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MHD AIR HEATER DEVELOPMENT
TECHNOLOGY

Report for the Period
October, 1978 - December, 1978

Fluidyne Engineering Corporation
5900 Olson Memorial Highway
Minneapolis, Minnesota 55422

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1.0 OBJECTIVE AND SCOPE OF WORK

Work to be done under this contract continues the ceramic heater development program begun under ERDA Contract Numbers E(49-18)-1537 and 76-C-01-2254. The statement of work divides the effort into three tasks:

Task 1 - Design Studies

The objectives of this task are to: 1) evaluate full-scale, directly- and indirectly-fired regenerative air heater systems for use in MHD power plants; 2) support testing of refractory materials, hot gas valves, and design concepts; 3) support design of a 5 MW test heater.

Task 2 - Design Support Tests

The objectives of this task are to: 1) support design of a 5 MW test heater; 2) identify and evaluate life of promising refractory materials for use in MHD heaters; 3) determine operating conditions and bed geometry (hole size, web thickness) which permit operation without clogging of heater passages due to accumulations of seed/slag or slag alone, 4) test valves for use in hot gas streams which are laden with seed/slag or slag alone.

Task 3 - Vertical Slice Test Bed

The objective of this task is to provide a preliminary design of a test heater which is a vertical slice of a full-scale heater. It will be sized for a thermal input of approximately 5 MW. Testing with hot gas streams containing seed/slag or slag alone will be accommodated in order to simulate both direct- and indirect-firing.

2.0 SUMMARY

During the period covered by this report, work was done on all three tasks and is summarized as follows:

Under Task 1, Design Studies, the influence of heater system layout, duct dimensions, and heater sequencing on flow distribution was studied further. One result was that localizing the bulk of the pressure drop in the heaters tends to minimize heater-to-heater flow differences. The task of integrating the temperature and pressure solvers was pursued further.

A subcontract was placed with STD Engineering to compare three possible MHD systems - directly-fired, separately-fired with atmospheric combustion products, and separately-fired with pressurized combustion products. Temperatures, pressures, and flows around the HTAH in each case were specified by FluidDyne such that the HTAH would be of reasonable size and cost. Results are due next quarter.

An analysis of current flow back up the air duct from the combustor was done. Results showed that the voltage gradient and power loss back up the air duct depend on the ratio of electrical conductivities of air and duct wall insulation. In directly-fired heaters, combustion air will contain some potassium sulfate vapor. Measurements of air conductivity would be useful together with results of the study mentioned above in order to estimate both the voltage profile and power loss in the air duct.

Under Task 2, Heat 201 was completed and much of the construction on the valve test rig was completed. Heat 201 was run with a Corhart X-317 (fusion cast magnesia-35% alumina, hereafter referred to as Corhart X-317 as this trade name designates not only composition, but microstructure,

impurity level and manufacturer's process) matrix in the rig. Plans had originally been made to test a chrome-alumina material but difficulties were encountered in drilling the holes for the matrix bricks. Efforts at obtaining Corhart X-317 were intensified and enough was received to allow rebuilding of the test rig using this material. As noted in earlier reports¹⁻⁴, Corhart X-317, has good corrosion and thermal shock resistance.

Matrix Test 7 (Heat 201) ran for over four hundred hours but was terminated early because of a restriction in the bed. This was caused by failure of the insulating lining in the hot gas duct between the burner and the matrix. This liner of magnesia-chrome bricks (RFG) had been used in earlier tests. Reactions with seed/slag occurred and the resulting high viscosity "slag" partially plugged the bed. At the end of the reporting period, plans were being made to repair the hot gas supply leg and replace its hot lining with the X-317 material mentioned above.

Under Task 3 a topical report describing the design of the 5 MW test heater system was prepared. At the end of this reporting period it was being reviewed.

A novel creep tester was also designed which would permit testing of specimens under "on gas" and "on air" cycling conditions. A memorandum describing the device was in press at the end of the reporting period.

