 hours is attributed to the collapse of a small pore on the side of the specimen.

TABLE 6

Experimental Conditions and Comments
For a Creep test on a Norton Spinel Castable,
LS-812, whose Graphical Presentation is given
in Figure 2

SAMPLE:	Norton Magnesia/alumina castable, LS-812, calcium aluminate binder cast and fired at Fluidyne
TEMPERATURE:	1400 K (lower matrix, support dome)
LOAD:	5.5 MPa
CREEP RATE:	Primary - 0.0288%/hr Bend - 0.0015%/hr Secondary - 0.0004%/hr
TEST LENGTH:	1350 hours
COMMENTS:	Casting procedures can easily alter the properties of any castable.

TABLE 7

Norton Spinel Castable LS-812
High temperature compressive strengths

<u>Temperature</u>	<u>Strength</u>
Room Temp.	16.76 MPa
1373 K	16.93 MPa
1473 K	15.87 MPa
1573 K	12.24 MPa
1673 K	9.94 MPa
1773 K	7.07 MPa

Figure 2. Percent deformation verses time for a Norton LS-812 castable sample. Experimental conditions simulated the support dome region of the preheater.

Figure 4. Compressive strength versus distance from the "hot" end of the MSU preheater. Note: The behavior of the samples at the different temperatures.

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TASK C
Preparation of Coals for Utilization in Direct Coal-Fired MHD Generation
B. Rhodes

I. OBJECTIVE AND SCOPE OF WORK

During the contract period from April 1978 through September 1979, fluidization drying studies of Rosebud seam coal are to be carried out to generate engineering data to characterize this coal drying. These experiments include measurements of drying rates, the equilibria between the dried coal moisture content and the off-gas humidity, heat and mass transfer coefficients, and entrainment losses for variable drying conditions. They also will include the effect of coal feed rate, inlet drying temperature, inlet humidity, drying gas mass flow rate, and coal particle size on the preceding parameters. The data shall be analyzed to obtain a better understanding of the mechanism of drying the coal to low moisture levels and, importantly, the inter-relationships among the operating and design variables needed to achieve various coal moisture levels.

II. SUMMARY AND IMPACT

A preliminary analysis to examine the benefits of burning coal with 95 percent ash removed prior to combustion was performed. Initial studies for coal cleaning, wet grinding, ash separation, and spray drying were planned.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

Further testing on the one-square-foot fluid bed drying unit was carried out.

A technical review was held and considerable new information will result in some modification to Task C work. A decision has been made to use extra oxygen in the combustor. The extra oxygen production will result in surplus nitrogen which can be used as a dry inert medium to transfer the exit gas heat from the steam bottoming plant to be used for drying coal. These changes are being incorporated into Task C fluid bed studies. Planning has progressed for trial runs in the Niro Spray Dryer, but no runs have been made.

IV. WORK FORECAST

Further testing in the fluid bed dryer will be carried out during the coming quarter. The spray dryer will be prepared for operation, and bench-scale ash separation tests will be initiated.

TASK D
Characterization of Volatile Matter in Coal
D. Beuerman

I. OBJECTIVE AND SCOPE OF WORK

The objectives of this task are to identify and quantify organic volatile matter evolved during the coal drying process and to assist in determining methods of preventing loss of organics.

II. SUMMARY AND IMPACT

The loss of organics during the drying process has been established and verified in previous reports. These losses have the following impacts on coal treatment processes.

- A. They possibly render the ASTM D-3302-74 method for determining moisture in coal invalid.
- B. They can cause a reduction in the Btu content of the coal.
- C. They are potential pollutants to the atmosphere and waste water if not properly controlled (especially lower aromatic compounds).

Results to date indicate that these losses can be decreased by controlling the operation parameters of the pretreatment plant.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

Work during the quarter consisted of the following.

- A. Preparation for the annual review by DOE in December.
- B. Development of methods to analyze gases and quench water from the fluidized bed dryer for organic matter. These methods involve sample preparation and measurement when using an Altex 110A high pressure liquid chromatograph and a Hewlett Packard Model 5830A gas chromatograph.

This task also is working with Task C to solve the organic elution problems by coordinating the operating conditions of their dryers with the analysis of their waste gases.

TASK N
MHD Materials Evaluation

J. J. Rasmussen, R. Parker, T. Morse, D. Sun, and G. E. Youngblood

I. OBJECTIVE AND SCOPE OF WORK

The objective of this task is to perform and coordinate MHD materials research and evaluation work in support of the national plan for MHD electrical power development formulated by the DOE-FE-MHD Division. The research emphasis is placed on elements of open-cycle MHD utilizing coal as the primary fuel.

II. SUMMARY OF PROGRESS TO DATE

Corhart X317 bricks, tested in the Fluidyne Engineering Company air heater assembly with exposure to Montana Rosebud fly ash and potassium sulfate for 750 and 1170 hours, was evaluated in terms of density change and chemical composition change due to slag/seed corrosion/erosion. The results showed a density loss in the top brick of the stack but the composition changes were minor.

In contrast to the Fluidyne tests where the X317 showed little degradation, the X317 showed strong evidence of corrosion/erosion when exposed to Rosebud fly ash alone for 200 hours in the Montana State University, Moderate Temperature Slag Flow Facility. This difference in behavior is indicative of the need to expose basic brick to basic slag and acidic brick to acidic slag to obtain long lifetime performance with minimal erosion/corrosion effects. The X317 has a base/acid ratio of about 56 (basic) while the Fluidyne slag/seed ratio is about 18 (basic) and the Montana Rosebud slag without added seed is about 0.67 (acidic).

Fracture toughness measurements of K_{Ic} of the refractory Monofrax A, which is basically an $\alpha\text{-Al}_2\text{O}_3$, were very similar to the K_{Ic} values for the polycrystalline Al_2O_3 standards even though the Monofrax A samples contained obvious cracks.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

A. Structural Characterization of MHD Materials

MERDI has continued to provide preheater materials evaluation for the Fluidyne Engineering Corporation. The work during the past quarter has centered on obtaining information on the Corhart X317 brick which were tested in the Fluidyne air heater assembly for times of 750 and 1170 hours. The brick in the stack were tested for 750 hours. A few top bricks were removed and replaced and the remainder of the stack was tested for another 420 hours. The brick were submitted to simulated MHD test conditions expected in a direct-fired air preheater. A reducing atmosphere with a fuel/oxygen equivalence ratio of 1.10 was maintained for 30 minutes to simulate the heat-up period. This was followed by a simulated blow-down for fifteen minutes with an equivalence ratio of 0.90

Fluidyne used a propane-air burner to produce the combustion gas and heat for the test. Fly ash from Montana Rosebud coal was added in the amount of 0.1 weight percent of the gas stream to simulate coal combustion by-product with 90 percent ash removal prior to reaching the preheater. Potassium sulfate was added to produce 1.0 weight percent potassium seed.

The analysis of the X317 brick removed from the Fluidyne test runs #201 and #202 is equivalent to the tests which were performed on Corhart RFG removed from the first core of the Moderate Temperature Slag Flow Facility (MTSFF) at Montana State University (MSU). These results were presented in the quarterly reports for January to March 1979 and April to June 1979.^{1,2} These results showed that the Montana Rosebud fly ash without potassium seed was very reactive with the MgO in the RFG brick at the top of the heat exchanger where the combustion gases entered.

The results for the Corhart X317 brick are given in Figures 1-3. The data reported in these figures is taken from one-half inch diameter cores taken from the bulk of the sample. As a result the data are not affected by surface effects of slag/seed interactions. Figure 1 shows the bulk density (density of solid plus closed porosity) of brick along the length of the test bed. The brick at the top and the 0.5m positions were removed after 750 hours of testing. The remaining brick were tested for 1170 hours total. The top brick is the only one which shows definite signs of deviation from the as-received material. The variation in the density of the other brick is no greater than would be expected from taking samples at various locations from a single block of X317.

