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MHD AIR HEATER DEVELOPMENT
TECHNOLOGY

Report for the Period
July, 1978 - September, 1978

FluidDyne 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-V-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, direct- and indirect-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 ~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, an analysis of several different insulating schemes for air heaters was done and a preliminary study of flow distribution in a heater system was completed. The study of insulating schemes showed that large cost differences are associated with these various methods. As part of the testing work, various insulating schemes have been used and the results of this cost comparison show the potential value of this effort. In general, castable materials cost less both in first cost and for installation. Several castable materials are being evaluated in the test program.

The study of flow distribution showed that significant ripple in flow and pressure could occur in a 24-heater system. These results, although preliminary in nature, demonstrate the utility of the performance code.

Under Task 2, Design Support Tests, a series of matrix tests was completed and the test rig was dismantled. Some modifications were made and by the end of this reporting period, the rig was being reassembled. Two materials tests were run using the hot gas supply duct of the matrix test rig and results of those tests are given in Sections 3.2.1 and 3.2.2. Design of the valve test rig was completed and purchase orders were placed for much of the hardware. Modification of the laboratory to accommodate the test rig was begun.

A summary of some of the results of the matrix tests is given below. A total of ~850 hours of testing was accumulated on the matrix which was constructed of RFG,

a rebonded fused grain material of $\text{MgO-Cr}_2\text{O}_3$ composition. Although this material is not considered a good candidate for matrix checkers, it was in reasonably good condition at the end of the test.

A total of 1590 kg (3505 lb) of seed/ash mixture was fed during the course of the tests. Perhaps the most remarkable observation was that no evidence of accumulation of slag in the bed was found. Photographs of matrix bricks are included in this report and show no slag deposits even on bricks which were in the heater at locations where slag should have been sticky ($\sim 1600\text{ K}$, 2400°F).

The last test, Heat 104, was terminated with a deposit in place at the bottom of the matrix. This was done deliberately in order to determine the nature of the deposits which would form if the bottom of the bed were allowed to run below the seed fusion temperature (1342 K , 1956°F). A measurement of the viscosity of this material, in the molten state, was made with the following results.

The material appears to have been nearly all seed, had a water-like viscosity, but when melted, a small amount of a denser, more viscous phase was observed.

Additional material studies were conducted on a number of refractory compositions. A fusion cast, MgO/spinel material (X-317) continues to show good corrosion and thermal shock resistance. Evidence is accumulating that both corrosion resistance and thermal shock tolerance are due largely to the microstructure which results from the fusion casting process. The next series of matrix tests will be run with a bed of X-317 in place.

Under Task 3, Design of a 5 MW Heater System, work was focused on the heater vessel, bed support, refractory lay-up,

etc. Some full-scale studies were done to assess the scalability of some of the heater design concepts.

The hot gas supply system was also studied. A gas-fired burner with seed/ash or coal injection is being given greatest consideration. The additional cost of a coal combustion system is not justified by the marginal improvement in quality of simulation for heater testing. The simulation requirements for heater testing were studied and results are included as an appendix to this report.

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		<div style="display: flex; justify-content: space-between;"> <div>FY 78:</div> <div>FY 79:</div> </div> <div style="display: flex; justify-content: space-between;"> <div> M A M J J A S O N D </div> <div> J F M A M J J A S O </div> </div>												
1.1	Revised Size/Cost Code													100/100
1.2	New Baseline Cases													100/100
1.3	Performance Code													65/65
1.4	Performance Studies													10/0
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)													30/0
2.6	Plan & Run Matrix Test 7													0/0
2.7	Modify Test Rig (As needed)													0/0
2.8	Plan & Run Matrix Test 8													0/0
2.9	Analysis of Data & Results													30/30
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

Boyd R. White for David G. DeCoursey

13. Signature of Government Technical Representative and Date

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MILESTONE PLAN AND MANAGEMENT REPORT

12/1/77

1. Contract Identification MIID Air Heater Development										2. Reporting Period July - September, 1978										3. Contract Number ET-78-C-01-3005									
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		FY 78												FY 79															
		M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O								
2.11	Final Design of VTR	██████████																								100/100			
2.12	Construct VTR	██████████												Δ												15/40			
2.13	Plan & Run Valve Test 1	██████████												Δ												5/20			
2.14	Modify VTR (As needed)													Δ												0/0			
2.15	Plan & Run Valve Test 2													Δ												0/0			
2.16	Analysis of Data & Results													Δ												0/0			
3.1	Hot Gas Supply	██████████												Δ												25/25			
3.1a	Select Hot Gas Simulator Concept	██████████																								100/100			
3.1b	Design Hot Gas Simulator	██████████												Δ												25/25			
3.2	Air Supply	██████████												Δ												25/25			
3.3	Gas/Air Exhaust	██████████												Δ												25/25			
3.4	Vessel/Matrix Insulation	██████████												Δ												25/25			
3.5	Cooling Water System													Δ												10/0			
3.6	Emissions Control													Δ												10/0			

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

Hayel R. White for David G. DeCoursey

13. Signature of Government Technical Representative and Date

13. Signature of Government Technical Representative and Date

3.0 DESCRIPTION OF TECHNICAL PROGRESS

3.1 Task 1 Design Studies

3.1.1 Size/Cost

Summary

The capability to size multi-layer insulation schemes was added to the Size/Cost program. This completes all of the planned modifications to the program and most options have been verified or cross-checked. Three parametric studies were completed using the Size/Cost program. They were: (1) sensitivity of air heater system cost to insulation schemes, (2) sensitivity of air heater system cost and heat loss to manifold flow area (see Section 3.1.3), (3) review of the directly-fired base case in order to include effects of new manifold sizing criteria, square-hole matrices, and other Size/Cost modifications. In addition to these studies, a comparison of three different MHD systems with high effectiveness air heaters is being made in order to understand the trade-offs among system efficiency, cost, and development risk. These have been sized for a 1000 MW electric plant and will include: (1) a directly-fired case with 2800°F delivered air temperature; (2) a clean, low pressure, indirectly-fired case with a 3000°F delivered air temperature; and (3) a clean, high-pressure, indirectly-fired case also with 3000°F delivered air temperature.

Review of the Directly-Fired Air Heater System

A prototypical directly-fired air heater system was described in a paper presented at the 1978 MHD Symposium. The principal air heater system design constraints are given in Table 1. In Table 2, the nominal operating conditions are given, and both the air inlet temperature

and the delivered air temperature are shown in an operating envelope plot, Figure 1.

In these studies, air heater systems were sized with two different insulation schemes which represent maximum and minimum insulation cost. Key insulation assumptions and other miscellaneous geometric constraints are given in Table 3. Cost data were revised to mid-1978 prices where new information was available, and the remaining items were inflated by 9% from the mid-1977 costs.

An important result of these studies was to show that insulation costs are a significant fraction of total system costs. If cheaper insulation schemes could be developed, then heater system costs could be reduced substantially.

These studies continued to show that system cost did not vary significantly with the number of heaters in a system. This result implies that other considerations will determine this parameter. Some of these considerations are:

- Ripple in properties of delivered air - the greater the number of heaters, the smaller the ripple.
- Valve diameter - the greater the number of heaters, the smaller the valve diameter assuming single gas and air inlet and outlet ducts. Size of valves will be limited (see below).
- Maintenance/reliability - it is intuitive that fewer heaters, and hence fewer valves, should lead to less maintenance and greater reliability.