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
MILESTONE PLAN AND MANAGEMENT REPORT

1. Contract Identification NIID Air Heater Development		2. Reporting Period October - December, 1978		3. Contract Number ET-78-C-01-3005										
4. Contractor (name, address) FluidDyne Engineering Corporation 5900 Olson Memorial Highway Minneapolis, Minnesota 55422		5. Contract Start Date 3-10-78		6. Contract Completion Date 10-10-79										
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1.1	Revised Size/Cost Code													100/100
1.2	New Baseline Cases													100/100
1.3	Performance Code													95/95
1.4	Performance Studies													20/40
2.1	Plan & Run Matrix Test 5													100/100
2.2	Redesign Rig													100/100
2.3	Rebuild Rig													100/100
2.4	Plan & Run Matrix Test 6													100/100
2.5	Modify Test Rig (As needed)													100/100
2.6	Plan & Run Matrix Test 7													30/40
2.7	Modify Test Rig (As needed)													0/0
2.8	Plan & Run Matrix Test 8													0/0
2.9	Analysis of Data & Results													50/50
2.10	Purchase Long Lead it. for VTR*													100/100

11. Remarks
*VTR Stands for Valve Test Rig. indicates work begun before scheduled start date.

12. Signature of Contractor's Project Manager and Date
 4-11-79

13. Signature of Government Technical Representative and Date

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
MILESTONE PLAN AND MANAGEMENT REPORT

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2.13	Plan & Run Valve Test 1																					75/75																																	
2.14	Modify VTR (As needed)																					0/0																																	
2.15	Plan & Run Valve Test 2																					0/0																																	
2.16	Analysis of Data & Results																					0/0																																	
3.1	Hot Gas Supply																					60/60																																	
3.1a	Select Hot Gas Simulator Concept																					100/100																																	
3.1b	Design Hot Gas Simulator																					60/60																																	
3.2	Air Supply																					60/60																																	
3.3	Gas/Air Exhaust																					60/60																																	
3.4	Vessel/Matrix Insulation																					60/60																																	
3.5	Cooling Water System																					50/60																																	
3.6	Emissions Control																					50/60																																	
11. Remarks The intermediate event shown is a decision point. Date for completion of the design will be reviewed at that time..																																																							
12. Signature of Contractor's Project Manager and Date 4-11-79											13. Signature of Government Technical Representative and Date																																												

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3.0 DESCRIPTION OF TECHNICAL PROGRESS

3.1 Task 1 Design Studies

Technical Overview

Most of the effort on this task has been in three areas:

- 1) size/cost studies of full-scale systems
- 2) development of a code, called SCAMP, for predicting the properties as a function of time of air delivered from a high temperature air heater system
- 3) support of tasks 2 and 3.

Also, a brief study was made on electrical isolation of the air duct from the MHD combustor.

3.1.1 Size/Cost

Figures 1 through 4 are schematics of three different MHD systems and a steam cycle which could apply to each. These three systems,

- F-1 Directly-fired
- F-2 Separately-fired with low pressure combustion products
- F-3 Separately-fired with pressurized combustion products

will be analyzed by STD Engineering Corporation to determine system efficiencies and heat and material balances.

Temperatures were specified around the heater systems by Fluidyne so that in none of the three cases would material problems prevent design.

Previous size/cost studies have indicated substantially reduced cost for the heater systems per se in the separately-fired case with pressurized combustion (case F-3). We plan to compare overall system efficiencies for these three systems and note the differences among hardware requirements. Differences in technological risk will also be noted.

3.1.2,3 Performance and Control Systems

The flow solver portion of the SCAMP model was used to study heater-to-heater differences in flow through a heater system. Results of this work are being summarized and will be issued as a topical report. We note here that significant variations in flow from heater-to-heater can occur if resistance to flow is distributed among ducts, manifolds, and the heaters. Localizing the bulk of the flow resistance in the heaters themselves minimizes these effects.

Concern about flow distribution is more significant in directly-fired systems because it is not practical to control reheat gas flow to each heater by use of control valves. High temperature at both inlet and outlet of a directly-fired heater and high particulate loading make operation of a control valve impractical. On the other hand, separately-fired systems can be designed with control of reheat gas flow to each heater.

3.1.4 Seed/Slag Deposition

Discussions were held with personnel at Argonne National Laboratory to monitor their work on development of a seed/slag deposition model.

3.1.5 Valves

No work was done on this sub-task during this quarter.

3.1.6 Bed Support

No work was done on this sub-task during this quarter.

3.1.7 Dome

No work was done on this sub-task during this quarter.