Figure 2 shows the "equivalent oxide" composition as determined by SEM/EDX from the relation

$$C_i \approx K_i \left[\frac{n_i}{\sum_j n_j} \right]$$

where C_i is the concentration of any element, n_i is the number of counts for that element, and K_i is a constant determined for each element which is dependent on the element matrix, the SEM hardware orientation, and the energy of the electron beam. The technique is explained in detail in the April-June 1979 quarterly report.² The results show that the top brick (750 hour exposure) and the 1.5m brick (1170 hour exposure) are the only ones to show substantial deviation from the as-received values. In each case there was an enhanced concentration of MgO and a reduced concentration of Al_2O_3 . This is significantly different than the results for the Corhart RFG/Rosebud slag without seed tests at MSU where the density reductions correlated directly with decreased MgO content and increased Al_2O_3 content. There was also little change in the Fe_2O_3 , SiO_2 , and CaO contents. No K_2O was detected in the cores examined.

Figure 3 shows the normalized ratios of MgO and $MgAl_2O_4$ X-ray peak height ratios. The results show a deviation from the as-received compositions for the bricks at the top, at 0.5m, and at 1.5m. There is an enhanced amount of MgO and a reduced amount of $MgAl_2O_4$ which corresponds with

Figure 1.--Bulk density of Corhart X317 at different locations along the bed-length after exposure to high seed air heater tests. (Test runs Fluidyne #201 and #202, 420 and 750 hrs., respectively).

Figure 2.--Composition of Corhart X317 at different locations along the bed-length after exposure. Dashed lines indicate nominal as-received compositions (Batch 2 material). Closed (open) symbols indicate exposure for 750 (1170) hours.

Figure 3.--Ratio of X-ray diffraction peak heights (PH) of Corhart X317 at different locations along the bed-length after exposure. Dashed lines indicate ratios for nominal as-received X317 (Batch 2).

the results shown in Figure 2. The net effect indicates that there is a mild interaction between the X317 and the seed/slag with a degradation of the spinel.

Table 1 compares the base/acid (B/A) ratio of several typical slags and refractory materials. In this table the B/A ratio is determined from the relation

$$B/A = \frac{(CaO+MgO+Fe_2O_3+FeO+MgO+Na_2O+K_2O)}{(SiO_2+Al_2O_3+TiO_2+P_2O_5+Cr_2O_3)}$$

with all concentrations in weight percent. The spinel compounds were considered to be neutral and thus do not contribute to the B/A ratio. This accounts for the high B/A ratio of the X317.

A large difference in the B/A ratio between the slag and the refractories under test would lead one to expect a large amount of corrosion attack on the refractories. This was evident in the 200 hour corrosion test at MSU reported on in July to September 1979 quarterly report.³ In this test the basic X317 (B/A ~56) was severely eroded by the acidic Rosebud slag (B/A 0.67) while the acidic Monofrax A, Monofrax E, and Monofrax K3 showed minor damage. Conversely, the basic X317 performs very well when exposed to the basic Fluidyne slag/seed mixture (B/A ~18). The results indicate that it is essential to match the B/A ratio of the bricks used with the B/A ratio of the slag or slag/seed mixture to minimize the effects of corrosion/erosion.

B. Thermal Transport Properties and Analysis

The replacement laser flash tube was received in December and installed. The unit is being checked out and a new operator trained to gather the experimental data.

Polycrystalline Al_2O_3 specimens were prepared and broken for fracture toughness baseline determinations. Seven specimens were broken with a K_{Ic} value of $3.987 \pm 0.204 \text{ MPa}\sqrt{m}$. Three Monofrax A ($\alpha \text{ } Al_2O_3$) samples were broken with a K_{Ic} value of $3.880 \pm 1.387 \text{ MPa}\sqrt{m}$. The standard deviation of the Monofrax A was high due to the presence of visible cracks along the surfaces of the samples.

C. Fabrication of MHD Materials

An attempt to precipitate a metallic coating on stabilized ZrO_2 powder and fabricate the powder into a cermet electrode was attempted. One of the personnel provided an acid solution of platinum which was neutralized with NH_4OH solution to precipitate the metal. A metallic deposit was obtained but the electrical conductivity was not enhanced. Apparently the metal phase was not continuous.

The Y_2O_3 stabilized ZrO_2 materials are expected to be tested by Westinghouse in late December or January.⁴

TABLE 1.--Base/Acid Ratio of Typical Slags and MHD Refractories.

<u>Slag</u>	<u>B/A Ratio</u>
Basic Open Hearth	3.07
Acidic Open Hearth	0.74
Montana Rosebud	0.67
Illinois No. 6	0.46
Fluidyne Slag/Seed	~ 18
<u>Refractories</u>	
X317	~ 56
RFG	2.4
Monofrax A	~ 0
Monofrax K3	acidic
Monofrax E	acidic

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TASK E
Operability of the Moderate Temperature Slag Flow Facility (MTSFF)
H. W. Townes

I. OBJECTIVE AND SCOPE OF WORK

The objective of this program is to determine the operational characteristics of a high-temperature packed-bed regenerative heat exchanger for a coal-fired open-cycle MHD system. There is considerable information on the operation of regenerative heat exchangers at temperatures up to 4200°F; but until several years ago, all work had utilized clean fuels such as natural gas. The present work is concentrated on the effects that coal slag and MHD seed material have on the performance of regenerative packed-bed heat exchangers. To date, the experimental work has concentrated on the effects of slag only in the combustion gas stream. Observed effects include the deposition of coal slag and seed materials along the surfaces, their obstruction of the passages, their chemical interaction with the heat exchanger material, and changes in the friction and heat transfer coefficients of the heat exchanger flow passages.

An experimental facility, the moderate temperature slag flow facility (MTSFF), has been built and is being operated to study the effects that typical open-cycle MHD channel-exit flows have on the high-temperature air preheater. The test core of the MTSFF consists of typical MHD air preheater ceramic bricks. A data acquisition and control system is utilized to record gas flow rates, pressures, and temperatures.

The effects of the coal slag on the heat exchanger performance are being determined initially with these typical operational parameters, a top ceramic temperature of 1750 K (2700°F), and gas velocities of 21-53 m/s (70-170 ft/sec; Reynolds number 3000-4800). The experimental system has been sized so that the above temperatures and velocities are achieved in a 19-hole brick with circular holes 19mm (0.75 inches) in diameter. Natural gas is used as the fuel. Coal ash is being added to simulate the combustion products of coal firing. The amounts of coal ash added to the combustion gas simulate a 10 percent slag carry-over (0.1 percent slag by mass in the combustion gas). The carry-over can be varied. The influence of particle size also has been determined.

The experimental runs utilizing the first core of the MTSFF were completed in June 1978. The first core was operated with slag only in the combustion gas for a total of 1150 hours. The six experimental runs made with the first core established the effect of particle size on the rate of pressure drop increase across the core. The objective of the experimental runs with core number two (installation completed December 1978) was a determination of the feasibility of a "melt out" of slag deposits in the MTSFF.

Six experimental runs were made with the second core for a total of 950 hours of operation. Four of the second core runs showed successful "melt out" of slag deposits while the other two runs were made strictly to test materials suitable for use in the third MTSFF core.

II. SUMMARY AND IMPACT

During the latter part of July 1979, a materials test was run utilizing six different materials as the top brick in the moderate temperature slag flow facility (MTSFF). The objective of the test was to select a material for slag-only operation which would be more resistant to slag attack than the Corhart RFG used in the first two cores of the MTSFF. The initial visual results of this test were reported in the previous quarterly report. Attached to this quarterly report is an analysis of the materials done by W. T. Staten at Carborundum, Technical Services Report R-3706-79-25.

The resistance to slag attack of the materials used in the test is only one factor which must be considered. Although the Monofrax K-3 showed the best resistance to attack by slag, this material also showed extensive thermal cracking. For this reason, K-3 is not considered suitable for use, at least in regions of the core which experience high thermal stresses. As a result of availability and reasonable performance enough material for two cores was ordered, one each of Monofrax A and E. As of December 28, 1979, the Monofrax A core has been installed in the MTSFF and the facility is scheduled for startup and checkout beginning in January 1980.

Since the indirectly fired air preheater is now considered useful only for closed-cycle MHD applications, it is intended that the MTSFF will be converted to operation with seed/slag injection. The core material which appears to best resist attack in the seed/slag environment is Corhart X-317. At the present time, inquiries are being made concerning the availability of Corhart X-317. A few minor modifications will be necessary to the MTSFF in order to operate with seed/slag injection.

III. DETAILED DESCRIPTION

The previous quarterly report contained photographs of the test specimens from the materials test. For more detailed information, reference should be made to the attached Carborundum report.