With respect to valve size, we are in contact with valve vendors to obtain their judgment as to maximum size. Conflicting information has been received with at least one vendor claiming that size is limited only by fabricating and shipping restrictions. In the literature*, a valve with a diameter of 2 m (6.6 ft) is described as being under development for use at pressure differences of about 5 atm and hot blast temperatures of 1800 K (2800°F). In this particular reference, there is a discussion of the mechanical factors affecting valve design such as both mechanical stresses due to pressure differences and thermal stresses. The discussion is fairly detailed and implies that mechanical design to cope with both mechanical and thermal stresses is a significant concern.

3.1.2 Performance

Summary

Performance analysis included three major tasks:

- (1) completion of work on the matrix solution algorithm;
- (2) complete flow pressure analysis of a heater system with a 24 heater array; and (3) continued development work on thermal field simulation. The results of Items 1 and 3, and a summary of Item 2 will be reported below. Details concerning the flow/pressure analyses will be issued as a topical report.

A matrix solution algorithm has been selected and it has been verified as being accurate and fast for both small and large heater arrays. The selected algorithm is SOLVE 3, and it is compared to the other candidates in Table 4. Note that both storage and run time have been reduced.

* Elinson, I.M., V.S. Vagin, and V.M. Shustorovich, "Stal," (1976), pp. 792-798.

The thermal field simulation has been written and is now being merged with the pressure/flow field simulator. It is anticipated that debugging and modifications will be completed next quarter and that results from the full program will be available sometime later.

A pressure/flow analysis of a large heater system (24 vessels) has been completed. Purposes of this study were as follows. Firstly, the effectiveness of the flow/pressure solver in a large heater system had to be tested. Secondly, the following information was developed:

- Design system pressure drop and flow were verified
- Heater-to-heater flow distribution was determined
- The effect on flow distribution due to an abnormal flow resistance in a single vessel was determined
- Two basic manifold concepts were studied ("U" versus "Z" types)
- The system manifold and valve sequence were shown to be reasonable choices.

The selected test case was a 24 heater, directly-fired system sized for a 1000 MW_e plant. Temperatures at various points in the heater system were set at representative values and were held constant. For the flow effects that were investigated, temperature variations would not affect the results.

The detailed results of this study will be issued as a topical report. A summary of the most significant results is given here.

- With ducts sized for a velocity of 53 m/sec (175 ft/sec) a significant variation in flow occurs due to pressure losses at tees and elbows.
- This variation can be reduced significantly by increasing the duct diameters.
- The cost increases due to increasing the duct diameters is modest because higher performance and, hence, cheaper heaters result.
- Using either a "U" or "Z" type manifold does not affect flow distribution significantly.

Two additional flow/pressure-loss case studies are being considered. One is for a heater system with a smaller number of heaters and one will be a study of the effects on flow/pressure distributions caused by valve switching and the pressurization/depressurization processes.

3.1.3 Control Systems

Work on control systems will be started after the SCAMP program is completed.

3.1.4 Seed/Slag

Work carried on at Argonne National Laboratory and Montana State University was reviewed.

3.1.5 Valves

Discussions with vendors have led to conflicting responses as to valve sizes. At least one vendor suggests

that valve size is limited by only the fabrication facility and shipping considerations. This is in disagreement with other vendors who have suggested that the limit stems from the ability of a reasonably constructed valve to withstand the pressure load in a closed position (See Section 3.1.1).

3.1.6 Bed Support

Support was provided to the 5 MW design study in this area.

3.1.7 Dome

No work was done in this area during this past quarter.

3.1.8 Electrical Isolation

The presence of potassium compounds in the air delivered to the combustor from a directly-fired heater system raises concerns regarding isolation. Certain questions come to mind such as will the electrical isolation devices used with clean, seed-free air work when seed is present? Another question is how far upstream in the air duct will a significant potential exist? That is, what is the voltage gradient back up the air duct from the combustor? Also, could steep voltage gradients exist and, as a result, could electrical breakdown, or arcing occur? Finally, what effects would liquid seed deposits on the duct wall have on electrical isolation? These are the primary concerns that we intend to address.

So far, the effort in this area has been devoted to scoping the problem and determining the kinds of calculations which would be helpful. In addition, some thought has been given to making measurements of electrical

conductivity in the air stream leaving our test rig (see Section 3.2.9).

3.1.9 Test Rig Performance

The 17 foot test bed with X-317 matrix bricks was modeled in detail for simulation with a finite difference computer program. The results of this simulation were then compared with the results of a simpler code which is easier to run and costs less. The simple model was then used to establish a base operating condition for the next heater test.

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 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.

Four matrix tests were completed during the preceding year, bringing the total time at test conditions with the matrix test facility to 850 hours. Following the fourth matrix test, Heat 104, the facility was dismantled and all of the cored bricks and adjacent insulation materials were removed. Deposits in the flow passages of the heater matrix and gas outlet duct were removed for analysis. Modifications to the design of the test facility were made, including a change in the matrix geometry and material, and reassembly of the test facility was begun.

The design of the valve test facility was also completed and reviewed with DOE during this year. The completed design included several modifications requested by DOE following this review. Materials required for construction of the facility were purchased, subcontracts were let for required laboratory modifications, and construction of the facility was begun.

Materials testing during the last year included piggy-back tests of a total of six ceramic material samples during the four matrix tests and two additional tests which were conducted in the hot gas supply leg of the matrix test facility during the disassembly and rebuilding of the cored brick matrix portion of the facility. Fifteen samples of ceramic materials were tested for a total of 72 hours in these two tests.

Details of the work accomplished during the first three quarters of the contract year have been reported in

previous progress reports. The additional work completed during the final quarter is presented in further detail in the following.

3.2.1 Matrix Tests - Materials

Evaluation of materials for air heater applications continues. During this quarter two heats were run to expose test samples to the environment of a directly-fired heater. The first, Heat 105, served to shake down the test apparatus and establish operating parameters. The second, Heat 106, was a 70 hour run with seed and coal injection and temperatures to 2000 K (3140°F).

Heat 105

The objective of Heat 105 was to gain additional information on the behavior of material in a seed and coal ash laden high temperature gas stream. Several new materials including a castable spinel had recently been received and all the materials tested are listed, with their properties, in Table 5.

This heat was to have been approximately 70 hours at the following conditions: 2000 K maximum temperature, 30 minute cycle with coal and potassium sulfate/carbonate injected during the gas phase.

Figure 2 is a sketch of the materials test rig. It consists, basically, of the hot gas supply duct of the matrix test rig with the addition of a section for holding test samples.

Several problems developed which forced shut-down after only a few hours operation. The shell overheated around the axial viewport and the inlet to the spray chamber became obstructed. Although it was possible to control the overheating, whenever the seed/ash feeder was started, the

obstruction became worse. In spite of efforts to maintain test conditions, seed and ash were fed for only three hours. Temperatures from 1600-2000 K (2420-3140°F) were maintained for approximately 80 hours.

Test results are given in the next section.

Heat 106

Modifications were made to eliminate overheating of the shell and to facilitate removal of deposits which formed at the entrance to the spray chamber. The test objective was unchanged but the sample order was altered for reasons that will be explained in the next section. The order is given in Table 7, with Number 1 being closest to the hot gas supply burner and 12 being farthest.

