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MHD AIR HEATER DEVELOPMENT TECHNOLOGY

Progress Report for Period November 26, 1979—March 31, 1980

NTIS-25
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May 1980

Work Performed Under Contract No. AC01-80ET15602

FluidDyne Engineering Corporation
Minneapolis, Minnesota

U. S. DEPARTMENT OF ENERGY

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MHD AIR HEATER
DEVELOPMENT TECHNOLOGY

Progress Report
For the Period

November 26, 1979 - March 31, 1980

Prepared for
United States Department of Energy
Division of Magnetohydrodynamics
Under Contract # DE-AC01-80ET15602

Prepared by
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Minneapolis, Minnesota 55422

Fluidyne Job 1228

May, 1980

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1.0 OBJECTIVE AND SCOPE OF WORK

Work to be done under this Contract will continue the technology development of the directly-fired high temperature air heater (HTAH) for MHD power plants. The work will extend the efforts begun under previous ERDA/DOE contracts, the most recent being Contract ET-78-C-01-3005. The Statement of Work specifies work to be done under three tasks as described in the following.

Task 1 - Materials Selection, Evaluation, and Development

The objective of this task is to continue development of ceramic materials technology for the directly-fired HTAH. The scope of the work under Task 1 will include compilation of materials data, materials selection for testing and design studies, materials property determination, liaison with refractory manufacturers and other organizations to encourage development of materials and fabrication technology, establishment of preliminary HTAH material specifications, analyses of test materials, and development of criteria for thermal stress limits for crack-tolerant refractory materials.

Task 2 - Operability, Performance, and Materials Testing

The objectives of this task are to demonstrate the technical feasibility of operating a directly-fired HTAH (including both the heater matrix and valves), to continue obtaining information on life and corrosion resistance of HTAH materials, and to obtain design information for full-scale studies and future design work. The scope of the work will include tests in the Matrix Test Facility (MTF) and Valve Test Facility (VTF) built and operated under contracts EX-76-C-01-2254 and ET-78-C-01-3005, emissions measurements in the MTF and VTF, design of a dilatometer for performing

creep measurements in the directly-fired HTAH environment, and characterization of the effluent air stream from the MTF.

Task 3 - Full-Scale Design Concepts

The objectives of this task are to begin the identification of HTAH control requirements and control system needs, and to continue full-scale study efforts incorporating updated materials and design information in order to identify development needs for the HTAH development program. The scope of the work will include size/cost analyses and parametric studies of design options using a size/cost code and other computer codes developed and refined under Contracts EX-76-C-01-2254 and ET-78-C-01-3005, dynamic HTAH system performance calculations using the SCAMP (System Cyclic Analysis of Multiple Preheaters) computer code developed under Contract ET-78-C-01-3005, preparation of system layouts and cost estimates, screening and definition of control systems and determination of operating methods, definition of requirements for a future test facility to test matrix support concepts at nearly full-scale, and development of design concepts for alternative heater systems and electrical isolation of the air duct from the MHD combustor.

1. Contract Identification		2. Reporting Period		3. Contract Number																							
MHD AIR HEATER TECHNOLOGY		Nov. 26, 1980 through Mar. 31, 1980		DE-AC01-80ET15602																							
4. Contractor (name, address)				5. Contract Start Date																							
FluidDyne Engineering Corporation 5900 Olson Memorial Highway Minneapolis, MN 55422				November 26, 1979																							
				6. Contract Completion Date																							
				November 25, 1980																							
7. Identification Number	8. Reporting Category (e.g., contract line item or work breakdown structure element)	9. Fiscal Years and Months												FY 81												10. Percent Complete	
		N	D	J	F	M	A	M	J	J	A	S	O	N						a) Planned	b) Actual						
1.1.1	Material Selection																									40	40
1.1.2	Property Determination																									35	35
1.1.3	Liaison																									35	35
1.1.4	Specifications																									0	0
1.1.5	Materials Analyses																									10	10
1.1.6	Thermal Stress Criteria																									35	35
1.2.1.1	MTF Inst./Data Acq.																									35	35
1.2.1.2	MTF Modifications																									0	0
1.2.1.3	MTF Testing																									0	0
1.2.1.4	MTF Analysis/Reporting																									0	0
1.2.2.1	VTF Inst./Data Acq.																									100	100
1.2.2.2	VTF Modifications																									100	100
1.2.2.3	VTF Testing																									40	35
1.2.2.4	VTF Analysis/Reporting																									0	0
11. Remarks																											
Detail by WBS																											
12. Signature of Contractor's Project Manager and Date										13. Signature of Government Technical Representative and Date																	
6-11-80																											

1. Contract Identification MHD AIR HEATER TECHNOLOGY										2. Reporting Period 26 Nov. 1980 through 31 March 1980										3. Contract Number DE-AC01-80ET15602										
4. Contractor (name, address) Fluidyne Engineering Corporation 5900 Olson Memorial Highway Minneapolis, MN 55422																				5. Contract Start Date November 26, 1979 6. Contract Completion Date November 25, 1980										
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				FY 80												FY 81														
				N	D	J	F	M	A	M	J	J	A	S	O	N													a) Planned	b) Actual
1.2.3		Emissions Measurements																										0	0	
1.2.4		Creep Testing Apparatus																										0	0	
1.2.5		Effluent Air Stream																										0	0	
1.3.1		Size/Cost																										35	35	
1.3.2		SCAMP																										35	35	
1.3.3		Layout Drawings																										35	35	
1.3.4		Cost Estimates																										0	0	
1.3.5		Control Systems																										5	5	
1.3.6		Matrix Support Test Facility																										5	5	
1.3.7		Alternative Heater Systems																										0	0	
1.3.8		Electrical Isolation																										0	0	
11. Remarks Detail by WBS																														
12. Signature of Contractor's Project Manager and Date <i>[Signature]</i> 6-11-80												13. Signature of Government Technical Representative and Date																		