Since the materials test, the MTSFF has been in the process of being rebuilt, utilizing the Monofrax A material as the core.

IV. REFERENCES

The work which is now being done in the MTSFF is being carried out in support of the closed-cycle MHD Program, since the operation of the MTSFF with the Monofrax A core will be restricted to slag injection. The objectives of the experimental runs with this core will be to demonstrate the feasibility of multiple meltouts of deposited slag layers and, if possible, the determination of the

effects of flow rate, temperature and slag injection rates on the rate of pressure drop increase. This work will directly support the MHD closed-cycle work at General Electric.

In addition to the work on the MTSFF, personnel from this task are also actively involved in the planning of a national, long-term, open-cycle air preheater development program at the request of DOE.

THE CARBORUNDUM COMPANY

Refractories Division
Advanced Technology Branch
Technical Services Department

TECHNICAL SERVICES REPORT R-3706-79-25

PETROGRAPHIC EXAMINATION OF ALUMINA, ALUMINA-CHROME AND MAGNESIUM-ALUMINUM
FUSED CAST SAMPLES AFTER A TEST EXPOSURE TO A MHD ENVIRONMENT

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October 26, 1979

The particular suite of materials selected for MHD testing was particularly interesting since they are all very similar in their constituent phases. All of the refractories tested except Monofrax A are spinel based, but differ depending on whether MgO or Al_2O_3 are in excess or in the presence, absence, or magnitude of concentration of chromic oxide.

The Monofrax L (S) sample is representative of a magnesium aluminum spinel refractory with an insignificant amount of other phases present. As shown in Figure 1, the spinel is attacked by the test environment - the spinel being taken into solution by the slag. One can also assume that a corroded surface such as that observable in Figure 1 would also be adversely affected by erosive action. Therefore, it is apparent that the spinel in Monofrax L (S) is insufficiently refractory to resist an environment represented by the test conditions.

Two of the tested refractories have excess magnesia over that necessary to form spinel and therefore contain periclase (MgO) as a separate and distinct phase. Monofrax L (E) has only a slight excess of magnesia and crystallizes with spinel and spinel-periclase intergrowth; the spinel-periclase intergrowth representing crystallization of a melt at the $\text{MgO-Al}_2\text{O}_3$ eutectic composition. This refractory was even more readily attacked in the test conditions than the Monofrax L (S) composition discussed earlier. The eutectic $\text{MgO-Al}_2\text{O}_3$ component was particularly sensitive. This clearly indicates that MgO is readily dissolved in the test environment. As in the Monofrax L (S) sample, the spinel is also corroded by the environment. This sample is probably more rapidly degraded than the Monofrax L (S) sample since the removal of the MgO enables a greater penetration of slag into the refractory and hence a greater surface area of spinel is subject to corrosion by slag. A photomicrograph of this sample is shown in Figure 2.

The second refractory sample containing excess magnesia is the Corhart X317 sample. This refractory contains about 50% periclase in the unused material; the remainder being spinel and spinel-periclase eutectic. As shown in Figure 3, this refractory is experiencing significant slag penetration in the test environment. Again, the MgO component, a major phase in this refractory is readily attacked. The removal of this phase then exposes a greater surface area of spinel to the corrosive effect of the slag. The performance of this material clearly suggests that refractories with excess MgO cannot be expected to perform well in conditions approximated by the test environment since the periclase is readily dissolved.

The Monofrax K-3 sample exhibits a significantly different response to the tested environment. As shown in Figure 4, Monofrax K-3 responds to the environment by forming additional spinel at the interface. The newly formed spinel appears to be a ferrochrome spinel where the iron apparently originates with the slag and the chrome with the refractory. The excess alumina and chrome that forms the R_2O_3 hybrid corundum phase of the Monofrax K-3 refractory seems to function by maintaining the buffered spinel interface. The interface is quite narrow (note the difference in magnification between Figures 1 - 3 and Figure 4). This interface is nearly continuous with only a small amount of included and interstitial glass.

The interface that formed on the Monofrax E sample was a very dense chrome spinel as shown in Figure 5. This interface, however, was not continuous and some of the R_2O_3 component of the Monofrax E was observed to extend to the exposed surface. Unlike the Monofrax K-3 sample, fracturing was observed to be quite extensive. Glass penetration along the fractures was also observed. This fracturing and slag penetration along the fractures was quite significant. Slag penetrating along fractures then exposes a greater surface area to corrosive effects of the slag. Furthermore, any cycling that would result in successive expansion and/or contraction of the fracture filling could adversely affect the integrity of the refractory.

The final tested sample was Monofrax A; a primarily α -alumina refractory with interstitial minor glass and β -alumina. The performance of the refractory at the exposed surface is portrayed in Figure 6. The general response of the α -alumina was a slow conversion of α -alumina to spinel. Having no spinel base to build upon such as in Monofrax E and Monofrax K-3, the usual spinel interface noticed to have formed on the spinel refractories, failed to form on the Monofrax A. However, the corrosion rate was quite slow and very little refractory was removed during the test. The interstitial β -alumina was readily dissolved by the slag; this permitting virtual complete penetration of the refractory by the slag. The α -alumina, however, is interlocking enough to maintain structural integrity of the refractory. Although the Monofrax A is not as readily corroded as the Monofrax L type magnesium-aluminum spinel refractories, it is not as resistant as the chrome spinel refractories - Monofrax K-3 and Monofrax E. Considerable grain boundary fracturing was observed in the Monofrax A sample.

CONCLUSIONS

The chrome refractories were found to have had the most favorable response to the test environment. In both Monofrax K-3 and Monofrax E a continuous or semi-continuous spinel interface formed with the R_2O_3 component originating with the refractory and the RO component (primarily FeO) originating with the slag. This spinel interface was built upon a spinel base found in the original refractory material. The Monofrax K-3, although having a less dense interface, appeared to have performed better than the Monofrax E sample primarily because the Monofrax K-3 sample did not have the comparatively extensive fracturing of the Monofrax E sample.

The Monofrax A sample did not appear to perform quite as well as the chrome-bearing refractories. The β -alumina was dissolved allowing extensive slag penetration, and there was considerably more fracturing than was observed in the chrome-bearing refractories. The extent of the corrosion, however, was fairly limited. It appears that although the α -alumina is attacked, the rate of reaction is rather slow under the conditions tested.

The magnesium-aluminum fused cast refractories were definitely inferior in the conditions tested. The spinel showed evidence of corrosion, and periclase, where present, was dissolved.

FIGURE 1. 50X Monofrax L (S)

In this material magnesium-aluminate spinel occurs with a small amount of interstitial glass. The exposed surface shows a network of solution of the spinel - this probably now easily removed by erosive action.

FIGURE 2. 50X Monofrax L (E)

In this material magnesium-aluminate spinel occurs with a periclase-spinel eutectic intergrowth (barely discernable in photomicrograph). The magnesia (periclase) is readily removed and a greater surface area of spinel is exposed to the corrosive action of the slag.

FIGURE 3. 50X Corhart X317

The periclase (MgO) that occupies about 50% of the original volume is readily removed leaving an open loosely constructed spinel structure. This open structure is probably then quite sensitive to both corrosive and erosive action of the slag.

FIGURE 4. 100X Monofrax K-3

A fairly dense and narrow ferrochrome spinel interface forms on the exposed surface of the Monofrax K-3 refractory. The original material contains both a hybrid corundum and spinel. The interface forms on the spinel base while the hybrid chrome-bearing corundum buffers the surface reaction.

FIGURE 5. 100X Monofrax E

As in Monofrax K-3, a spinel forms at the surface but this is both discontinuous and much more dense. Corrosive effect of the slag on the refractory is apparently quite small but fracturing and subsequent glassy slag penetration of that fracturing is significant.

FIGURE 6. 100X Monofrax A

The β -alumina has been completely removed allowing penetration of slag into the interior of this predominantly α -alumina refractory. The α -alumina is fairly corrosion resistant but the serrated grain margins reveal that some corrosion took place.