The unit was brought up slowly to 1600 K (2420°F), whereupon coal feed was started. This was done as an experiment to determine if the coal ash would coat the chrome refractories and reduce volatilization and seed reaction. When 2000 K (3140°F) was reached, cycling was begun with 15 minutes on air, 15 minutes on gas. The burner was adjusted to produce a sample bar temperature of 1850 K (1580°F) on air and 2000 K (3140°F) on gas. The gas phase was operated at 107% excess fuel to produce a reducing condition. With these conditions, the test was run for approximately 70 hours before seed and coal were shut off and the unit was gradually brought back to ambient conditions.

3.2.2 Matrix Tests - Analytical Results

Results of the two material test heats are summarized in Tables 5, 6, and 7. The following will discuss the material with respect to the two tests together in as much as the first test provided primarily a shakedown of the test apparatus.

X-317 - Heat 105-12, Heat 106-1

In Heat 105 the position of this sample relative to the others was farthest downstream from the burner (Position 12) and it showed only surface discoloration with no apparent subsurface damage after the test. This sample was placed nearest the burner (Position 1) in Heat 106. At the conclusion of that test, only a small piece of the original test bar was found on the support shelf. No remains were found on the bottom of the duct or in the spray chamber.

Several explanations are possible. One is that the bar attrited until only a small piece remained partially protected by the support notch. A second is that it fractured due to thermal shock and the pieces fell to the bottom of the duct and dissolved in a pool of slag. Previous work has shown that the material is readily dissolved when immersed in liquid coal ash.

SEM/EDX analysis of the small portion that was recovered from the test confirmed that it was X-317 but indicated no excess of seed or ash components or disruption of the micro-structure. In our judgment, this test is an anomaly and does not reflect the expected performance of X-317.

Trans-Tech Spinel S-71, 78, 98, 110

Both S-71 and S-78 failed by thermal shock in Heat 105 (where they were in Position 1 and 2 respectively). S-98 suffered corrosion and crack damage. S-110 showed only surface damage. S-78 was not tested in Heat 106. S-110, 98 and 71 were in Positions 9, 10 and 11, respectively. S-71 and 110 showed both erosion and plastic deformation while 98 experienced erosion and multiple fracturing.

Several trends are evident in these results. As in the case of X-317, the farthest upstream location imposed a more severe environment on the material. However, even in the downstream position, degradation was quite severe with regard to surface attrition, creep and fracture. The latter may be expected in high density, fine grained ceramics subjected to a cyclic environment. However, the deformation indicated very limited hot strength at these temperatures, approximately 1900 K (2960°F).

Monofrax A and H

These materials are essentially aluminum oxide and, based on our early work, we did not expect them to resist alkali attack. While they suffered only surface damage in Heat 105, each was reduced to a small vestige in Heat 106. Failure was probably due to attack by potassium.

Monofrax E and K-3

These materials are respectively 80% and 30% chromium oxide; the remainder being alumina with other mixed oxides. Degradation modes appear similar with loss of material from the surface at rates somewhat greater than the best performing spinel. These materials both have demonstrated very good performance in slag immersion tests. It is suspected that the high vapor pressure of chromia is a major cause of degradation in this environment.

Taylor X-13233

This a a bonded stoichiometric spinel material with high (16%) porosity typical of refractory grade ceramics. In spite of this porosity, it performed very well. In Heat 106 it was in position three, which was closest to the burner after the samples at positions one and two had failed.

Cerodyne Hot Pressed Spinel

This material suffered some cracking and surface reaction in Heat 105 and further erosion and creep in Heat 106.

Taylor X-13337

This is a castable refractory compounded of fused grain magnesia alumina spinel with essentially stoichiometric composition. It was placed in the wall of the test section and appears to have performed at least as well as and perhaps better than RFG. Further evaluation is planned.

AP Green 3346 DD8

This isostatically pressed fine grained spinel suffered minor erosion but extensive crack formation.

Viscosity of Seed Residue

A viscosity measurement was made by NBS on material collected from the bottom of the matrix after Heat 104. This material was a loosely agglomerated mass with a yellowish tint.

Viscosity was measured over the range of 1340 to 1675 K and was below the range for their instrument (< 0.16 poise). It was concluded that the viscosity of this material was many times more fluid than unseeded slag. Solidification of the melt occurred at 1306 K (1891°F). The melting temperature of potassium sulfate is 1342 K (1956°F).

Some immiscibility was observed with a small amount of darker material separating on the bottom of the crucible. It was present in such small quantity that it did not influence the viscosity measurement. Analyses of samples of both phases will be reported in the future.

Fracture Behavior of Fusion Cast Spinel

SEM microstructural examination of fusion cast magnesia plus spinel (X-317) indicates a possible mechanism for resistance to thermal stress damage. The manufacturer reports that this material resists cracking and spalling like a lower density bonded refractory. In most high density ceramics (either fusion cast or sintered) once cracks initiate, they travel uninterrupted through the body.

Figure 3 shows the path of a crack. In this instance it is seen to propagate through the spinel matrix and terminate upon reaching the "loose" boundary with the magnesia. In previous reports, the presence of microcracks

between magnesia grains imbedded in the spinel matrix was noted and these microcracks are believed to confer thermal shock resistance on this material.

3.2.3 Matrix Tests - Bed Geometry

The design for the cross section to be used in the next test with this facility is shown in Figure 4. The matrix itself consists of a 9 in (229 mm) x 6 in (152 mm) brick of fusion cast spinel plus magnesia (Corhart X-317). The bed geometry in this matrix brick design consists of 1 in (25.4 mm) holes on equilateral triangular pitch and 1/2 inch (12.7 mm) webs. This geometry is considered feasible for full scale air heaters on the basis of available information to date and has been used extensively in analytical size/cost/performance studies. Testing with this geometry will provide specific information useful for such analytical studies as well as specific full scale design considerations.

Matrix testing completed during the preceding year was conducted with a matrix geometry of 3/4 inch (19 mm) holes and 1/4 inch (6 mm) webs. Thus, correlation of the performance data extracted from these tests with future matrix tests will provide information on the effect of bed geometry on bed performance.

3.2.4 Matrix Tests - Seed/Ash Deposition and Removal

The primary objective of further testing with the matrix test facility is to run for long periods, on the order of several hundred hours, without altering test conditions. This will provide a better understanding of the problems associated with seed/ash deposition and required removal from air heaters in MHD service. In order to achieve this goal, several modifications were made to the test rig in order to eliminate nuisances in operating the facility

which could require altering test conditions or shutdown of the facility.

The configuration of the test facility for the next test series is shown in Figure 5. One important design change was the removal from the system of the slag trap at the bottom of the matrix. Previous experience showed that the slag trap design did not function properly in any of the previous tests. In addition, the gas outlet from the test rig was altered to discharge directly into the lower spray chamber (following a 90° change in flow direction), thus eliminating the common length of duct for air inlet and gas outlet which often exhibited a buildup of solid material. The upper burner leg design was changed to provide a 5° slope in order to promote drainage of slag rather than pooling in the bottom of the ducting. Finally, a test section for sample bars was added upstream of the matrix in order to minimize the effect of sample materials (previously located immediately above the matrix) on the gas inlet to the matrix.