3.1.8 Electrical Isolation

There are several concerns related to electrically isolating the air duct from the MHD combustor. In the case of a directly-fired system, these concerns are aggravated by the presence of seed vapor in the air and the resultant increase in its electrical conductivity. One question is, how far up the air duct will the voltage from the combustor be felt? It is possible to calculate the voltage gradient up the air duct assuming a fairly simple physical model.

It is assumed that over the plane of the air duct-combustor interface there exists a constant potential, V . It is further assumed that current leaks through the insulating refractory lining to the outer duct wall which is at ground potential.

Figure 5 shows reduced voltage plotted against reduced distance along the air duct. The parameter h is defined as

$$h = \left(\frac{K_I}{K_G} \right) \left(\frac{a}{P} \right)$$

where

K_I = overall electrical conductivity of the insulation

K_G = electrical conductivity of the air

a = radius of the air duct

P = inside circumference of the air duct

Figure 5 shows that the distance up the air duct at which a significant voltage will persist is a strong function of h , the ratio of electrical conductivities of insulation and air. This result is intuitively appealing because one expects that if leakage through the insulation is low, then a significant voltage will exist up the air duct and vice-versa.

The equation for power loss due to current leakage from the combustor into the air duct is

$$W = 4\pi ah^2 K_G V^2 \sum \frac{1}{\alpha_n^2 (h^2 + \alpha_n^2)}$$

where the α_n are eigenvalues which depend on h . Numerical values for the first six are given below for three different values of h .

h	α_1	α_2	α_3	α_4	α_5	α_6
0.01	.141	3.83	7.02	10.2	13.3	16.5
0.1	.442	3.86	7.03	10.2	13.3	16.5
1.0	1.256	4.08	7.16	10.3	13.4	16.5

The table below shows how power loss depends on h:

h	Reduced Power, $W/4\pi a K_G V^2$
0.01	0.0353
0.1	0.111
1.0	0.327

An interesting result is that a 100-fold increase in h leads to approximately 10-fold increase in power loss. This suggests that a modest sacrifice in power could be taken if safety concerns required that the voltage gradient up the air duct be made as steep as possible.

Another interesting result is the sensitivity of the calculations to h, which in turn depends on the ratio of insulation conductivity to air conductivity. For this particular aspect of the electrical isolation problem, measured values of air conductivity would be most valuable.

3.2 Task 2 - Design Support Tests

Technical Overview

The experimental work under Task 2 consists of air heater materials and operability testing in three basic areas. The three types of testing are:

1. Matrix Tests - Conducted in the five meter cored brick matrix test facility. The primary objective

of these tests is to obtain heater performance and operability data.

2. Valve Tests - Conducted in the valve test facility. The objectives of these tests are to obtain valve performance and operability data and to assess the effects of pressure cycling on insulation and valve performance.
3. Materials Tests - Conducted either as "piggyback" tests in the matrix test facility or in a smaller test module using the hot gas supply for the matrix test facility. The primary objective of these tests is for refractory and metal materials screening for air heater service.

The testing work in these three areas will provide needed information for the development of MHD air heaters. The work under Task 2 is coordinated with the Task 3 design work to aid in development of design criteria and with the Task 1 analytical work to provide experimental data against which mathematical predictions can be compared.

A matrix test, Heat 201, was run during the preceding quarter. This was the first test with the new Corhart X-317 matrix. The duration of the test was 435 hours with top of matrix temperature greater than 1648 K (2500 F). A total of 1043 kg (2297 lbm) of potassium sulfate seed and 47 kg (103 lbm) of Rosebud ash were injected into the hot gas stream during this test.

The target goal of 500 hours of testing at fixed conditions was not met due to severe degradation of the hot gas supply duct liner near the main burner. The Corhart RFG (rebonded fused grain magnesia chromite) liner material was severely attacked and reaction products of RFG and coal slag

flowed into the matrix passages. This material could not be removed even by raising the bottom of matrix temperature to 1755 K (2700 F). The hot gas supply duct was redesigned to allow smaller heat loss in the duct and thus lower combustion temperatures. The duct will be rebuilt with a liner of X-317 material, the matrix holes will be cleaned out, and another test will be run.

Construction of the valve test facility continued throughout the quarter. All parts and materials have been received except the test valve itself. Construction will be completed during the next quarter.