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MILESTONE LOG

Identification Number	Description	Completion Date		Comments
		Planned	Actual	
1.1.1A	Select. Matls for Full Scale	Jan 80	Jan 80	
1.1.1B	Select. Matls. for Matrix Test	May 80		
1.1.1	Materials Selection	Sep 80		
1.1.2	Property Determinations	Nov 80		
1.1.3	Liaison	Nov 80		
1.1.4	Specifications	Nov 80		
1.1.5A	Analysis of Matrix and Valve Test Samples. Heat 202, VTF 1&2	Dec 79	Dec 79	
1.1.5B	Analysis of Valve Test Samples	July 80		
1.1.5C	Analysis of Matrix Test Samples	Oct 80		
1.1.5	Materials Samples Analyses	Nov 80		
1.1.6	Thermal Stress Criteria	Nov 80		
1.2.1.1	Instrumentation/Data Acquisition	Aug 80		
1.2.1.2A	Design Hot Gas Supply Duct	Jun 80		
1.2.1.2B	Test Hot Gas Supply Duct	Jul 80		
1.2.1.2	Reassemble Matrix	Aug 80		
1.2.1.3	Matrix Test	Sep 80		
1.2.1.4	Matrix Analysis/Reporting	Nov 80		
1.2.2.1	Instrumentation/Data Acquisition	May 80		
1.2.2.2A	Replace Valve Castable	Dec 79	Dec 79	
1.2.2.2	Reassemble VTF	Feb 80	Feb 80	
1.2.2.3	Valve Test	May 80		
1.2.2.4	Valve Analysis/Reporting	Nov 80		
1.2.3A	Assemble Hardware	Aug 80		
1.2.3	Emissions Measurements	Sep 80		
1.2.4	Creep Testing Apparatus	Nov 80		
1.2.5A	Assemble Hardware	Aug 80		
1.2.5B	Measurements	Sep 80		
1.2.5	Characterize Effluent Air Stream	Nov 80		

Identification Number	Description	<u>Completion Date</u>		Comments
		Planned	Actual	
1.3.1A	Define Base Case Dimensions	Dec 79	Dec 79	
1.3.1	Complete Parametric Studies	Nov 80		
1.3.2A	Design Point Performance	Feb 80	Feb 80	
1.3.2B	Off Design Performance	Jun 80		
1.3.2	Complete Performance Studies	Nov 80		
1.3.3	Critical Component Design Concepts - Base Case	Nov 80		
1.3.3A	Layout Drawings	Apr 80	Apr 80	
1.3.4	Cost Estimate	Nov 80		
1.3.5	Control Concepts	Nov 80		
1.3.6	Matrix Support Test Facility	Nov 80		
1.3.7	Alternate Heater Systems	Nov 80		
1.3.8	Electrical Isolation	Nov 80		

2.0 SUMMARY

During the reporting period from November 26, 1979 through March 31, 1980 contract negotiations were being carried out with DOE. Since FluidDyne was not under contract during this period, the level of effort was reduced somewhat compared to a steady expenditure rate over the entire performance period of November 26, 1979 through November 25, 1980. This initial reduction in expenditures is reflected in the Management Plan.

Under Task 1, efforts were carried out in several areas. Work on the computer data base for material properties was begun. Data was compiled for several HTAH materials. Materials selections for Valve Test 3 and full-scale studies were made. Test conditions were defined for and creep results obtained from Montana College of Mineral Science and Technology concerning candidate matrix and hot liner materials. Liaison efforts with refractory manufacturers were continued, and information was provided to Argonne National Laboratory and Babcock and Wilcox concerning the HRSR design. Analyses of materials samples from previous matrix and valve tests under Contract ET-78-C-3005 were completed. Finally, a thermal stress cycling experiment to be carried out at Montana Tech was designed.

Under Task 2, efforts were directed toward running Valve Test 3. Problems were encountered with the VTF hot gas supply duct which necessitated two intermediate shutdowns without reaching the final test goal of 300 hours. Modifications necessary to complete the test were begun.

Under Task 3, an example HTAH system was defined which will be used as a focal point for screening and definition of control systems and determination of operating methods. The system was defined using the size/cost and other HTAH computer codes. A layout of the system was made, and steady state performance was calculated with the SCAMP code.

3.0 DESCRIPTION OF TECHNICAL PROGRESS

3.1 Task 1 - Materials Selection, Evaluation, and Development

The work under Task 1 during the reporting period included compilation of materials data, selection of materials for Valve Test 3 and for full-scale studies, creep work with the Montana laboratories in defining material properties, liaison efforts with refractory manufacturers, analysis of materials from the MTF (Heat 202) and VTF (Tests 1 and 2), and design of a thermal stress cycling experiment for refractory materials.