FluidDyne's laboratory facilities were also upgraded in the area of chemical analysis capabilities. The increased capabilities will be used to perform a greater number of in-house analyses of deposited seed and ash material in ducts and spray chambers, water samples from the recirculating water system, and collected seed/ash material in the baghouse. This will allow for a better correlation of matrix deposition analyses and measurements with the overall balance of material injected into the air heater and recovered downstream of it.

3.2.5 Emissions Control

A new baghouse was purchased primarily to provide emission control for the valve test facility. This baghouse will also be used for emissions control in future

testing with the matrix test facility. This baghouse is a pulse-jet type baghouse with top bag removal. The total cloth area is 600 ft^2 (59 m^2), and the length to diameter ratio of the bags is 16. The baghouse used previously was a pulse jet filter with a cloth area of 250 ft^2 (23 m^2) and a bag length to diameter ratio of 17.

Provisions will be made to sample the baghouse inlet and effluent gas for particulate, allowing baghouse efficiency measurements. Present plans call for operating the valve test facility and the matrix test facility with different mass flow rates. This will result in different air-to-cloth ratios of the baghouse and provide limited information on the effect of air-to-cloth ratio on baghouse performance with the MHD test facility exhaust. Limited efforts will be expended in this area as deemed useful during the test periods.

3.2.6 Matrix Tests - Bed Support

A stepped-arch bed support is being installed (see Figure 6). The materials for this support will be Corhart X-317, as is the matrix material. A similar concept was also used to support the previous matrix (used for Heats 100-104). The different hole size and total weight of refractory in the bed result in a slightly different stress level in the support bricks. The bricks were notched as seen in Figure 6 to allow for thermal expansion.

3.2.7 Valve Tests - Pressurization/Depressurization Effects on Insulation

The insulation scheme designed for the pressurization/depressurization tests in the valve test

facility is shown in Figure 7. During the preceding quarter, techniques were developed for fabricating the materials for this refractory lay-up. The two inner layers of insulation are shown in Figure 8. Cast bricks were used in the second layer since this allowed the use of a material of proven performance in low pressure test work in a form which would not be destroyed by pressurization. The use of materials which have performed well and have been evaluated in low pressure tests will help to determine whether any degradation is due to pressurization/depressurization effects.

3.2.8 Valve Tests - Valve Performance

Construction of the valve test facility has been delayed for several reasons. First, changes made to the design as a result of the review meeting with DOE caused a delay in letting a contract for pressure vessel fabrication. Second, delays were encountered in obtaining general and electrical contractors for required laboratory modifications. Finally, a number of ancillary equipment items, such as the baghouse, as well as the test valve itself, have not been delivered on original schedules. These delays have been reflected in a modified Milestone Plan.

Construction was begun during the last quarter and should be complete by the end of this calendar year. Valve testing will then begin as soon as the system can be shaken down.

3.2.9 Electrical Isolation

No effort was expended in this area during the last quarter. Feasibility studies for electrical conductivity measurements are expected to continue at a future date.

3.2.10 Diagnostics

A microprocessor based system developed by FluidDyne was completed during the last quarter to provide diagnostic information to the operators of the matrix facility. The system consists of pressure and temperature transducers used to compute the total mass flows being supplied to the burners in the matrix test facility system and to display this information in digital form. The system was shaken down during the two materials screening tests, Heat 105 and Heat 106, and proved to be very useful for controlling the operation of the tests.

In addition, the microprocessor system permits sequencing of automatic scanivalve pressure transducers and allows collection of the pressure data for the system in the form of punched tape. This will greatly improve the data acquisition capability during tests of the matrix facility.

3.3 Preliminary Design of a 5 MW Test Heater

During this report period, design effort was focused on the areas listed below.

- Process diagrams showing all major equipment items
- Heater conceptual design
- Hot gas and air supply systems
- Process analysis including system controls
- Cost estimate

The details of this design effort will be given separately in a topical report. A brief summary is given here.

A major effort in the conceptual heater design was directed toward developing a "hot" bed support. That is, ceramic or cooled metallic structures were devised to support the matrix bricks in the heater. These supporting schemes would permit operation of the bottom of the bed at temperatures in excess of 1370 K (2000°F). By comparison, hot blast stoves are designed with bed supports good to ~530 K (~500°F). The need for such high temperatures is apparent for directly-fired heaters. Seed in the form of potassium sulfate solidifies at 1342 K (1956°F). If the bottom of the bed were operated continuously below this temperature, it would plug due to seed deposits.

In the case of indirectly-fired heaters, if the heating gas is coal-derived then slag carry-over is almost a certainty. The only question is, how much slag carry-over. Although slag solidifies at much higher temperatures, it might

still be possible to deal with it if either

1. the bed could be heated to a high enough temperature or,
2. if slag-fluxing additives could be introduced either continuously or periodically to flush out slag deposits.

In either case, the higher the temperature at the bottom of the bed, the easier it would be to deal with slag carry-over.

Figures 9 through 13 are a process schematic and equipment layout plan and elevation views of the proposed system. These sketches show the major equipment items and how they are connected.

The system would operate much like the smaller matrix test rig which is being run currently. That is, the operation of a full-scale heater would be simulated as closely as possible. Hot gas would be generated via propane or natural gas combustion with seed and coal or ash addition. Coal combustion was considered but was rejected because of the cost and the relatively slight improvement in quality of simulation. The rationale for this decision is discussed in an appendix.

Inclusion of the bypass loop will permit continuous operation of the hot gas supply system. The added operating costs would be justified by better reliability due to reduced thermal cycling of refractories and greater ease in operation.

A significant difference between operation of the existing matrix test rig and the proposed 5 MW system is that the air heating cycle would be pressurized. With

volatile salts present - either seed in directly-fired systems or perhaps a slag-fluxing agent in coal-fueled, indirectly-fired heaters - there is the possibility of penetration of these volatiles into the refractory lining due to pressurization/depressurization cycles. Rapid corrosion of refractories could occur as a result of this penetration. The 5 MW system would permit study of this potential problem.

Process analyses including heat and material balances and control systems are described in the topical report.

4.0 CONCLUSIONS

After 850 hours of testing in a simulated regenerative heater, no deposits of slag were found in the heater passages. During the course of testing, 1590 kg (3505 lb) of seed/ash were fed. Five per cent of this material was slag. In similar tests run at other laboratories, significant quantities of slag were found deposited in the heater passages. We conclude from these tests that the presence of seed together with slag either prevented its deposition or facilitated its removal once it had deposited.