TASK F

Slag-Seed Equilibria and Separations Related to the MHD System

R. Howald, R. Woodruff, R. Jones, and F. Dewalt*

I. OBJECTIVE AND SCOPE OF WORK

The objective of Task F is the measurement and interpretation of vapor pressures over high-temperature oxide systems and the thermo-dynamic analysis of these systems. The systems for study are primarily synthetic mixtures, actual slags, and seeded slags. The measurements are performed using atomic absorption to measure atom concentration in high-temperature graphite tube furnaces produced by diffusion from vapor pressure cells. The analysis is aimed at providing accurate equations for vapor pressure and activity in multicomponent systems for use in engineering design work wherever slags and seeded slags are encountered in the MHD system.

II. SUMMARY AND IMPACT

Potassium vapor pressure measurements were made over $KO_{.5}-SiO_2-CaO-AlO_{1.5}$ model slags and in particular in the composition ranges of melilite ($KCaAlSi_2O_7$) and gehlenite ($Al_2SiCa_2O_7$).

Good progress is being made on a new computer program for calculations on four-component systems.

Although experimental progress has been impeded by instrument failures, the measurements of potassium vapor pressures are proceeding satisfactorily. Preliminary measurements are lacking for only three samples: KCAS 62, 63, and 64. Unsuccessful attempts have already been made to analyze these samples. It is hoped that the new cell design will permit measurements of their vapor pressures to be made in a more amenable temperature range.

Thermodynamic analysis of this data is being carried out. The results will appear in a future report.

III. DETAILS OF TECHNICAL PROGRESS

A. Development of Analytical Techniques

The constant temperature furnace was modified to eliminate temperature fluctuations due to electrical arcing and to improve the efficiency of the inert gas flushing system.

*Acknowledgement to F. Dewalt for his valuable technical assistance without which the measurements for this report could not have been made.

Effusion cells were made with thicker walls to increase cell life spans. Larger orifice size was tried in order to avoid the higher temperatures where glasses form in the cells. This experiment was successful in that these cells never required the days or even weeks of soaking in hydrofluoric acid heretofore needed.

B. Vapor Pressure Measurements

Preliminary potassium vapor pressure measurements were made over these samples prepared during the previous quarter: KCAS 65, KCAS 66, KCAS 67, KCAS 68, KCAS 69, KCAS 70, and KCAS 71. The compositions and results of the measurements are tabulated in Table 2 and represented graphically in Figures 1, 2, and 3. Data for KCAS samples 52 through 61 and 72 through 74 are tabulated in a previous report.

C. Thermodynamic Analysis of Model Slags

Having completed the analysis of the binary and ternary systems in the $KO_{.5}-AlO_{1.5}-CaO-SiO_2$ quaternary, the effort this quarter has been directed toward development of accurate computer treatments of four-component systems. These methods are being written up for publication and will be included with the results of their application in future reports.

Table 1.--Sample Compositions

SAMPLE IDENTIFICATION	x_{K_2O}	x_{SiO_2}	x_{CaO}	$x_{Al_2O_3}$	x_{CaO} $(x_{CaO} + x_{SiO_2} + x_{Al_2O_3})$		$x_{Al_2O_3}$ x_{SiO_2}	
KCAS 62	0.10	0.418	0.063	0.418	0.07		1.0	
KCAS 63	0.15	0.395	0.059	0.395	0.07		1.0	
KCAS 64	0.20	0.372	0.056	0.372	0.07		1.0	
KCAS 65	0.25	0.349	0.052	0.349	0.07		1.0	
KCAS 66	0.30	0.326	0.049	0.326	0.07		1.0	
KCAS 67	0.10	0.270	0.36	0.270	0.4		1.0	
KCAS 68	0.15	0.255	0.34	0.255	0.4		1.0	
KCAS 69	0.20	0.240	0.32	0.240	0.4		1.0	
KCAS 70	0.25	0.225	0.30	0.225	0.4		1.0	
KCAS 71	0.30	0.210	0.28	0.210	0.4		1.0	
KCAS 72	0.10	0.200	0.499	0.200	0.67		1.0	
KCAS 73	0.20	0.178	0.444	0.178	0.67		1.0	
KCAS 74	0.30	0.156	0.389	0.156	0.67		1.0	
KCAS 75	0.10	0.300	0.600	0.0	0.67		0.0	
KCAS 76	0.30	0.233	0.467	0.0	0.67		0.0	

Table 2.--Potassium Vapor Pressures as a Function of Composition and Temperature

SAMPLE	COMPOSITION				TEMP K	(1/Temp) K ⁻¹ x 10 ⁴	PRESSURE Atm x 10 ⁶
	X _{KO.5}	X _{SiC₂}	X _{CaO}	X _{AlO_{1.5}}			
KCAS 65	0.25	0.349	0.052	0.349	1768	5.556	20.68
					1654	6.046	4.31
					1809	5.528	39.38
					1890	5.291	132.1
					1753	5.705	20.58
					1817	5.504	45.38
					1688	5.924	4.54
KCAS 66	0.30	0.326	0.049	0.326	1614	6.196	5.86
					1693	5.907	19.21
					1744	5.734	44.08
					1657	6.035	8.52
KCAS 67	0.10	0.27	0.36	0.27	1603	6.238	3.58
					1666	6.002	15.411
					1714	5.834	30.23
					1788	5.593	67.80
					1846	5.417	112.4
					1747	5.724	22.36
KCAS 68	0.15	0.255	0.34	0.255	1455	6.873	0.164
					1581	6.325	2.23
					1534	6.519	0.846
					1448	6.906	0.158
					1498	6.676	0.512
					1544	6.477	1.47
					1479	6.761	0.451
					1403	7.128	0.100

Table 2 (continued)

SAMPLE	COMPOSITION				TEMP K	(1/Temp) $K^{-1} \times 10^4$	PRESSURE Atm $\times 10^6$
	$x_{K0.5}$	x_{XiO_2}	x_{CaO}	$x_{AlO_{1.5}}$			
KCAS 69	0.20	0.24	0.32	0.24	1450	6.896	0.497
					1398	7.153	0.138
					1471	6.798	0.701
					1523	6.566	1.89
					1469	6.807	0.545
					1429	6.998	0.214
KCAS 70	0.25	0.225	0.30	0.225	1372	7.289	0.207
					1394	7.174	0.382
					1444	6.925	1.198
					1390	7.194	0.252
					1337	7.479	0.068
					1379	7.252	0.162
					1448	6.906	0.647
					1385	7.220	0.172
KCAS 71	0.30	0.21	0.28	0.21	1298	7.704	0.026
					1314	7.610	0.058
					1364	7.331	0.286
					1419	7.047	0.992
					1375	7.273	0.082
					1423	7.027	0.327

Figure 1.--Potassium Vapor Pressures Over Samples KCAS 65 and 66

Figure 2.--Potassium Vapor Pressures Over Samples KCAS 67, 68 and 69

Figure 3.--Potassium Vapor Pressures Over Samples KCAS 70 and 71

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TASK G
Thermionic Emission of Coal and Electrode Materials
G. Lapeyre and J. Anderson

I. OBJECTIVE AND SCOPE OF WORK

The objectives of this project are 1) to measure the thermionic emission properties (e.g., thermionic work function) of coal slag, including slag-seed mixtures and 2) to measure the thermionic emission properties of ceramics considered to have applicability as electrode materials of ionic migration occurring in heated coal slag as a result of electric currents and applied electric fields in the slag.

The slag thermionic emission studies will include measurements in vacuum of synthetic slags of various compositions and will be extended to natural slags. Auger electron spectroscopy will be used to correlate the thermionic emission results with surface composition. The thermionic emission studies will later be extended to measurements under a known low pressure of potassium vapor.

The rationale for the ion migration experiments is to characterize physical processes which contribute to chemical segregation and electrolysis in coal slag with a consequent degradation of electrode properties due to chemical attack and shorting. Measurements with X-ray fluorescence and scanning Auger microscopy methods will be used to map out the distribution of various elements in the slag subsequent to passing a known amount of charge through the slag and as a function of slag composition and temperature.

Evaluation of the need for thermionic emission data on electrode materials will be made in the context of clean electrodes in hot-wall, coal-fired channels, and exploratory measurements.

Initial measurements will be performed on synthetic slags of various compositions at temperatures both below and above the temperature at which the slag is liquid.

Since the actual surface composition is of paramount importance in determining the work function and the thermionic emission, in situ surface analysis will be carried out by Auger electron spectroscopy. Materials desorbing and evaporating from the surface will be determined by mass spectrometry.