3.1.1 Materials Selection

Work was begun on a computerized data base for compiling engineering data on HTAH materials. The data base will be arranged in a format such that it is accessible by Fluidyne's size/cost and performance computer codes and is readily accessible for editing whenever new or updated data is available. The information stored in the data base will include, for each of the materials compiled:

- 1) Manufacturer's designation
- 2) Generic designation
- 3) ASTM designation (if any)
- 4) Method of fabrication
- 5) Manufacturer's name and address
- 6) HTAH application (including service condition restrictions)
- 7) Experience to date in MHD testing
- 8) Composition
- 9) Mixing and curing instructions (for castables)

- 10) Data source and estimate of validity for engineering calculations
- 11) Cost information
- 12) Materials properties including density; porosity; temperature dependent values of modulus of elasticity, Poisson's ratio, thermal conductivity, specific heat, thermal stress limit, thermal expansion coefficient, electrical conductivity, modulus of rupture, compressive strength, critical stress intensity factor (K_{IC}); and load and temperature dependent values of creep rate.

This information will provide the basis for size/cost and performance studies under Task 3 and for future design of HTAH systems.

Much of this data has been compiled for five materials as shown in Tables 1-5. These materials are Corhart X-317, Norton LS-812 castable, Johns Manville Yuma, C-22Z, and Superex 2000. Corhart X-317 is a fusion cast magnesia-spinel suitable for the directly-fired heater matrix and hot liners. Norton LS-812 is a stoichiometric spinel castable suitable for hot liners (or for the matrix at temperatures below 1589 K (2400 F)). The Johns Manville materials are suitable for backup insulation, allowing no contact with the directly-fired reheat gas. The data was extracted from References 1 through 5. If no reference is indicated in Tables 1-5, the values represent estimates by FluidDyne.

Materials and insulation layups were selected for the FY 80 case (see Section 3.3) for a full-scale HTAH. These material layups will be used in all of the size/cost and performance calculations under Task 3. A summary of the 21 areas for which materials and layups

were selected is shown in Table 6. An example of one of the areas, the gas inlet duct, is shown in Table 7.

Materials were also selected for the modifications made for Valve Test 3 (see Section 3.2). Before the start of this test, Norton LS-812 castable was selected for use as the insulation in the test valve and in part of the VTF hot gas supply duct. This calcium aluminate bonded, stoichiometric spinel castable had shown excellent performance as the valve insulation and as a matrix hot liner in tests under contract ET-78-C-01-3005. A second stoichiometric spinel castable, Taylor X-13337, was also used as valve insulation in these earlier tests but showed poor corrosion/erosion resistance.

In Valve Test 3, the LS-812 used for valve insulation continued to show good corrosion and erosion resistance. However, in the high temperature region of the hot gas supply duct downstream of the combustor, the LS-812 showed significant erosion and reaction with the gas stream, and was replaced with Corhart RFG, rebonded fused grain magnesia chrome. This material was used originally in the VTF duct and performed better than the LS-812 during Valve Test 3.

Material selection for the hot gas supply ducts of the test facilities, where the simulated MHD gas is produced through combustion of propane and injection of solid seed and ash particles, remains the most difficult problem in the subscale test program. Both the gas temperature, on the order of 2033 K (3200 F) or greater and the need for vaporizing seed and melting ash (resulting in solid and liquid particles in the stream for some distance) represent more severe corrosion/erosion conditions than will exist in an actual directly-fired HTAH.

Future work under this subtask will include selection of materials for the MTF testing which will be conducted under this Contract and programming of the data base for information retrieval and editing.

3.1.2 Property Determination

The objectives of this subtask are to define needs and test conditions for HTAH material property determination work being carried out at other laboratories and to interpret the results in terms of the materials data base.

During the reporting period, high temperature deformation data has been measured for Corhart X-317 and Norton LS-812 by Montana College of Mineral Science and Technology. The test conditions were specified by FluidDyne. The measurements consisted of creep curves for X-317 and creep curves, activation energy, and stress exponent for LS-812.

The results of the Montana Tech measurements are shown in Figures 1-4. The activation energy Q and stress exponent n are determined for an assumed steady state stress model, i.e.,

$$\dot{\epsilon} = A (\sigma/G)^n e^{Q/RT}$$

where:

$\dot{\epsilon}$ = steady state creep
 A = constant $\cdot T^{-1}$
 σ = stress
 G = shear modulus
 R = gas constant
 T = temperature

The X-317 material is shown to expand even under compressive loads up to 2.8 MPa (406 psi). Compressive creep is seen at higher stresses. The cause of this behavior is presently under investigation. The LS-812 exhibits more typical compressive creep behavior.

Future work will be directed toward obtaining and improving information for the materials data base as outlined in Section 3.1.1.

3.1.3 Liaison

Discussions have been held on a continuing basis with a number of refractory manufacturers. As a result of Fluidyne's liaison work, Norton Company has begun development work on a sintered spinel brick. This material would have properties similar to other high temperature materials already manufactured by Norton with the additional advantage of corrosion resistance for the HTAH environment. Another result of the liaison efforts has been a development program for MHD materials begun by Carborundum. Materials developed by these and other manufacturers will be tested in the sub-scale test facilities (VTF and/or MTF).

Information was provided to Babcock and Wilcox concerning material selection for the HRSR during the reporting period. Fluidyne's materials testing experience in the MTF and VTF as well as earlier materials screening work was shared in response to inquiries from Argonne National Laboratory and Babcock and Wilcox.

The primary goal of future liaison work will be to encourage development of manufacturing techniques for fusion cast cored brick shapes and of castable insulation suitable for the HTAH.