TABLE 1

DIRECTLY FIRED HIGH TEMPERATURE AIR HEATER SYSTEM CONSTRAINTS

Constraint	Value	Units	Reason
Gas Inlet Temperature	≤ 1978 (3100)	K (°F)	Maximum steady state service temperature of liner. Critical location, gas inlet ducts.
Mean Top of Bed Temperature	≤ 1922 (3000)	K (°F)	Maximum cycling service temperature of bed material.
Cyclical Bottom-of-the-Bed Solid Temperature	≥ 1400 (2060)	K (°F)	Minimum required for cyclical seed removal from bed.
Seed Dew Point Temperature	1500 (2240)	K (°F)	Nominal value.
Seed Solidification Temperature	1344 (1960)	K (°F)	Nominal value.
Bed passage hydraulic diameter	≥ 2.54 (1.0)	cm (in)	To permit cyclical seed accumulation without significant performance degradation.
Bed Passage Spacing	≥ 1.27 (0.5)	cm (in)	Mechanical limit for bed material, grain size is key factor.
Thermal stress	≤ 8100 (1175)	kPa (psi)	Mechanical limit for bed material, referenced to simplified equivalent elastic tensile stress.
Bed height	≤ 9.0 (30)	meters (feet)	Mechanical limit for bed material, creep determined.
Number of Units on Air	≥ 3.0	Vessels	To limit ripple.
Number of Units on Gas	≥ 3.0	Vessels	To limit ripple.
Air Outlet Temperature	≤ 1811 (2800)	K (°F)	Practical limit to avoid very high NTU beds.
Gas Pressure Drop	≤ 4.1 (0.6)	kPa (psid)	Practical limit for probable MHD system.
Air Inlet Temperature	≤ 1144 (1600)	K (°F)	Limited by metallic low temperature air heater capability.
Liner Thickness	23 (9)	cm (in)	Minimum for free standing cylindrical wall and for seed penetration.
Cold Face Temperature of Backup Insulation	≤ 1256 (1800)	K (°F)	To prevent seed penetration.
Outlet Air Temperature Ripple	≤ 27.8 (50.0)	K (°F)	Nominal limit for channel combustor.
Coarse Time	≥ 1800	sec	Nominal limit with regard to valve and refractory life.
Erosion Velocity Limit	$\leq 55(180)$	m/sec (ft/sec)	Nominal upper limit to prevent refractory erosion.
Valve Diameter	$\leq 3.05(10)$	m(ft)	Nominal upper limit consistent with current practices.

TABLE 2
BASE CASE DIRECT-FIRED OPERATING CONDITIONS
1000 MW_e Plant

Item

Air Flow Rate	612 Kg/sec	1350 lbm/sec
Air Inlet Temperature	1068 K	1460°F
Mean Air Outlet Temperature	1811 K	2800°F
Air Pressure Level	827 kPa	120 psia
Allowable Air Pressure Loss	34.5 kPa	5.0 psid
Maximum Air Temperature Drop	+111 K	+200°F
Combustion Products ("Gas") Flow Rate	694 Kg/sec	1530 lbm/sec
Gas Inlet Temperature	1978 K	3100°F
Mean Gas Outlet Temperature	1400 K	2060°F
Gas Pressure Level	110 kPa	16.0 psia
Allowable Gas Pressure Loss	4.14 kPa	0.6 psid
Nominal Heat Rate	550 MW	.52x10 ⁶ Btu/sec

Note: Secondary effects due to vessel heat loss, valve heat loss, valve leakage, and pressurization were included in the sizing of the air heater system. These parasitic losses were evaluated, however, and were shown to be small (less than 5% effect).

TABLE 3 INSULATION ASSUMPTIONS AND OTHER GEOMETRIC CONSTRAINTS

Mid-1978 Insulation Assumptions

Item	Inside Diameter Inches (Meters)	Material Type	Density lb/ft ³ (kg/m ³)	Maximum Thickness Inches (Meters)	Maximum Cold Face Temp, °F (K)	Material Type	Density lbm/ft ³ (kg/m ³)	Maximum Thickness Inches (Meters)	Maximum Cold Face Temp, °F (K)
Liner	>120 (>3.0)	Spinel Brick	187 (3000)	9 (0.23)	3200 (2033.0)	Castable Spinel	187 (3000)	3.0 (0.076)	3200 (2033.0)
Liner	≤ 120 (≤ 3.0)	Spinel Brick	187 (3000)	4.5 (0.11)	3200 (2033.0)	Castable Spinel	187 (3000)	3.0 (0.076)	3200 (2033.0)
Back-Up	All	Spinel Brick	85 (1400)	4.5 (0.11)	1860 (1289.0)	Castable Spinel	56 (900.0)	3.0 (0.076)	2800 (1811.0)
Outer Layer	All	Fire- brick	As re- quired	None	250 (394.0)	Castable Ins.	As required	2.0 (0.051)	250 (394.0)
Valve	All	Thin (1.0 inch, 0.0254 m) Castable				Thick Two Layer Castable			

Other Geometric Assumptions

Item	Mid 1977	Mid 1978	Units
Matrix Hole Type	Round	Square	-
Matrix Hole Pattern	Equil. Triangle	Square	-
Matrix Hole Dimension	1.0 (0.0254)	1.0 (0.0254)	Inches (meters)
Web Dimension	0.5 (0.0127)	0.5 (0.0127)	Inches (meters)
Bottom-of-Bed Thermal Stress *	1175 (8100.)	1175 (8100.)	psi (kPa)
Stand-By Units	1	1	Vessels
Clean-Out Units	1	1	Vessels

*Referenced to simplified analysis

TABLE 3 INSULATION ASSUMPTIONS AND OTHER GEOMETRIC CONSTRAINTS (Cont'd)

<u>Item</u>	<u>Mid 1977</u>	<u>Mid 1978</u>	<u>Units</u>
Pressurization Units	1	1	Vessels
Surface Temperature	450(505.0)	250 (394.0)	F (K)
Air Duct Design Pressure	150 (1030.0)	150 (1030.0)	psig (kPa)
Gas Duct Design Pressure	7.5 (52.0)	7.5 (52.0)	psig (kPa)
Manifold Velocity	170 (52.0)	85 (26.0)	ft/sec (m/sec)
Upper Plenum	Conical	Conical	
Lower Plenum	Spherical	Spherical	

TABLE 4
RESULTS OF INVESTIGATION OF MATRIX SOLUTION
ALGORITHM 24 HEATER SYSTEM

<u>Algorithm Name</u>	<u>Trids</u>	<u>SOLVE 3</u>	<u>Simult</u>
Per Iteration (sec)			
Matrix Set-up	.94	.95	.95
Matrix Solution	1.5	.5	.8
*Per Converged Solution (sec)	19.5	11.6	14.0
Matrix Set-up	7.5	7.6	7.6
Matrix Solution	12.0	4.0	6.4
Core Requirements (Full Program)	110272	50372	55310
Core Requirements (Pressure Solver)	6565	6354	5050

TABLE 5
HEAT 105/106 MATERIALS SUMMARY - PRISTINE PROPERTIES

Name	Type	Source	Physical Properties					Chemical Composition w/o									
			Modules of Rupture 293 K kPa	Bulk Den- sity ₃ g/cm ³	Porosity %	Thermal Expan- sion 0-1500 K K ⁻¹ x10 ⁻⁶	Thermal Conduc- tivity 1500 K w/m·K	Specific Heat 0-1500 K cal/cm·K	Al ₂ O ₃	MgO	SiO ₂	Fe ₂ O ₃	Cr ₂ O ₃	CaO	TiO ₂	Na ₂ O	Other
S-71	Spinel	1	N.D.	3.51	2.2	7.1	4.0		71	29	-	-	-	-	-	-	
S-78	Spinel	1	N.D.	3.41	5.0	7.8			66	34	-	-	-	-	-	-	
S-98	Spinel	1	N.D.	3.52	1.9	9.8	4.5		32	68	-	-	-	-	-	-	
S-110	Spinel	1	N.D.	3.52	1.9	11.0	5.0		16	84	-	-	-	-	-	-	
X-317	Spinel	2	40,000	3.4	6.0	11.3	4.9		31.9	67.1	0.2	0.1	-	0.5	-	0.15	
X-13233	Spinel	3	16,000	3.00	15.8												
3346	Spinel	4	63,000	3.4	6.0	11.0			59.9	39.1	0.14	0.10	-	0.15	-	-	
Monofrax A	Fused Alumina	5	40,000	3.76	1.1	7.9	7.2	0.28	99.34	-	0.08	0.06	-	0.13	-	0.39	
Monofrax E	Fused Chromia	5	39,000	4.4	5.0	7.4	4.6	0.25	4.7	8.1	1.3	6.1	79.7	-	-	0.10	
C-104	Fused Magnesia Chromia	2	8,300	3.08	12.0	11.0			8.0	56.0	2.5	11.0	20.0	0.5	1.5	-	
Monofrax K-3	Fused Alumina Chrome	5	55,000	4.0	4	7.9	2.9	0.25	60.4	6.0	1.8	4.2	27.3	-		0.3	
Monofrax H	Fused β Alumina	5	10,000	3.06	4.9	6.4	3.5	0.28	93.9	-	0.18	0.8	-	0.1	0.3	5.6	0.05
Ceradyne	Hot Pressed Spinel	6		3.51	2.2				71	29							
RFG	Magnesia Chrome	2	17,000	3.27	14.0	10.8	2.5		8.0	56	25	11.0	20.0	0.5	1.5		
X-13337	Spinel Castable	3	5,000	2.75					70	28							1.0P ₂ O ₅