II. SUMMARY AND IMPACT

The apparatus for measuring slag thermionic emission under potassium vapor has been constructed and assembled except for the ovens and potassium source. Its general operation in measuring thermionic emission was tested using a sample piece of iridium.

Previous slag thermionic emission measurements in vacuum have provided good data on the work function of slag and the effect of potassium in the sample. Such measurements had a disadvantage in that the surface coverage of potassium could not be well controlled and the potassium evaporated from the surface at high temperatures. In an actual channel, however, the slag and potassium is continuously being replenished from the plasma. The experiments planned for this phase of the project are designed to provide more information on the thermionic emission properties of coal slag under conditions more closely resembling actual MHD conditions than did those of the vacuum experiments. By heating the experimental chamber and a source of metallic potassium to the temperature range of 200 to 300°C, the vapor pressure of potassium can be adjusted up to about 10^{-4} atmospheres. In this way, it should be possible to simulate the potassium replenishment process as it occurs in a channel and adjust the surface coverage of potassium at will while making the thermionic emission measurements.

In the part of the project relating to electrical conduction mechanisms in slag, we have been working on the use of X-ray photoemission spectroscopy methods to measure the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio in iron-containing slags.

It has been recognized for some time that the conduction mechanism in slag, electronic or ionic, has an immediate bearing on the magnitude of the conductivity and electrochemical effects that take place in the slag and at the slag-electrode interface. The electronic part of the conductivity depends on the electrons moving from Fe^{2+} to Fe^{3+} so that this contribution depends on the relative numbers of the two iron ions.

A small but measureable difference in the binding energies of inner shell electrons in the two iron species forms the basis for an accurate measurement of the relative numbers of the ions.^{1,2} This chemical shift is reflected in a difference in the kinetic energies of electrons photoemitted from those shells. However, elaborate background subtraction and curve fitting computer routines are required to extract the desired information.

We have set up such an experiment and have taken a number of spectra from slag samples (as well as samples of Fe_2O_3 , Fe_3O_4 , and iron metal). The difficult part of the operation--data reduction--remains to be completed.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

During this time period, the major portion of the apparatus for measuring slag thermionic emission under potassium vapor was constructed. Its design is shown in Figure 1. For the measurements, the work chamber will be evacuated to a high vacuum and sealed off with a valve. The chamber as a whole and a reservoir containing potassium metal will then be

heated to a sufficient temperature to produce the desired vapor pressure of potassium. Typically, the temperature will be 200 to 300°C for a vapor pressure of up to 10^{-4} atm.

As in the vacuum thermionic emission measurements, the slag sample will be held on an iridium foil and the emission measured using the standard anode-guard ring assembly. The emission current will be conducted out of the work chamber using a special guarded triaxial feed-through to minimize leakage currents.

The work chamber and pumping system have been constructed and assembled and the chamber has been evacuated. However, the ovens for heating the system to the required temperature and the potassium source have not yet been assembled.

The measuring system has been tested by measuring the thermionic emission in vacuum from an iridium specimen.

During the construction and assembly of the apparatus described above, experiments were performed which are connected to the electrical conductivity mechanism in slag. These X-ray photoemission (XPS) experiments were preliminary in nature and designed to assess the feasibility of using equipment at hand in the laboratory for determining the ratio $\text{Fe}^{2+}/\text{Fe}^{3+}$. The electronic conductivity is maximum when there are equal numbers of the two species and is less when one or the other predominates.

The different oxidation states of iron (including metallic iron Fe^0) are distinguished from one another in an XPS spectrum by virtue of the fact that the local environments of those species are different; thus, the inner core electrons are bound in the atom with slightly different binding energy. As a result, when these electrons are ejected from the material containing the iron atoms using monochromatic X-rays, they will leave the surface with slightly different kinetic energies. This is called a chemical shift. A high resolution electron energy analyzer can, in principle, separately detect electrons of different kinetic energies and thus identify the emitting element and, if the chemical shift is large enough, the state of chemical combination of the element.

As an example of how this works, Figure 2 shows two spectra: one taken from a piece of iron metal and the other from a specimen of hematite. The peaks from the $\text{Fe } 2p_{3/2}$ level are separated by 4.3 eV which is easily discernible in the XPS apparatus. The measurement of such spectra is useable in the study of the oxidation of an iron surface.

Figure 3 shows an XPS spectrum taken from a sample of K 488 synthetic coal slag. The various peaks labeled with chemical element symbols are due to electrons emitted from inner shells of the corresponding element. The notation "Auger" refers to peaks caused by electrons emitted as a result of the Auger process. The right-hand member of the pair of Fe peaks at the binding energy of ≈ 720 eV has been identified by

other workers^{1,2} as an iron XPS peak in which the position shifts slightly depending on the oxidation state of the iron. In those works, it was found that the Fe^{2+} and Fe^{3+} peaks were displaced only a small amount so that they were not well resolved and fairly elaborate background subtraction and curve fitting procedures were required to separate them. When that was done, however, they obtained an accurate measure of the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio.

Our work was an effort to determine the procedures for routinely extracting the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio from the spectra guided by the results of the experiments cited in References 1 and 2. Because of the small separation, the Fe^{2+} peak should appear as a weak shoulder on the right-hand side of the Fe^{3+} peak shown in Figure 2. After setting up the experiment and determining the optimum operating parameters, a number of spectra were taken from several slag samples and such a shoulder was not discernable to the eye. It became apparent that the fitting routines described in References 1 and 2 would have to be used, but this work has not been completed yet.

Figure 1.--Design of major portion of apparatus for measuring slag thermionic emission under potassium vapor.

Figure 2.--XPS Spectra for Iron $Fe\ 2p_{3/2}$ Levels
Showing the Chemical Shift Between Neutral
Iron and Fe^{+3}

Figure 3.--XPS Spectrum for Synthetic Slags K488 Showing Emission Peaks for Various Elements as Indicated

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I. OBJECTIVE AND SCOPE OF WORK

The work to be performed is in the general area of MHD systems, instrumentation, and control. The three categories of work are defined below.

A. Combustor-Nozzle-Channel-Diffuser Model

A time-dependent nozzle-channel-diffuser (NCD) model has been completed in sufficient detail to study some configurations of supersonic MHD/steam power plants. Several CDIF and ETF case studies have been started and will continue to be analyzed. In order to properly simulate the strong coupling between the combustor and the channel present in subsonic MHD flow, the theory of a time-dependent (dynamic) one-dimensional, two-stage combustor model is to be developed suitable for coupling to the present NCD model to form a dynamic CNCD model when programming is completed. The plug-flow combustor model from the MHD steam plant modeling task will be used to provide the initial state conditions for the model.

B. Consolidation/Inversion Simulator

The design of a table-sized generalized consolidation/inversion simulator is to be undertaken to provide the basis for study and evaluation of several proposed dc to ac power conversion schemes. The system should be modular to permit the maximum flexibility possible in the interchangeability of components; studies of hybrid schemes involving the best features of competing designs then will be possible.

Component selection will emphasize existing devices and technology to minimize subsequent development efforts for commercial-scale systems.

C. Hybrid Modeling

A study is to be performed to evaluate the potential of a hybrid computer system for detailed analysis of complete MHD/steam power plant systems designs and control.

II. SUMMARY AND IMPACT

A. Time Dependent Combustor-Nozzle-Channel-Diffuser (CNCD Model)

The CNCD model was completed during the quarter and initial computer runs have been made on the sensitivity of combustor pressure and operation for up to ten percent step changes in electrode voltage (load induced). Initial runs indicate relatively little change in combustor pressure and operation (≈ 2 to 5 percent change in pressure). However, some instability

of the program to larger than ten percent voltage changes was noted; these appear to be generated by small discontinuities in the slope of the functions representing the nozzle profile. A tighter control curve fit (spline function) is being introduced into the program in an attempt to reduce this sensitivity. This should also permit a larger time step integration increment with consequently shorter computer runs.

B. MHD Inverter System

Initial square wave three-phase output for the force commutated system has been obtained. The additional microprocessor speed necessary to introduce harmonic suppression by notch filtering could not be met by a single Z80. Therefore, three additional Z80's have been added so that notch filtering per phase and data acquisition can be performed simultaneously. Self commutation and line commutation configurations can both be handled by the system. Depending upon budget restrictions, the system is being expanded to four-electrode pairs.