Materials testing during the preceding quarter included piggyback testing of 7 bar samples of 6 ceramic materials during Heat 201. Samples of the slag material and matrix bricks from Heat 201 were collected for analysis. Analysis of test data and materials samples from previous tests were also continued.

3.2.1,2 Matrix Tests - Materials and Analytical Results

This section will describe the evaluation of several spinel type materials in various "slags" which were sampled during the course of Heat 201. The material includes Corhart X-317 and two stoichiometric spinel castables: phosphate bonded (P), and calcium aluminate bonded (C). The "slags" examined included flyash used to simulate coal combustion, and the refractory slag deposited in the matrix during Heat 201.

Corhart X-317

This material was obtained and used to construct the magnesia-spinel matrix. Due to differences in processing, it proved to be somewhat less dense (2890 kg/m^3 , 180 lbm/ft^3)

(Figure 6) than previously obtained material. This was manifested partially as microporosity which was expected to reduce overall chemical resistance. Composition determined from Energy Dispersive X-ray analysis (Table 1) showed chemical similarity to material which had been obtained from the same supplier at an earlier date.

TABLE 1
COMPOSITION OF MAGNESIA-SPINEL

Approximate Wt. %
(from EDX Uncorrected)

<u>Element</u>	<u>A-Batch</u>	<u>B-Batch</u> (Used for Heat 201 Matrix Test)
Mg	62	62
Al	34	34
Si	0	0
Ca	1	1
Fe	0	2

Fusion cast billets were cut and diamond core-drilled to form the matrix. Each 25.4 mm (1 in) diameter 100 mm (4 in) deep hole required about 100 seconds to drill. Drill life was approximately 300-400 holes. Fifty bricks (1100 holes) were drilled to form the matrix.

Upon examination after Heat 201, the matrix bricks were judged to be in good condition with only minor erosion damage. Only the uppermost brick appeared to suffer web fracture. A complete disassembly was not made; only the top seven bricks were removed for inspection.

Fracture of webs in cored brick regenerators has been shown to result from stresses developed during thermal cycling. Also, during earlier tests with magnesia chrome refractories, cracks developed which are thought to result from stresses developed from irreversible thermal expansion. This behavior may be influenced by chemical reaction with the atmosphere and components of the ash.

Cracking and deformation of the uppermost magnesia-spinel matrix bricks (Fig. 6) was much less severe than the magnesia chrome bricks. This fusion cast material, in spite of its high density, has been reported to have very good resistance to thermal shock.⁵ Examination of the microstructure indicates a possible mechanism to explain this good thermal shock resistance. Cracks which initiate as a result of high stress are impeded by the relatively loose interface between the MgO and MgAl_2O_4 phases. In the micrograph, Fig. 7, a crack in the spinel beginning at the upper left appears to terminate at the interface with the MgO grain. The thermal stress resistance is also enhanced, no doubt, by the material's high thermal conductivity, strength and fracture toughness.⁶

The two castables also performed well as side wall material with recession rates at least equal to the magnesia chrome refractory. Analytical work is in progress and will be reported later.

3.2.3 Matrix Tests - Bed Geometry

Analysis of calculated and measured temperature profiles and assessment of the thermal performance of the test facility during Heat 201 are underway. The bed had 25.4 mm (1 in) holes and 12.7 mm (1/2 in) webs. This data will provide specific information useful for analytical studies and full scale design considerations. This is an ongoing effort which will be continued with all future testing.

3.2.4 Matrix Tests - Seed/Slag Deposition and Removal

Analysis of deposits from the lower portion of the matrix from Heat 201 is underway. Initial observations indicate that the deposits are comprised of coal slag with additional compounds from the refractory material. Mass balance data on the seed/slag material for Heat 201 is also being analyzed. Further information from Heat 201 will be reported when these analyses are complete.

3.2.5 Emissions Control

The new baghouse has been installed; exhaust piping from the mist eliminators to the baghouse and from the baghouse to the induced draft fan will be completed shortly. This system will be used to control emissions from the matrix test facility and the valve test facility in future testing.