¹ Trans-Tech, Inc. - Gaithersburg, MD

² Corhart Refractories Company - Louisville, KY

³ Taylor Refractories Div NL Industries - Cincinnati, OH

⁴ A.P. Green Refractories Company - Mexico, MO

⁵ Carborundum Company - Niagara Falls, NY

⁶ Ceradyne Inc. - Santa Ana, CA

TABLE 6
HEAT 105 SUMMARY

<u>Position</u>	<u>Material</u>	<u>Description</u>
1	S-71	Thermal Fracture, Several Pieces, Some Dissolution
2	S-78	Thermal Fracture, Several Pieces, Some Dissolution
3	S-98	Surface Crazing, Single Transverse Fracture, Some Erosion
4	S-110	Surface Crazing, Slight Erosion Only
5	X-13233	Slight Surface Cracking and Discoloration
6	3346	Thermal Fracture, Slight Erosion
7	Monofrax A	Slight Erosion - Retained for Heat 106
8	Monofrax E	Slight Surface Crazing
9	C-104	Slight Deformation from Preexisting Crack
10	Monofrax K-3	Transverse Fracture - Slight Surface Reaction
11	Ceradyne	Surface Crazing - Retained for Heat 106
11A	Monofrax H	Slight Surface Attack
12	X-317	Slight Surface Discoloration
Ductwall	13337	No Noticeable Change

Note: The column labeled "Position" in Tables 6 and 7 refers to the sample location in the test rig. Results of Heats 105 and 106 indicate that the position of the test sample was a significant factor.

TABLE 7
HEAT 106 SUMMARY

<u>Position</u>	<u>Material</u>	<u>Description</u>
1	X-317 (105)	90% Destroyed, Small Piece Remained on Shelf
2	Monofrax A (105)	90% Destroyed, Small Piece Remained on Shelf
2A	Monofrax H (105)	90% Destroyed, Small Piece Remained on Shelf
3	13249	Slight Deformation and Erosion
4	Monofrax E	Moderate Erosion, ~30% Material Removed
5	Monofrax K-3	Slight to Moderate Erosion, ~20% Material Removed
6	C-104	Moderate Erosion, Fissuring, and Deformation
7	Ceradyne HPS (105)	V. Slight Erosion, Single Transverse Crack, "Eyelidding"
8	B-3346	Moderate Erosion
9	S-110	Moderate Erosion and Deformation
10	S-98	Slight Erosion, Multiple Fracturing
11	S-71	Moderate Erosion and Deformation
12	RFG	Slight Attack
(13)	X-13337	Little Change

Note: The column labeled "Position" in Tables 6 and 7 refers to the sample location in the test rig. Results of Heats 105 and 106 indicate that the position of the test sample was a significant factor.

FIGURE 1 OPERATING ENVELOPE WITH RESPECT TO BED LIMIT TEMPERATURE

MHD MATERIALS TEST UNIT HEATS 105 - 106

FIGURE 2

FIGURE 3. X-317 MICROSTRUCTURE SHOWING CRACK CIRCUIT

FIGURE 4. CROSS SECTION OF MATRIX TEST FACILITY

FIGURE 5 CONFIGURATION OF MATRIX TEST FACILITY

FIGURE 6. MATRIX SUPPORT BRICKS

FIGURE 7 INSULATION SCHEME FOR PRESSURIZED SECTION OF VALVE TEST RIG

FIGURE 8. INSULATION FOR PRESSURIZED SECTION
OF VALVE TEST FACILITY

FIGURE 9 PROCESS DIAGRAM

FIGURE 10 EQUIPMENT LAYOUT - PLAN

FIGURE 11 EQUIPMENT LAYOUT - ELEVATION VIEW A

FIGURE 12 EQUIPMENT LAYOUT - ELEVATION VIEW B

FIGURE 13 FACILITY - PLAN VIEW

APPENDIX
HOT GAS SIMULATION
FOR THE 5MW MHD HEATER

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INTRODUCTION

This review was made to establish the hot gas stream simulation requirements for the 5MW heater design and, also, to provide general information for the overall program. The 5MW heater is to be capable of simulating directly-fired heater (therefore with seed and slag) and an indirectly-fired heater using clean fuel or fuel with some ash carry-over. The primary purpose is to test the heater and valve systems with "dirty" gas. Thus, the emphasis in simulation is the case with seed and slag (or slag only) in the gas stream. Under these conditions corrosion of refractories and deposition of solids are major concerns and since the chemistry of the gas and process conditions will affect both corrosion and deposition rates it is obvious that full-scale and experimental conditions should be matched as closely as is reasonably possible.

To assess the adequacy of simulation for any given situation it is necessary to know what the fullscale conditions should be. This is a problem - reliable experimental information is missing and the complexity of accurate prediction makes analytical estimates suspect. Nevertheless, the areas where uncertainty is most troublesome can be pinpointed. The most important variables will be identified and some of the information which can be used to set fullscale values will be presented. Areas of uncertainty will be identified and the seriousness of that uncertainty will be assessed.

SIMULATION GOALS

Differing simulation requirements exist for various components of an MHD system and, it is important to note that a simulation need in the combustor or channel may not be a simulation need for the heater system. Each component should be viewed separately to establish simulation needs for that particular component.

In the case of heater testing with a gas stream that contains condensible seed and/or slag, simulation needs must be assessed in view of the most important technical problems, viz:

1. corrosion of refractories, and
2. operability, i.e. to what extent will deposits of seed/slag restrict heater performance

Underlying all of the considerations regarding simulation are these two problem areas. If a variable does not affect either corrosion or operability, it may not be necessary to simulate it in heater testing. For example, the water content of the MHD gas affects electrical conductivity and hence is important in channel testing. However, within certain limits, gas phase water content does not appear to affect either corrosion or operability and hence, within limits, it is not important in heater testing.