C. Hybrid Computer Formulation

Work has begun on formulation of the dynamic CNCD equations for integration on the VAX 11/780-ADI-10 computer system. The system is scheduled for delivery August 1, 1980. It appears possible to integrate the CNCD state-space, one-dimensional MHD dynamic equations in nearly real time on the ADI-10.

III. DETAILED DESCRIPTION

A. MHD Inverter System

The single Z80 microprocessor SCR controller used to provide three-phase notch filtering (Figure B-1), line synchronization, and voltage regulation underwent testing early in the quarter. These tests confirmed code correctness but also quickly pointed out that timing constraints, when providing all three functions, were beyond the capacity of a single Z80 microprocessor. The control system was modified from that of Figure B-2 to include two additional Z80 microprocessor controllers, as shown in Figure B-3. This provides one Z80 system per phase and should remove the timing problem when providing filtering, synchronization, and regulation.

Software has been completely rewritten to synchronize the three Z80 systems while running. A hardware time-base counter provides both phase-to-phase and line synchronization signals parallel to the three systems. Initial filtering and synchronization tests have been run and perform as anticipated. The filtering tests were run with the inverter driving a resistive load. The multiple 5.8 degree notch duration voltage waveform, as shown in Figure B-1, was applied to various loads up to our system capability of 2KW. Provision has been made for voltage control in the software; however, to date, it has not been completely implemented.

The LSI-11/03 will now be used to control the output voltage via serial commands transmitted to each individual Z80 microprocessor. A fourth Z80 microprocessor may be added to the system, as shown in Figure B-3, for housekeeping operations and data taking purposes.

The inverter in use at the beginning of the quarter was constructed and tested for use with pulse width amplitude control. The commutation element values were not optimized for the high-speed requirements of notch filtering, and considerable effort has been expended this quarter to optimize these values. Correlation between calculated values and values currently in use is still under investigation.

Figure B-1. Notch Filtering Timing Diagram for Harmonic Suppression

Figure B-2. Z80 SCR Firing Angle Control

Figure B-3. MHD Consolidation/Inverter Simulator System Diagram

TASK H3

Combined MHD-Steam Plant Cycle Analysis and Control

D. A. Rudberg, D. A. Pierre, D. Goldsworthy, and C. K. Fang

I. OBJECTIVE AND SCOPE OF WORK

We are developing system component models which are suitable for control system simulation studies. The purpose of these studies is to determine control structure and controller parameter values which result in safe, stable, fast, and smooth transitions in operating points. The results of the studies are to be generally applicable to the ETF and commercial MHD-steam power plants. By performing these studies now, it may be possible to influence the design of MHD-steam plants to make them more reliable, efficient, and easier to control.

The time-dependent combustor model is important from the view points of combustion stability and channel response. Combustion stability is an extremely important topic because it affects plant integrity and safety and smoothly controllable response. A time-dependent model incorporating compressible fluid flow, chemical equilibrium and enthalpy, char particle heating and burnout kinetics, devolatilization (its rate and general endothermic nature), and heat loss from radiation and convection will be an effective tool in studying combustion stability and associated topics of acoustic wave propagation and standing waves within the combustor.

The time-dependent combustor model will also constitute an essential part of the overall time-dependent model that will permit analysis of channel electrical and fluid dynamic response to perturbations originating in the combustor. It will be one of the parent model sets used in generating input-output models, which are described below. The model will be a combination of fluid dynamic equations and solution techniques from time-dependent channel work done by other researchers at MSU and of chemical equilibrium, char burnout kinetics, heat loss, etc. from a steady-state, plug-flow, two-stage combustor model developed in our previous efforts.

From the detailed time-dependent models, input-output models will be produced for specific ETF and base-load MHD components. Input-output models contain no internal detail, consisting only of a set of curve fits of desired outputs to input values. Parameters of the system are implicit in the curve fit coefficients. In this manner, models of large systems can be run in orders of magnitude less time and greatly reduced computer requirements than if detailed parent models were used. A change of system parameters requires only that another set of input-output models be made from the detailed parent models, thus embodying those new parameters.

Several input-output modeling runs already have been made using existing parent models of the plug-flow, steady-state combustor for combustor input-output models and detailed chemical-equilibrium, electrical conductivity, and enthalpy programs for channel gas modeling. An automatic parameter sweeping routine is used, and the results are stored in a file for reduction to input-output models by an existent multi-variable curve fitting routine.

The computer-controlled combined-cycle plant model is an important step in the progression from conceptual system studies to a functional piece of hardware. There is a tendency to confuse control system information flow and selection of information processing algorithms with the completion of the control problem. But the selection of system topology, information flow, and control algorithms is only an initial step (albeit an essential one) in the process of ultimately exerting effective control. The mechanization of specified information flow, of algorithmic computation, and of assertion of control variables at proper points in the controlled plant are the finale in real time control.

It has been the investigators' experience in providing real time computer control for an aluminum processing plant and other smaller projects that actual coding of algorithms and supervisory programs immensely sharpens the understanding of preceding conceptual studies. It crystallizes the notion that a physical plant (in this case the MHD/steam plant) having a set of measurable variables, a set of controllable variables, and a system of dynamics by which it operates is being dealt with.

The investigators will use their set of system models to act as the plant. The computer controller will be a set of algorithms and a simple supervisory routine to properly sequence data inputs, algorithm computation, and control signal assertion at proper points. The value of beginning this essential step as early as possible lies in its intrinsic feedback to the conceptual process as well as its being a necessary bridge between conceptual studies and hardware.

II. SUMMARY AND IMPACT

A first-principle dynamic control system model is being developed for combined-cycle MHD-steam power plants. The model, called System Model IV, is being coded in FORTRAN and will be used both to test alternative dynamic control strategies and to obtain controller coefficients.

System Model IV is composed of two parts: (1) a non-dynamic model of the MHD topping plant, consisting of combustor, nozzle, channel, and diffuser (the CNCD model), and (2) a fully dynamic model of the steam bottoming plant, containing the feedwater system, radiant steam generator, drum, superheaters and reheaters, air heaters, air compressors, coal feed system, steam lines, turbine, and generator-exciter combination. The CNCD model is non-dynamic because its time constants are so much shorter than those of the remainder of the system that for all purposes it exhibits instantaneous response.

Generation of System Model IV is supported by a number of other routines, principally a pulverized-coal-fired combustor model, a chemical equilibrium routine for gas property predictions, a channel-diffuser design program, a steady-state energy balance routine for steam plants, and dynamic models of steam plant components.

System Model IV fits into this task's goals as the dynamic plant model shown in the upper portion of Figure 1. It will be responsive to control inputs (e.g., set points for throttle valve, combustor air flow, coal flow, drum level) to power grid disturbances (voltage fluctuations, faults, etc.), and to internal disturbances (inverter failure, flow rate disturbances, complete loss of channel power extraction) and will predict the states of the combined cycle plant. The lower portion of Figure 1 is the set of coordinated control algorithms that will exert control over the dynamic model. Synthesis of control policies is a part of future work.

I II. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

System Model IV

The combined MHD/steam bottoming plant dynamic digital simulation model, known as System Model IV, is being developed in accordance with the schedule outlined in Figure 2. It involves the parallel development of a dynamic steam bottoming plant and a non-dynamic combustor-nozzle-channel-diffuser (CNCD) model. These parallel paths have advanced near to the point of convergence into the complete model. The bottoming plant has reached the last stage shown in Figure 2 (that of subsystem model development and tests), while the CNCD model is complete and is producing input/output models for use in System Model IV. The current status of the combined dynamic system is thus an overlap of the final stages of subsystem model development and tests, with the stage that combines all components (steam plant subsystems and CNCD) into an overall model. Because the final system model is being assembled, no fundamentally new results will be available until it is tested. The first checkout runs of System Model IV are expected in January 1980, with representative responses available by March 1980. A technical summary of System Model IV will be a part of the January-March 1980 quarterly report of this task, and a complete technical report of the dynamic combined-cycle plant will be published about June 1980. Previous quarterly and annual reports and a paper at the 18th MHD Symposium have reported on individual component and subsystem modeling.

Overview of System Model IV Organization

The combined system model is a top-down, modular program. An overall supervisory and calling routine coordinates calling of the subsystem models which are linked through sets of input variables and output variables pertinent to each subsystem and to those subsystems with which it must communicate. Subsystems are in turn composed of sets of components, linked by input and output variable sets that have apparent communication within that subsystem only. This philosophy of structure makes program maintenance and modification relatively easy and uncomplicated through the avoidance of so-called spaghetti code (confusingly intertwined transfers of program control) and the observance of strict protocols of data transfers.