3.1.4 Specifications

The objective of this task is to develop preliminary specifications for the refractory materials needed in the HTAH. No effort was expended on this subtask during the reporting period.

3.1.5 Materials Analyses

Materials analysis results obtained during the reporting period included analyses of three spinel-based refractories in their pristine condition, deposits of material from the matrix flow passages from Heat 202, and refractory samples and deposits from Valve Tests 1 and 2.

Table 8 shows the compositions of Norton LS-812 castable, Taylor X-13337 castable, and Corhart X-317. The castables are the stoichiometric spinels used as insulation for the test valve as described in Section 3.1.1.

A startling result is the absence of phosphate in the Taylor material which has been called a "phosphate bonded" castable. The analyzed sample was removed from the test valve by the valve manufacturer prior to testing. The absence of phosphate could well explain the lack of green strength and subsequent poor performance of this material as opposed to more favorable test results which had been obtained using samples of this material in the MTF. The "corundum" in this material may well have been calcium hexaluminate which probably acted as the bonding agent for casting in the valve. Both of the castables differed slightly from the actual stoichiometric ratio of 28% MgO to 71% Al_2O_3 .

Analysis of the material deposited in the matrix flow passages during Heat 202 is shown in Table 9. It had been postulated earlier that these deposits consisted of degradation products from the X-317 hot liner in the hot gas supply duct, which had deteriorated badly and flowed into the matrix. The analyses in Table 9 verify this assumption. As in the case of deposits from Heat 201, presented in previous reports, the magnesia content of the deposits (37-47%) is far greater than that of Rosebud coal ash (7%). In the Heat 202 deposits the alumina content (38-52%) also greatly exceeds that of Rosebud ash (20%) in the deposits near the top of the matrix. Calcia and iron oxide are also present in the deposits, but at levels (1-4%) greatly reduced from coal ash (15% and 7%, respectively). Thus the deposits are seen to consist of reaction products of the hot gas supply duct liner and the injected coal ash. The character of the deposits varied with position in the matrix, the alumina content decreasing and the magnesia and silica increasing as the deposits flowed toward the bottom of the matrix.

Analyses of test valve refractories and deposits removed after Valve Test 2 are shown in Table 10. A number of results can be observed. The gate area, which is shielded from the gas stream during the gas phase, showed minimal chemical change to the refractory insulation. The other areas of the valve, such as the body and the follower ring, which were exposed to the gas stream all exhibited a decrease in alumina and often showed formation of potassium aluminum silicate (KAlSiO_4). This may be due to reaction of K_2O with Al_2O_3 from the bond phase, since even in the Taylor castable alumina apparently plays a part in the bonding. The iron content is probably due to the presence of steel reinforcing fibers in the valve insulation. Little unreacted ash is seen, even in the deposits on the floor of the gate cavity. These deposits are seen to be degraded refractory, having reacted with both seed and ash, and are thought to be the cause of scratches on the valve seats (see Section 3.2.2).

In general, the refractory in contact with the gas is seen to be undergoing reactions with both seed and ash. Further analysis of the Norton material will be made after longer testing time has been achieved.

3.1.6 Thermal Stress Criteria

As the first step in developing design information for HTAH materials that relates stress and fracture to thermal cycling, an experiment was designed to subject solid cylindrical samples to cyclic thermal stresses. The stresses generated are comparable to those which a cored matrix brick would experience in a full-scale HTAH. The cyclic temperature and stress are shown in Figure 5.

The experiment will be carried out by Montana Tech. A furnace meeting the specifications for the thermal stress cycling experiment is being built.

3.2 Task 2 - Operability, Performance, and Materials Testing

During the reporting period all efforts under Task 2 were directed toward completion of Valve Test 3.

3.2.1 Matrix Test Facility (MTF)

No effort was expended under this subtask during the reporting period. Future efforts will include redesign and testing of the MTF hot gas supply and running of Heat 203 in the MTF. The gas supply work will be done to insure that refractory degradation in this duct will not prevent a successful long term operability test as occurred under Contract ET-78-C-01-3005 (Heats 201, 202). Heat 203 will have a duration of at least 300 hours and is intended to demonstrate operability of the cored brick matrix over long duration without fouling of the flow passages by seed/slag deposits.

3.2.2 Valve Test Facility (VTF)

The overall objectives of testing in the Valve Test Facility are to assess reliability and performance of directly-fired HTAH sequencing valves and to assess the effects of pressurization/depressurization cycles on vessel and valve insulation materials. Concerns related to reliability and performance of valves include the capability to operate in the HTAH service environment; corrosion, erosion, and cracking resistance of castable refractories used for valve insulation; and assessment of valve leakage, wear, and heat loss.

Valve Tests 1 and 2 were run under Contract ET-78-C-01-3005. The specific objectives of the tests were to shake down the facility and establish baseline data on the test valve and vessel insulation performance under clean flow conditions during Test 1, and to operate the VTF for several hundred hours with seed/ash injection to begin the evaluation of the overall objectives as stated above during Test 2.