Variables which do need to be controlled are:

- Gas inlet temperature
- Gas inlet pressure
- Gas composition
- Gas velocity

Under gas composition is included:

- Chemical composition of the gas phase
- Quantity of solid and liquid particulates
- Particle size distribution of both solids
and liquids
- Chemical composition of solids and liquids
- Degree of homogeneity of solids and liquids

With respect to the hot gas itself, there are no other variables of significant concern. There are two other equipment-related variables common to most development efforts involving scale-up, viz:

- Surface/volume ratio
- Duration of experiments (needed to estimate
corrosion, refractory life, etc.)

In discussing the simulation question both within FluidDyne and with other contractors, a variable which can be named "thermal history" of the gas stream is often cited as important. From an intuitive standpoint it is reasonable to suspect that the extreme temperatures and rates of change of temperature with time will affect the MHD gas. However, those effects must be reflected in the gas composition in some way. Hence, for the sake of this discussion, we consider the effects of thermal history as being included in the gas phase composition.

The major concerns in simulation are related to the hot gas supplied to the heater. This is so because it is both harder to define and to achieve a good simulation of gas reheat than to do the same on air heating. Nevertheless, a few comments need to be made concerning the air cycle.

An oxidizing environment must be provided to the heater refractories on air reheat and this is not a problem from an experimental viewpoint. Air temperatures at the bottom of the bed are not expected to exceed 1100 K (1500°F) in full-scale systems. In experimental systems, this temperature can be reached easily via modest vitiation. There is no evidence that the relatively small decrease in oxygen content or presence of combustion products will affect the quality of simulation.

The pressure at which air is supplied is another matter. Pressurization/depressurization cycles might affect the corrosion of heater refractories. Both seed vapor and liquid slag droplets could be forced into the pores of refractories due to pressure changes. Changes in corrosion rates could result. Both the level of pressure and the rate of change of pressure with time during pressurization and depressurization could be significant variables.

SPECIFIC VARIABLES

A list of variables was set down in the previous section and each item of this list is discussed in this section.

Specification of temperature and pressure of the hot gas is set by system considerations and the ability of refractories to cope with high temperature. The latter limitation is usually determined by a combination of extrapolation of lower temperature data and engineering judgement.

Satisfying the requirements with respect to temperature and pressure is at least straightforward. We know what values we are trying to match, and, in any case, they can be treated as independent variables.

Hot gas velocity has been set by experience in the steel industry, where flow in hot gas ducts is limited to 175-200 ft/sec by erosion considerations. Since different materials will be required in MHD service, in order to withstand attack by seed/slag, the validity of this choice can be questioned. Nevertheless, it is a reasonable place to start.

The greatest uncertainty regarding simulation centers on the gas phase composition. As indicated above, five separate areas can be identified, viz:

- Chemical composition of gas phase
- Quantity of solid and liquid particulates
- Particulate size distribution of both solids
and liquids
- Chemical composition of both solids and liquids
- Homogeneity of solids and liquids

Each of these areas is discussed below with focus on the two major heater-related concerns: corrosion and deposition of solids and liquids. There are other considerations, such as NO_x decomposition, which are not considered. The quantity of NO_x should have no bearing on either corrosion of refractories or deposition of solids/liquids. A discussion of the oxidizing/reducing environment will be given and it is understood that NO_x decomposition is an important factor which bears on whether or not an oxidizing or reducing gas is fed to the heaters.

Chemical Composition of the Gas Phase

Two considerations have a major impact on the design of test hardware. These are whether an oxidizing or reducing gas is provided and what the H/C ratio of the fuel should be. In an effort to understand the impact of choices of fuel and the oxygen partial pressure of the combustion products we had some equilibrium calculations run. Dr. E. Plante of the National Bureau of Standards performed the computations based on a request from Mr. Kevin Drake of FluidDyne⁽¹⁾. Results are discussed here for three different fuels of varying H content. Figures 1 and 2 are plots of gas phase mole fractions of

In all cases the total mole per cent of K was set at 1%. Figure 1 shows results for 5% oxidizing conditions and Figure 2 for 5% reducing conditions.

The knee in the curve of K_2SO_4 vs T occurs at the point where seed begins to condense. Under reducing conditions the dew point is ~ 1500 K, oxidizing - 1600 K. Under reducing

conditions significant quantities of O_2 -lean salts (such as K_2S) should form since significant quantities of H_2S and KOH are both present. Under oxidizing conditions, P_{H_2S} is $< 10^{-6}$ and significant amounts of K_2S should not form as explained below.

Potassium oxide (K_2O) is unstable in the gas phase of temperatures characteristic of heater testing and, therefore, potassium sulfide (K_2S) may also be unstable. However, K_2S does have a well-defined melting point and the analogous sodium compound, sodium sulfide (Na_2S) is recovered as a liquid from recovery boilers used in the Kraft process for making paper. Hence, we expect that under reducing conditions K_2S will be a part of the liquid salt condensate in heaters.

Potassium sulfide can form via either a vapor phase or heterogeneous reaction as indicated below:

Refractory corrosion could be influenced by the presence of K_2S in either the gas or liquid state. Operability could also be affected due to a change in melting point. Subsequent treatment of seed (regeneration) will certainly depend on its composition.

The amount of K_2S which will form depends on whether reducing conditions are present. Hence, test rigs should be designed so that either oxidizing or reducing atmospheres can be supplied, and tests should be run under both conditions.

There are direct effects on refractories due to variations in oxygen partial pressure. In general, cycling refractory

materials between oxidizing and reducing environments leads to poor life. In the specific case of iron-containing refractories, it is known that valence changes of iron can cause severe damage. In the even more specific case of MgO Al_2O_3 spinel, exposure to iron and oxidizing/reducing cycles can result in the so-called "bursting" phenomena, a swelling and weakening of the structure.

Because of these well-known effects due to oxidizing/reducing cycles, there is a need to be able to vary the oxygen partial pressure in the hot gas supply to the test heater.

The previous discussion has been focused on the oxygen partial pressure. Another concern is the water vapor content of the combustion products fed to the heater. This is determined largely by the hydrogen content of the fuel. Figures 1 and 2 shed some light on the effects of water vapor on seed dew point and liquid seed composition.

These curves imply that the water content in the gas phase does not affect either seed dew point or liquid seed composition significantly. Water vapor partial pressure was found to vary from about 0.06 to 0.15 atm depending on the hydrogen content of the fuel. In none of the cases did the amount of water in the vapor phase change significantly over the temperature range of 1200 - 2000 K. This suggests that enough water was present even in the most hydrogen-lean case so that it never became a limiting reactant in any reaction in which it was a participant.

Quantity of Solid and Liquid Particulates

The quantity of solids and entrained liquids carried into the heater by the MHD exhaust is ill-defined. It depends on a number of factors including the quantity of

slag rejected by the combustor and the amount lost from the gas phase onto the walls of the duct, diffuser, and radiant boiler. However, this is not such a serious problem from a testing standpoint. It simply means that the amount of slag could be treated as a variable and tests run at two or more different levels.

Particle Size Distribution of Both Solids and Liquids

Various models of the deposition process have been proposed in which it is assumed that deposition rates depend on particle size distribution. Some experiments have been run which tend to confirm this assumption.⁽²⁾ Differences in deposition rates for slag particles of different size range have been observed.

The particle size distribution which can be expected at the heater entrance in a full-scale system cannot be predicted and we do not know of any experimental measurements that help define it. One could treat particle size distribution as an independent variable and test with at least two different distributions. But, before doing that, one should be satisfied that the effect is large enough to justify the effort of including it as a variable.