Schematic diagrams of the three major plant cycles present in System Model IV are shown in Figures 3 and 4, along with a list of abbreviations pertinent to succeeding figures. Figures 5 through 9 show the five subsystems that comprise the steam bottoming plant. Each subsystem diagram has a list of inputs and outputs required to link that subsystem to other subsystems in a horizontal manner. Inputs to a subsystem may be externally imposed (e.g., controlled valve parameters imposed by the overall system controller) or may be the output of another subsystem (e.g., steam conditions at the throttle valve are inputs of both the boiler feedwater pump turbine of the feedwater subsystem and the power turbine of the turbine-generator subsystem and are outputs of the superheat subsystem).

Each subsystem is itself composed of a set of individual component models. The component models are at the level of primitive physical dynamics, with behavior described by first-principle models. Individual component models of a given subsystem communicate explicitly with each other within the subsystem and implicitly with other subsystems through data transfer protocols between subsystems.

Typical of such components is the primary superheater of the superheat subsystem. Its dynamic responses to a ramp change of input gas temperature (such as might occur if the channel experiences a power extraction failure) are shown in Figure 10 and its responses to a step decrease in output steam flow rate (such as might occur with rapid load shedding) are shown in Figure 11.

The CNCD model is distinct from the steam plant model in that it is non-dynamic. This is because time constants of the MHD topping section are so much shorter than those of the bottoming plant that, for all purposes, MHD response is instantaneous when overall plant control is considered. Of course a control loop must be applied to the channel and inverters, but this loop will be very fast acting (effectively transparent to the remainder of the plant). It is not a part of System Model IV but is implicitly assumed to exist by the nature of the CNCD model.

The basic function of the CNCD model is to produce, from curve fits, values of output variables (e.g., useful channel power, diffuser outlet, temperature and enthalpy, cooling water and heat transfer) as a function of operating conditions. The steps in generating a set of input/output curves are depicted in Figure 12.

Figure 1.--Coordinated Plant/Controller Modeling

SPECIFICATIONS OF OVERALL MODEL

BOTTOMING PLANT

- * SYSTEM CONFIGURATION
- * MAIN OPERATING POINTS
- * STEADY-STATE PLANT ENERGY BALANCE
- * DYNAMIC EQUATIONS
- * INDIVIDUAL COMPONENT TESTS
- * SPECIFICATIONS FOR SUBSYSTEM MODELS
- * SUBSYSTEM MODEL DEVELOPMENT AND TESTS

CNCD

- * GAS PROPERTY CURVE FITS
- * COMBUSTOR OUTPUT CURVE FITS
- * NOZZLE-CHANNEL-DIFFUSER OPERATION

- * COMBINATION INTO OVERALL MODEL
- * CONTROL IMPLEMENTATION AND TESTS
- * GENERALIZATION OF RESULTS

Figure 2.--Development of System Model IV

WATER/STEAM CYCLE

AIR CYCLE

Figure 3.--Water/Steam Cycle and Air Cycle of Combined Plant

GAS PATH

ABBREVIATIONS

ATH	Atmospheric	ECON	Economizer
AUX	Auxiliary	ESP	Electrostatic Precipitator
B1	Steam Bleed Point #1	FWH	Feedwater Heater
B2	Steam Bleed Point #2	GEN	Generator
BFP	Boiler Feed Pump	HTAH	High Temperature Air Heater
C	Control Point	LTAH	Low Temperature Air Heater
CFP	Condensate Feed Pump	PRI	Primary
CHAN	MHD Channel	RB	Radiant Boiler
CIR	Circulation	RECY	Recycled
COMB	Combustor	SC	Seed Condenser Chamber
COMP	Compressor	SEC	Secondary
COND	Condenser	SH	Superheater
DIF	Diffuser	SPRAY	Spray Attenuator
DRUM	Steam Drum	TURB	Turbine
DST	Deaerator Storage Tank	WW	Waterwall

Figure 4.--Gas Path and List of Abbreviations of Combined Plant

INPUTS

Drum Pressure
 Pressure and Temperature in DST
 Pressure of Condenser
 Pressure and Temperature of Steam at Control Valve
 Pressure and Enthalpy of Steam at Bleed Points in Turbine
 Flow Rate of Water to Spray Attenuator
 Gas Temperature and Flow Rate into Economizer
 Heat Lost to Walls in Channel and Combustor
 Controlled Valve Parameters

OUTPUTS

Steam Flow Rates through Bleeds and BFP Turbine
 Water Flow Rates into and out of Feedwater System
 Pressure at BFP Outlet
 Temperature and Enthalpy of Water into Drum
 Gas Temperature and Flow Rate out of Economizer

Figure 5.--Feedwater Subsystem

INPUTS

Temperature, Enthalpy, and Flow Rate of Feedwater entering Drum
 Flowrate of Steam out of Drum
 Gas Temperature and Flow Rate out of Diffuser
 Temperature and Pressure of Recycled Gas
 Temperature and Pressure of Secondary Air
 Controlled Valve Parameters for Circulating Water, Recycled Gas
 and Secondary Air

OUTPUTS

Drum Pressure
 Drum Level
 Gas Temperature and Flow Rate out of Furnace
 Temperature of Seed Condenser Outlet

Figure 6.--Steam Drum and Waterwalls Subsystem

INPUTS

Pressure from Drum and resultant Steam Enthalpy and Temperature
 Flow Rate of Steam through Throttle Valves
 Pressure and Temperature of Feedwater out of BFP
 Gas input Temperature and Flow Rate into PRI SH
 Heat Transfer to SEC SH
 Controlled Valve Parameter

OUTPUTS

Steam Conditions at Throttle Valves
 Flow Rate of Steam out of Drum
 Gas Temperature and Flow Rate out of PRI SH
 Flow Rate of Feedwater for Spray

IMPORTANT

Metal Temperatures in Superheaters
 Steam Temperature at Throttle

Figure 7.--Superheat Subsystem

INPUTS

Steam Conditions at Throttle
Gas Temperature and Flow Rate into LTAH
Combustor Pressure
Controlled Throttle Parameter

OUTPUTS

Flow Rate of Steam through Turbine
Gas Temperature and Flow Rate out of LTAH
Air Temperature and Pressure out of HTAH

IMPORTANT

Metal Temperature of LTAH
Amount of Fuel Flow into HTAH

Figure 8.--Air Circuit Subsystem

INPUTS

Pressure, Temperature, and Enthalpy of Steam at SH Outlet
 Pressure of Condenser
 Mass Flow Rates of Bleed Steam
 Desired Output Power

OUTPUTS

Steam Flow Rate through Turbine
 Pressures and Enthalpies of Steam at Bleed Points
 Real and Apparent Power out of Generator

IMPORTANT

Shaft Speed
 Throttle Valve Actuating Signal

Figure 9.--Turbine-Generator Subsystem

Figure 10.--Primary Superheater Response to Ramp Increase of Input Gas Temperature

Figure 11.--Primary Superheater Response to Step Decrease of Output Steam Flow

Figure 12.--Three Stages of CNCD Modeling

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TASK J
Slag Physical Properties:
Electrical and Thermal Conductivity
R. Pollina

I. OBJECTIVE AND SCOPE OF WORK

The objective of this task is to study the physical properties (thermal, electrical, and mechanical) of slags and refractory materials. Two- and four-lead dc and two-lead ac electrical conductivity measurements are being done to 2000 K in an oxygen-containing environment and to 2600 K in vacuum or inert atmospheres. Thermal expansion measurements are being made with and without applied mechanical loading to 1925 K. An on-line microprocessor controlled data acquisition system is used and offers the capability of studying long-duration time-dependent effects in these experiments. The effect of slag corrosion on these properties is also studied. This and other materials capabilities are part of an overall materials effort to study high-temperature air heaters and other downstream components.