The objectives of Test 1 were satisfactorily achieved. Test 2 was terminated after 55 hours of testing, short of the intended goal, when the test valve leakage increased suddenly. Inspection of the valve showed that degradation of the phosphate bonded spinel castable insulation used in the bulk of the valve had apparently caused scratching of the valve seats, and the increased leakage was attributed to this. The calcium aluminate bonded spinel castable, Norton LS-812, which was used in only the outlet throat of the valve held up well. In Test 2, basic feasibility of operating a gas inlet valve under HTAH service conditions was demonstrated and initial measurements of valve leakage and heat loss and thermal conductivity of the insulating refractories over the course of operating with pressure cycling

and seed/ash injection were made. Thus, most of the test objectives were met; the single objective of operating for several hundred hours was not met due to the failure of the phosphate bonded castable.

During the reporting period, as a result of the observations from Tests 1 and 2, the valve insulation material was removed and replaced entirely with Norton LS-812 and Valve Test 3 was begun. The objective of Test 3 is to extend the operating time of the test valve for a longer duration than achieved during Test 2 and continue the evaluation of the overall VTF objectives. Since the test valve leakage was still small (even though it had increased during Test 2), the valve seats were left in the condition they were in following Test 2. No seed/slag deposits were evident.

A second modification to the VTF was also made. During Tests 1 and 2, the flow rate through the main burner was limited by flow instability resulting in extensive vibrations of the VTF at the design flow rate. For example, Test 2 was run with a flow rate of 0.16 kg/sec (1245 lbm/hr) instead of the intended 0.20 kg/sec (1556 lbm/hr). In order to correct this deficiency before running Test 3, the hot gas duct inside diameter was increased from .15 m (6 in) to .28 m (11 in) in the lowermost section of the VTF. The duct liner chosen for this section was LS-812 as explained in Section 3.1.1. A transition from the new expanded diameter to the existing .15 m (6 in), RFG lined duct was made by removing part of the RFG liner immediately above the new burner section.

Valve Test 3 was started on February 25. The full design flow rate was readily achieved with the burner modification described above. However, after 55 hours of operation with seed/ash injection, the flow rate had decayed to approximately 70% of the design flow and become very erratic, accompanied by recurrence of the vibration problem. The facility was shut down for inspection at this point, and it was found that the main burner opening had become partially blocked by a thin slag-like layer and that the LS-812 castable has deteriorated and eroded substantially.

The main burner section was then relined with an RFG liner, as discussed in Section 3.1.1. In addition, a cylindrical insert was added to the burner outlet, extending the burner throat by .15 m (6 in) and providing an area for accumulation of slag without restricting the burner opening. Test 3 was restarted on March 24. However, after 50 hours of operation with seed/ash injection, the thinner than normal RFG hot liner in the transition section from the .28 m (11 in) combustion chamber to the .15 m (6 in) duct cracked and failed. As a result, the backup insulation material was attacked by the hot, seed/ash laden gas stream. Insulating firebrick flowed into the gas supply duct, filling in the slag accumulation region around the cylindrical insert at the bottom of the test channel and depositing on the walls of the gas supply duct and the test valve cavity and seats.

This insulation failure caused a second shutdown of the facility. All sections of the VTF gas supply upstream of (below) the test valve were removed, and the refractory will be replaced. The test valve gate was also removed for cleaning and removal of the firebrick deposits. When these repairs are completed, the VTF will be reassembled and Test 3 will be restarted. The additional costs incurred due to the two shutdowns and required repairs may result in a necessary reduction in efforts in the MTF testing later in the project.

Preliminary analysis of the pressure- and temperature-time histories from Test 3 have indicated that the test valve leakage during operation of the facility did not vary significantly during the course of operation of the VTF. However, reduction of the raw data is not complete.

A significant observation during Test 3 was that the test valve leakage appears to be less during periods of operation with seed/ash injection than with clean flow. Figures 6 and 7 are extracted from the pressure/temperature strip chart recordings made during Test 3. Figure 6 indicates two successive cycles of the test valve; during the first cycle seed/ash injection was underway, while during the second cycle the reheat gas was clean. The recording clearly indicated an increase in the pressure decay rate, and thus the valve leakage. Figure 7 shows successive cycles at a later period when seed/ash injection was begun again. In this case the leakage clearly decreased when seed and ash were present.

This effect is apparently due to deposits of the seed material in scratches on the valve seats. This deposited material is a fine soft powder which readily falls from the seats when the valve is cycled. However, it may fill in the potential leakage gaps and allow the valve to effect a better seal even if the seats are damaged by slag particles or refractory grains. This result is very encouraging for potential HTAH valve designs.

Further analysis of the test data is underway and will be presented in the next quarterly report.

3.2.3 Emissions Measurements

No effort was expended under this subtask during the reporting period. The measurements will be conducted during Heat 203 of the MTF.

3.2.4 Creep Testing Apparatus

No effort was expended under this subtask during the reporting period. Final design of a dilatometer for creep measurements in the directly-fired HTAH environment will begin during the next quarter.

3.2.5 Effluent Air Stream

No effort was expended under this subtask during the reporting period. Samples of the effluent air stream from the MTF will be collected for analysis during Heat 203.

3.3 Task 3 - Full-Scale Design Concepts

Work during the reporting period was focused on definition of an example HTAH system denoted the "FY 80 case." This system will be used for dynamic system analyses and for screening and defining control systems and operating methods. Performance of the FY 80 case in steady state operation was determined with the SCAMP code and a system layout was developed.

3.3.1 Size/Cost Analysis and Parametric Studies

The objective of this subtask is to identify HTAH development needs and define goals for the development program through use of the size/cost computer code. During the reporting period, a parametric study of the HTAH was conducted to assess the implications of various constraints placed on the heater system. The FY 80 case, which will be used as a focus for the performance and controls studies, was defined on the basis of the parametric study.