Chemical Composition of Both Solids and Liquids

In the heater, both liquid seed and slag may be present. The liquids are not miscible and need to be considered separately.

Seed

As noted earlier, the oxidizing/reducing environment will affect the composition of the liquid. As the oxygen partial pressure is reduced, the concentration of oxygen deficient potassium compounds like K_2S will increase. Both the freezing point and the corrosive nature of the liquids will be affected. In full-scale systems the composition of the liquid seed in the heater should be determined largely by the gas phase oxygen partial pressure, the seed species originally fed, and the sulfur content of the coal. If good sulfur pick-up by the seed is achieved, and if oxidizing conditions are maintained, then the seed will be a mixture rich in K_2SO_4 . If reducing conditions are maintained, the seed will be relatively lean in K_2SO_4 and have a somewhat lower melting point. From an experimental standpoint the oxygen partial pressure needs to be varied so that the effects of different seed composition can be determined.

Slag

In the MHD combustor, temperatures will be hot enough to vaporize silica and other slag components and the possibility of fractionation of slag exists. A less volatile slag fraction, lean in silica, may be rejected by the combustor or be collected in the diffusor or radiant boiler.⁽³⁾ The extent to which this might occur depends on many factors including the combustor design.

The previous paragraph describes a specific difference in composition which could exist between slag entering an MHD heater and ash from the coal. In addition, there is a concern that is harder to define which is related to the time-temperature history of the MHD gas stream. Cooling

rates and temperature ranges in various MHD components are indicated below:

<u>Component</u>	<u>Cooling Rate</u>	<u>Temperature Range</u>
Duct	$\sim 10,000-30,000^{\circ}\text{K/sec}$	2200-2600 °K
Diffuser	$\sim 7,000^{\circ}\text{K/sec}$	2200-2400 °K
Radiant Boiler	$\sim 500^{\circ}\text{K/sec}$	2000-2200 °K

In the combustor and at the duct entrance, temperatures are in the range where SiO_2 has significant vapor pressure. One would expect SiO_2 which has vaporized to condense as the gas passes through the duct. Cooling rates are so high that fume should form. The nature of the slag which emerges from this process is hard to predict.

Certain questions come to mind:

How uniform is it?

How much seed has been absorbed?

and more generally -

Does it behave the same way as slag produced from lower temperature combustion?

If the only concern relative to slag behavior in a heater were its silica content, one might be able to cope with that. Perhaps feeding additional silica would permit the study of the effect of silica enrichment. However, the last question above, relative to slag behavior is harder to answer. Of all the uncertainties in simulation, questions regarding slag composition and physical characteristics are

the hardest to answer and affect the credibility of heater test results the most.

CONCLUSIONS

Before applying the considerations of this study to the selection of hot gas simulation hardware, it will be useful to summarize our thinking.

- (1) Variables which can be specified reasonably or treated as independent variables are:

- Temperature
- Pressure
- Gas Velocity
- Quantity of seed and/or slag

- (2) The greatest concern relative to quality of simulation is due to uncertainty about gas phase composition.

- (3) With respect to chemical composition of the gas phase, whether a reducing or oxidizing environment is provided affects:

- Seed dew point
- Composition and physical properties of liquid seed
- Composition and physical properties of slag

- (4) Variables such as:

- Slag composition
- Slag particle size distribution
- Physical character and homogeneity of slag

cannot be predicted and could affect the credibility of heater testing.

- (5) Equilibrium computations can be used to predict the composition of liquid seed.
- (6) Test results in the form of analyses of seed deposits can be used to check the validity of these predictions.
- (7) Over the range of water contents resulting from combustion of hydrogen-lean and hydrogen-rich fuels, the effect of water partial pressure is small. This implies that combustion of propane or methane with coal injection as an ash source should be nearly as acceptable in terms of simulation as coal combustion, other things being equal.
- (8) Both the pressure level and rate of change of pressure with time can affect the amount of seed and slag which penetrates refractories. Test rigs should be designed so that both the pressure level and rate of change of pressure with time on the air cycle can be varied.

TABLE 1. A Comparison of Hot Gas Simulation Systems

Fuel	Slag Source	Temp	Ox/Red	Relative Cost
Propane/Methane	Flyash	~ 3300°F	Vitiation(a)	1.0
Propane/Methane	Coal	~ 3300°F	Vitiation(a)	1.03
Propane/Methane	Coal	~ 3700°F	Air Preheat and downstream cooling (DC) (b)	1.1
Coal	Coal	~ 3700	Air preheat and DC	1.4
Coal	Coal	~ 4700	Air preheat and Rapid DC (c)	2
Coal	Coal	~ 4700	Channel, etc.	>>2

- (a) Vitiated air feed to combustor provides controllable oxygen partial pressure and inlet T at combustor.
- (b) Downstream cooling - radiant cooler downstream of combustor and upstream of hot gas inlet valve.
- (c) Rapid downstream cooling would be by water spray injection. If water were added at a rate of 50 to 100% of combustion product flow, then with combustion product T of 4700°F, get T of ~ 3300°F and cooling rate ~ 10,000°K/sec.

Application to the Design of Experimental Test Rigs

The previous discussion has been directed toward quality of simulation only. When considering actual test hardware, other factors must be included viz, cost and reliability. In this section, a series of possible hot gas simulation schemes is described and evaluated.

Six possible systems were considered and the results of evaluating them are summarized in Table 1. Fuel, source of slag, combustion temperature, and the method used to provide a reducing gas are shown along with criteria used to characterize each system. The schemes are listed in order of increasing quality of simulation.

Three systems utilized either propane or methane as fuel; the other three utilized coal. In the simplest scheme, fly ash would be the slag source. A slightly more complex scheme would use coal. The most complex case not including a channel would involve a coal combustor using pre-heated air followed by rapid cooling via water spray injection. Not shown explicitly are all of the extra hardware requirements e.g. in the case just mentioned, a coal preparation and supply system along with air pre-heaters would be required.

The last column in the table is the ratio of cost of a given scheme to the cost of the simplest system. As the quality of simulation increases, so does cost.

Comparing these possible schemes impresses one with the uncertainty in assessing quality of simulation and also the cost one would incur in trying to achieve a better simulation. It is our judgment in the face of both the uncertainty in ranking these schemes and the costs involved that the simplest systems are the best. Hence, a gas-fired combustor has been selected for the 5MW heater.

Fig. 1 Gas Phase Mole Fractions of K_2SO_4 & KOH For Combustion Products
Seeded With 1% K at 105% Stoichiometric Air;
Three fuels, Propane, $CH_{1.5}$, & Coal $CH_{.78}$

Fig. 2 Gas Phase Mole Fractions of K_2SO_4 & KOH For Combustion Products Seeded With 1% K at 95% Stoichiometric Air; Three Fuels, Propane, $CH_{1.5}$, & Coal $CH_{.78}$

REFERENCES

- (1) Support Testing & Design Study;
Evaluation of Regenerative Air Heaters -
Fourth Quarter Report, October - December, 1976,
FluidDyne Engineering Corporation, Contract No. E (49-18) - 2254
- (2) Professor Harry Townes, Department of Mechanical Engineering
Montana State University, Private comm.
- (3) Heywood, J.B. & G.B. Womack,
Open Cycle MHD Power Generation pp 282 ff. Pergamon (1969)
Attempts at verifying silica vaporization and resultant
loss of silica from slag were not successful as documented
here.