3.2.6 Matrix Tests - Bed Support

The bed support used for the matrix in Heat 201 had a design bearing stress of 282 kPa (40.9 psi) and a shear stress of 77 kPa (10.4 psi). Maximum temperature service during Heat 201 was 1755 K (2700 F). Inspection from the bottom following Heat 201 showed the support bricks to be structurally sound with the exception of two cracks in one of the bricks. The result of the cracking was to reduce the effective shear area slightly. The support bricks will be retained for further matrix testing.

3.2.7 Valve Tests - Pressurization/Depressurization Effects on Insulation

Construction of the valve test facility is underway.

3.2.8 Valve Tests - Valve Performance

Construction of the valve test facility is underway.

3.2.9 Electrical Isolation

No effort was expended in this area during the last quarter.

3.2.10 Diagnostics

Several problems with the data acquisition system were encountered during Heat 201. Freezing temperatures caused failure of a draft control valve in the exhaust line for the test rig which resulted in the test rig being subjected to vacuum at intermittent intervals. This resulted in fouling of several pressure transducers with water from the manometry system before the problem was corrected. Condensation in the pressure lines from the test rig aggravated this situation. As a result, the pressure transducers are being relocated and liquid traps installed to prevent the possibility of this occurrence in future testing. The microprocessor based data acquisition system will continue under evaluation in the future tests.

3.3 Task 3 Preliminary Design of a 5 MW Heater

A topical report has been prepared describing the design of this heater test system. It will be issued to DOE shortly.

As an extension of this work, an "in vivo" creep testing device was designed based on work at Montana College of Mineral Science.⁷ A report has been written and will also be issued to DOE shortly.

4.0 CONCLUSIONS

There are no new conclusive results to report at this time.

DIRECTLY-FIRED MHD SYSTEM

FIGURE 1. CASE F-1

INDIRECTLY-FIRED, LOW PRESSURE COMBUSTION PRODUCTS

FIGURE 2. CASE F-2

INDIRECTLY-FIRED, HIGH PRESSURE COMBUSTION PRODUCTS

FIGURE 3. CASE F-3

FIGURE 4. STEAM CYCLE

V = Voltage at combustor - air duct interface

$$h = \frac{K_1}{K_G} \left(\frac{a}{p} \right)$$

K_1 = Electrical conductivity of duct wall

K_G = Electrical conductivity of air

p = Inner circumference of the air duct

a = Duct radius

$v(\zeta, 1)$ = Voltage at inner surface of air duct

z = duct length

FIGURE 5. REDUCED VOLTAGE VS. DISTANCE UP THE AIR DUCT

FIGURE 6. MAGNESIA-SPINEL MATRIX BRICK SECOND FROM TOP AFTER HEAT 201.

FIGURE 7. SEM MICROGRAPH SHOWING ARRESTED CRACK IN FUSION CAST MAGNESIA-SPINEL.

REFERENCES

1. "Progress on the Testing of Refractories for Directly-Fired MHD Heater Service," J.E. Fenstermacher, Jr., D.G. DeCoursin, and R.R. Smyth, FluidDyne Engineering Corporation, 15th Symposium on the Engineering Aspects of MHD, University of Pennsylvania, Philadelphia, Pennsylvania, May 1976.
2. "Progress on the Testing of Refractories for Directly-Fired MHD Air Heater Service," J.E. Fenstermacher, Jr., L.R. White, and R.R. Smyth, FluidDyne Engineering Corporation, 16th Symposium on the Engineering Aspects of MHD, University of Pittsburgh, Pittsburgh, Pennsylvania, May 1977.
3. "Progress in the Testing of Materials and Design Concepts for Direct-Fired MHD Air Heater Service," R.R. Smyth, G.G. Brucker, and L.R. White, FluidDyne Engineering Corporation, 17th Symposium on the Engineering Aspects of MHD, Stanford University, Stanford, California, March 1978.
4. "The Status of Air Heater Development in the United States for MHD Systems," L.R. White and D.G. DeCoursin, FluidDyne Engineering Corporation, and A.W. Postlethwaite, U.S. Department of Energy, Joint US/USSR Colloquium on MHD, Washington, D.C., October 1978.
5. Jackson, Darrel, Corhart Refractories Company, Private Communication.
6. Rasmussen, J.J. and J.R. Youngblood, Quarterly Progress Report, October 1, 1978-December 31, 1978, DOE Contract ET-78-C-01-3087.
7. K. Kitto, Montana College of Mineral Science, Private Communication, November 1978.