The HTAH flow rates and allowable pressure losses used in the parametric study were taken from work done by STD Engineering Corporation under subcontract to FluidDyne under Contract ET-78-C-01-3005. The air inlet temperature was reduced to 922 K (1200 F) from the value of 1000 K (1340 F) used in the STD work to represent more reasonable performance of the low temperature air heater.

The air inlet temperature and the gas inlet temperature represent major operating constraints on the HTAH. Another major constraint results from the requirement that seed and slag be allowed to drain from the heater during each gas phase; this requirement translates into a lower limit on the maximum bottom of matrix solid temperature, i.e., the temperature of the bottom of the matrix at the end of the gas phase. The allowable thermal stress in the webs between heater flow passages is another operating constraint on the system since high thermal stresses could damage the ceramic heat storage medium.

Results of the parametric study are shown in Figures 8-10. The constraints used were that the air inlet temperature was 922 K (1200 F), the maximum bottom of matrix solid temperature must reach 1400 K (2060 F), and the maximum allowable thermal stress was 25.5 MPa (3700 psi) as calculated by the size/cost computer code. The results are presented in terms of air temperature delivered to the combustor vs required bed height for various radiant boiler outlet gas temperatures and three different heat exchanger flow passage diameters. The cost relative to the FY 80 case (discussed in the following) and heat exchanger effectiveness are also indicated.

As seen in Figures 8-10, for a given air temperature delivered to the combustor, requiring a lower gas temperature from the radiant boiler (as would be required if materials having insufficient temperature service limits were used) results in an increase in required bed height and cost. Thus, ceramic materials capable of withstanding the highest possible temperature remain critically important to

the HTAH development program. A radiant boiler outlet temperature of 1994 K (3130 F) and a heater system gas inlet temperature of 1978 K (3100 F) are considered the maximum achievable with commercially available materials. Another limitation of the exit temperature from the radiant boiler is NO_x decomposition. If a temperature lower than 1927 K (3000 F) is required, the heater bed length must be increased and delivered air temperature decreased. Figures 8-10 enable estimates of this trade-off to be made.

Another result seen in Figures 8-10 is that the effect of requiring large flow passage diameters is significant at delivered air temperatures greater than about 1550 K (2300 F). The percentage increase in bed height and cost required for larger hole diameter is roughly the same for all temperature levels; as the bed height and cost become larger for higher delivered air temperatures, the penalty due to larger hole diameters becomes large. At present, 25.4 mm (1 in) holes are considered the smallest feasible flow passages. If slag fluxing additives or operating techniques are developed to allow the use of smaller holes without fouling of the flow passages, higher air outlet temperatures will be achievable for the same bed height.

The matrix support is an item of major importance in the HTAH development program. The matrix support must be capable of withstanding temperatures up to 1400 K (2060 F) to accommodate removal of seed and slag from the directly-fired heaters, as discussed above. In addition, the matrix support must have sufficient corrosion/erosion resistance and the support structure must withstand the cyclic thermal stress imposed by regenerative air heater service. Commercial experience in the area of secondary ammonia reformers has demonstrated the feasibility of perforated ceramic dome type supports

which operate at temperatures in the range of 1280 K (1850 F) to 1310 K (1900 F) and at loads of about 200 kPa (30 psi). These supports have been limited to about 4 m (13 ft) in diameter.

The HTAH matrix support represents an extension of state-of-the-art technology with respect to both seed/slag removal and thermal cycling. A further extension of the technology in the form of increased diameter would add to the risk. The major implication of limiting the diameter of the individual heater beds is that a large number of heaters will be required for large system flow rate requirements. For example, HTAH for a 1000 MW_e power plant would require 28 active heaters plus one each for periods of pressurization and depressurization or a total of 30 heaters if the individual heater beds are restricted to a diameter of 4.3 m (14 ft).

The use of such a large number of heaters initially may seem to imply reduced reliability due to the large number of flow sequencing valves required in the HTAH system. However, the use of a large number of heaters results in the diameter of the valves being reduced if single valves are used for each heater duct. Restricting the size of valves to approximately the present level of blast furnace valve technology will very likely result in increased valve reliability over the much larger valves required if fewer heaters were used. If more than one valve is used for each heater duct due to valve size limitations, the number of valves and thus, the overall valve reliability is not affected by the number of heaters. Should larger diameter matrix support concepts and valves be developed and reliability demonstrated, a reduction in the total number of heaters in the HTAH should be considered.

Based on the above considerations, a HTAH gas inlet temperature of 1978 K (3100 F), corresponding to a radiant boiler outlet temperature of 1994 K (3130 F), and a total of 30 heaters were chosen as inputs for the FY 80 case. With these inputs, as well as the constraints of 922 K (1200 F) air inlet temperatures and 1400 K (2060 F) maximum bottom of matrix solid temperature, the parametric curves shown in Figures 11-15 were constructed. In these figures, bed diameter, bed height, thermal stress, cycle time, and cost relative to the FY 80 case are shown. The FY 80 case was defined by requiring that the bed diameter not exceed 4.3 m (14 ft) and the bed height not exceed 6.7 m (22 ft) as implied by the matrix support limitations discussed above, and that the total cycle time be at least 30 min. to limit the number of cycles/year required of the sequencing valves. A flow passage diameter of 25.4 mm (1 in) was also selected based on expectations of seed/slag fouling prevention requirements. Specifics of the FY 80 HTAH are given in Table 11.