II. SUMMARY AND IMPACT

We have completed our task of studying the electrical conductivity of Rosebud coal slag with potassium carbonate seed. This data is presented in this report as well as computer modeling data obtained by fitting the conductivity data. We are using this data to analyze the conductivity behavior of a slag layer on an electrode wall. In particular, we can calculate the conductivity in the Faraday direction of a slag layer of uniform composition to determine the ease with which current can reach an electrode covered with a slag layer, and we can calculate the slag layer leakage resistance. We also can calculate the voltage drops and electric field gradients. These calculations could be used to establish lower limits in wall temperature for diffuse mode operation of an MHD channel. Related calculations can be applied to ion migration and some of the electro-chemical effects which lead to slag layer instabilities, arcing, and electrode degradation in MHD channels.

The data presented in this report are important for three reasons. First, using this data, we can calculate the leakage resistance of a slag layer on an electrode wall. These calculations are correct under all conditions of operation of an electrode, arcing or diffuse. This data, therefore, is of immediate use in channel design. Second, we can estimate the limits for diffuse-mode current flow in a well-behaved slag layer. In the event that electrodes compatible with the ionic conductivity of a slag layer are found, there would be diffuse-mode current flow and the data would determine the limits within which these electrodes could operate. This mode of operation is the research goal we should set for future MHD development. The third and perhaps most important reason why this data is useful is that since we now have the electrical conductivity of the slag layer, we are in a position to calculate the electro-chemical and ion migration effects which can occur in a slag layer under the passage of diffuse electric current. With the exception of the high-temperature boil-off which occurs in an arc, the electro-chemistry and ion migration characteristics of a slag layer are the major factors in determining electrode performance and life expectancy in current channel designs. In future reports, we shall present applications of our data which will help in understanding these effects.

III. DETAILED DESCRIPTION OF TECHNICAL PROGRESS

We present graphically a complete summary of the electrical conductivity of seeded Rosebud ash up to a seed content of 30 weight percent K_2O . Temperatures range from 700 to 1450°C. Figure 1 shows the electrical conductivity as a function of weight percent K_2O from zero to 30 percent at selected isotherms indicated on the figure. The purpose of Figure 1 is to show how accurately our computer fit to the electrical conductivity (solid lines) agrees with the data points collected in the laboratory (open circles). Note that only in regions of the phase transitions where there are anomalous variations in the electrical conductivity is there any appreciable discrepancy between the computer modeling fit and the data points themselves. Even at these points, the departure of the data from the line is not very significant.

Figure 2 is a more detailed plot of the same data showing the computer fit at isothermal intervals of 50°C. In this case, we have deleted the laboratory data points. The isotherms cover the complete range at 50 degree intervals from 700 to 1450°C. At the lower temperatures, the data is characterized by a very closely spaced family of curves up to approximately 1100°C at the low K_2O concentrations and 1250°C at the high concentrations.

Above this closely spaced family of curves, there is a region of anomalous behavior in the conductivity data that extends the full range of seed levels. This represents the temperature region in which a glass network forms within the slag layer. Above this glass network formation at the temperatures indicated previously, we have a region of very little variation in the electrical conductivity as a function of K_2O percent. This is a region in which the slag layer is predominantly liquid. At the extreme low percentages of K_2O up to approximately 6 percent, we have a phase boundary for the crystallization of anorthite in the liquid slag. In the region where the curves are essentially flat, there is some evidence of the existence of a high-temperature form of $KAlSiO_4$. Further work, however, must be done on the phase diagram of coal slag in this region before we can be certain of this. Some effects of these anomalies and flat areas in slag conductivity behavior will be noted when we discuss the slag layer calculations presented in this report.

Figure 3, which shows the same data in a complete three-dimensional plot, graphically illustrates (in a parametric space of conductivity, temperature, and seed level) the region for which we have obtained electrical conductivity data on Rosebud coal slag. A dashed line in the region of phase transition marks the crystallization of anorthite in the coal slag as the slag is cooled. The broad, solid line represents the glass network formation temperature. At temperatures below this broad line, Rosebud coal slag is a mixture of glass and crystalline phases.

With a slag layer of uniform composition on an electrode wall with a slag plasma temperature of 1720 K with electrodes of dimensions 15cm x 1cm and electrode spacing of 2mm, we can calculate, for certain wall temperatures, both the voltage drop through the slag layer and the leakage resistance of the slag layer for a given diffuse mode current density. These calculations are shown in Table 1 for three selected wall temperatures (1000, 1300, and 1600 K) and for three selected weight percentages (K_2O , 0.5, 23, and 30 percent). We have

assumed a Faraday current density of 1 cm/cm^2 and have used the results of Koester and Nelson¹ for the slag layer thickness. Note that the leakage rate is virtually insensitive to the wall temperature and only slightly sensitive to the seed level of the adhering slag layer. The reason for this is that the leakage resistance is primarily determined by the portion of the slag layer that is close to the plasma. The temperature range for this portion of the slag layer corresponds to the uppermost isotherms in Figure 2 where conductivity is relatively insensitive to K_2O content.

In our calculation of the voltage drop through a slag layer for a one amp per square centimeter Faraday current, we find an enormous dependence of this voltage drop both on the wall temperature and on the seed level of the slag. Thus, for wall temperatures at 1300 K and below, we would have extremely high voltage drops in the slag layer for 0.5 percent K_2O . This is a situation which would lead to arcing of the slag layer. At 23 weight percent K_2O , wall temperatures at 1000 K and lower might lead to arcing because of a large voltage drop across the slag layer. At 1600 K, the calculated voltage drops in the slag layer are quite low, and there would be no problem for the passage of Faraday current at the level of one amp per square centimeter.

Finally, Figure 4 shows the voltage drop in the slag layer and the potential gradient (or electric field) in a slag layer for several selected percentages of K_2O . These are calculated values based on the same assumptions as described for Table 1. The data is presented as a function both of distance from the wall in millimeters and of slag temperature in degrees Kelvin. The dashed lines in Figure 4 are a plot of the voltage at any point on the slag layer referenced to the wall and, therefore, are plotted as volts above wall potential. We have plotted four selected weight percents of K_2O from 20 to 30 percent. These are 20, 22, 24, and 30 weight percent. Note that in the region between 20 and 24 weight percent K_2O that the data falls in a relatively narrow band. This corresponds to the percent seed level expected for ash on an electrode wall.² The breaks in the dashed lines at approximately 1460 K result from a glass network transition which affects the electrical conductivity. This is the same phase boundary that was plotted on Figure 3 as a broad, solid line. Note that if we elevate the wall temperature from 973 K to 1173 K, we reduce the potential drop in the slag layer to one-third of its value at a 973 K wall temperature. Similarly, the solid lines are a plot of the potential gradient of the electric field assuming a one amp per square centimeter diffuse mode conduction in the slag layer. Potential gradients are plotted in kilovolts per meter. Note again that between 20 and 24 weight percent K_2O , the data falls in a narrow band. This is fortuitous for generator operation. A large variation in this range as a function of seed content would pose serious stability problems for an MHD channel. At 30 percent K_2O , the electric field gradients within the slag layer are small, relative to the vertical scale of the figure. By contrast, for 15 weight percent K_2O , the field gradients are extremely large, four times what they are in the 20 to 24 weight percent region. This is significant because it delineates the area of diffuse mode stability which one can expect for conduction through a slag layer. Again, if we raise the slag layer temperature by 200 K, we have a reduction in these electric field gradients; for example, at 15 weight percent K_2O , we have a reduction of almost a factor of 6 in the potential gradient. These facts are significant if we ever hope to have stable, diffuse mode operation in an MHD channel.

Table 1.--Slag Layer Voltage Drop and Leakage Resistance

Assume: 15cm x 1cm electrodes
 2mm electrode spacing
 Slag-Plasma Temperature = 1720 K

Wall Temp.	% K ₂ O	Voltage Drop (V)	Leakage Resistance (Ω)
1000 K	0.5	22,500 V	19.7 Ω
	23	308	6.0
	30	16.7	1.1
1300 K	0.5	950	19.9
	23	54	6.1
	30	2.9	1.2
1600 K	0.5	4.7	21.9
	23	0.9	8.2
	30	0.2	1.9

ELECTRICAL CONDUCTIVITY ISOTHERMS OF SEEDED ROSEBUD SLAG

Figure 1

ELECTRICAL CONDUCTIVITY ISOTHERMS OF SEEDED ROSEBUD SLAG

Figure 2

ELECTRICAL CONDUCTIVITY OF ROSEBUD SLAG

Figure 3

Figure 4A

Figure 4B.

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