The results are shown in Figures 11-15 as function of heat exchanger effectiveness, where

$$\text{EFFECTIVENESS (Air Side)} = \frac{T_{\text{AIR OUT}} - T_{\text{AIR IN}}}{T_{\text{GAS IN}} - T_{\text{AIR IN}}}$$

It can be seen that the bed height, cycle time, and cost increase sharply over the FY 80 case values if the air outlet temperature is increased above about 1750 K (2690 F) while the bed diameter is relatively insensitive to air temperature. The increase in bed diameter with hole diameter is due to decreased geometric porosity achievable with larger holes and to the need to balance heat transfer and pressure drop considerations. The thermal stress decreases with increasing air temperature because the thermal stress is the limiting design criterion at

air temperatures less than a particular value for a given hole diameter, i.e., 1756 K (2700 F) for 19 mm (.75 in) holes, 1833 K (2840 F) for 25.4 mm (1 in) holes, and 1878 K (2920 F) for 31.8 mm (1.25 in) holes. Bed diameter and cost do not decrease significantly for air outlet temperature less than the FY 80 case value of 1788 K (2758 F), but the bed height and cycle time show significant decreases. Based on the results of the parametric study, the FY 80 case represents a reasonable vehicle to use for the performance and control studies.

The ideal temperature history for an individual heater for the FY 80 case is shown in Figure 16. The inlet gas and air temperatures and flow rates include effects due to heat loss in the ducts and manifolds and mass loss due to valve leakage and pressurization/depressurization. The code used for this calculation (STRHEX) allows the use of variable material properties and heat transfer coefficients with temperature and position in the heater matrix. The ideal performance shown in Figure 16 will be used to assess the degree of variability in individual heater performance determined from the dynamic system performance model (see Section 3.3.2). Many computer runs have been made with the STRHEX model; the result of these studies has been to verify that individual heater performance can be scaled by heat exchanger effectiveness in the same manner as indicated in Figures 8-15.

3.3.2 Dynamic System Performance Simulation (SCAMP)

The SCAMP code was used to calculate the performance of the FY 80 case heater system. Steady state performance of the heater was determined. Future runs of the SCAMP program will examine system response to variation in

inlet gas temperature and effects on performance due to duct/manifold size, heater sequence, or other design parameters.

The sequencing of the heater system for the first performance calculations is summarized in Tables 12-14 for the FY 80 case. The events through which an individual heater is cycled and the time scale are shown in Table 12. The FY 80 system as described in Table 11 has 30 individual heaters. The layout of the heaters (see Section 3.3.3) is symmetric such that it consists of two identical groups of 15 heaters with the attendant manifolds, ducts, and valves. The heater sequence selected for the SCAMP studies consists of a particular pattern which is identical for each of the 15 heater groups, but offset by half of an individual heater cycle. Each 15 heater group receives half the total gas flow and delivers half the total air flow. This allows the SCAMP code to be run for only a 15 heater system at greatly reduced computer cost as compared to a 30 heater system, and the total system output is determined by adding together two output curves skewed by half a cycle.

Details of the sequence for each 15 heater group are given in Table 13. This sequence is repeated for each of the 15 heaters. A summary of the total cycle for the 30 heater system is shown in Table 14. This cycle is similar to the individual 15 heater group cycles except that pressurization or depressurization may be occurring in 2 heaters at the same time in the 30 heater cycle. Figure 17 identifies the heaters and the sequence for the 15 heater FY 80 case SCAMP studies. The ideal flow rates through an individual heater based on this heater sequence are shown in Figure 18; this situation would result if all heaters participated equally in the flow distribution.

Having identified the operating sequence as above, the SCAMP computer code was used to calculate the system performance in steady state operation for the FY 80 HTAH. Some of the results are shown in Figures 19-26.

The temperature of the outlet air from the 30 heater system is shown in Figure 19. The temperature exhibits a short term ripple of about 15 K (27 F) with a period of about 1.5 min due to the droop in outlet air temperature from each individual heater. This ripple is superimposed on a longer term oscillation with a period of about 15 minutes due to the location of the individual heaters relative to the air and gas manifolds. The resulting temperature variations amount to roughly 2% of the average delivered air from a 30 heater system cycle. The total system gas outlet temperature is shown in Figure 20. The outlet gas temperature also shows the short term ripple and longer term oscillation, and a total variation in temperature of less than 2%. Similar results were observed in an earlier case with 10 heaters; the periods of oscillation were longer and the total temperature variations were somewhat larger.

The outlet air temperature shown in Figure 19 represents the discharge of the HTAH air manifold. The duct needed to carry this air to the combustor will act to further damp the oscillation in delivered air temperature. Definition of the air duct requirements and definition of allowable air temperature fluctuations at the combustor will be needed in order to establish the HTAH control needs and to assess the effectiveness of control schemes studied.

The long term oscillation in the system outlet temperatures is due to the fact that each individual heater in the system does not receive the ideal flow rates as shown in Figure 18 and thus does not exhibit the ideal performance shown in Figure 16. Unequal distribution of flows results from pressure losses due to the required branching and manifolding as illustrated schematically in Figure 17. For example, a heater which is far from the inlet gas manifold will tend to receive lower than the ideal gas flow; if the heater is also near the inlet air manifold, it may receive higher than the ideal air flow. The result will be a lower than ideal outlet air temperature from this particular heater.

In addition to the overall system outputs as shown in Figures 19 and 20, the SCAMP code can be used to study the performance of the individual heaters. For example, the performance of a typical heater (Heater 14) is illustrated in Figures 21-24. The solid temperatures at the top and bottom of the matrix are shown in Figures 21 and 22, and the outlet air and gas temperatures are shown in Figure 23. These temperatures can be compared with the ideal temperatures shown in Figure 16 to assess the degree of variation of each heater from the ideal case. Similarly, the air and gas flow rates through each individual heater (illustrated for Heater 14 in Figure 24) can be compared with the ideal flow rates in Figure 18.

Such comparisons for the individual heaters in the FY 80 case are underway. The degree of flow maldistribution and resulting variation in individual heater performance will be determined and possible control schemes to decrease the individual heater variations will be studied with future SCAMP runs.

The HTAH system pressure losses are shown in Figures 25 and 26. The system inlet air pressure is 867 kPa (125.81 psia) and the gas inlet pressure is 107 kPa (15.58 psia). The air pressure loss shows a number of sharply decreased spikes which are due to pressurization/depressurization of the various heaters. These spikes represent changes in the pressure loss on the order of 20% of the average pressure loss of 27.6 kPa (4 psi) or pressure surges of about 0.7% of the system air pressure. Similar spikes are seen in the gas side pressure loss on the order of 11% of the average 4.1 kPa (0.6 psi) loss or surges of 0.4% of the system gas pressure. In addition to these sharp spikes, an oscillation of much smaller amplitude is also seen in the air and gas pressure losses. Again, definition of the pressure requirements at the combustor will be needed to establish control needs and assess effectiveness of control methods. Figures 19-26 illustrate the type of performance calculations which will be made with the SCAMP code in order to screen and define control systems and operating methods.

3.3.3 System Layouts

The objective of this subtask is to prepare HTAH system layouts for the purpose of integrating individual component modeling or design studies. The level of effort for the layouts will be consistent with that needed to identify development needs which should be addressed in the HTAH development program.

A layout of the FY 80 case has been completed and is shown in Figure 27. Key items which were considered in arriving at this layout were overall insulation layups; compactness of the overall HTAH system; valve orientation, insulation and installation requirements; the design of sub-manifolds, including a catenary shaped arch up to cross sections of 46 m^2 (500 ft^3); the design of main manifolds, including multiple catenary arches; individual heater vessel plenums, matrix support and arrangement of flow passages; and problems related to the intersections of large diameter, refractory lined ducts and manifolds.

Items which will be considered in future work include pressurization/depressurization hardware, expansion joints, electrical isolation, and the mechanical interface with the MHD plant.

3.3.4 Cost Estimates

The objective of this subtask is to prepare a cost estimate for the FY 80 case based on the system layouts as established under Section 3.3.3. The intent of the cost estimate is to provide a check of the ability of the size/cost computer code to produce realistic cost estimates to aid in identifying areas of the HTAH where significant cost savings can be achieved. Since the design of actual HTAH systems will not be accomplished for many years, the cost estimate will not be carried out to a great deal of accuracy.

No effort was expended in this area during the reporting period.

3.3.5 Control Systems

The objective of this subtask is to screen and define HTAH control needs and systems. The performance data from dynamic modeling with the SCAMP computer code will be used to assess control needs and to determine system response to various control concepts.

3.3.6 Matrix Support Test Facility

The objective of this subtask is to identify the requirements which must be met by a future test facility for testing matrix support concepts at nearly full-scale. Data concerning the bed support for the FY 80 case will be reviewed and alternate support concepts will be considered.

No effort was expended in this area during the reporting period.

3.3.7 Alternative Heater Concepts

Several concepts have been identified which may bear investigation as possible directly-fired air heaters, including staged regenerative heat exchangers and regenerative heat exchangers incorporating greatly reduced inlet air and gas temperatures and/or upflow on the gas phase. These concepts will be investigated at a low level of effort to evaluate potential advantages over the basic concept as symbolized by the FY 80 case.

The objective of this subtask is to identify HTAH development needs in the area of electrical isolation of the HTAH system. A gas equilibrium program has been located at Argonne National Laboratory which has the capability for calculation of electrical conductivity. This program will be obtained and calculations of the effluent air stream conductivity will be made. This work will be compared with results from the subscale testing (see Section 3.2.5). Data on electrical conductivity of refractories will also be collected.

4.0 CONCLUSIONS

Material property data is being collected in a formal materials data base. Cooperation of outside organizations such as Montana Tech, MSU, and MERDI in performing measurements according to test requirements established by FluidDyne has proved to be extremely useful in assembling this information and will be needed in the future to insure that the data base requirements are achieved. Liaison with refractory manufacturers has been effective, resulting in programs for development of HTAH materials and fabrication techniques.

Valve testing has been hampered by problems with the VTF hot gas supply duct. Preliminary investigation of the data from Valve Test 3 indicates little change in the valve leakage over the course of testing to date. Modifications to the VTF hot gas supply required to complete Test 3 are underway.

An example HTAH system has proved to be useful in focusing the performance calculations and design studies. Dynamic system performance calculations for this case will provide the information necessary for studying HTAH control systems.

REFERENCES

1. Youngblood, G.E., Montana Energy and MHD Research and Development Institute, private communication.
2. Kitto, K.L., Montana College of Mineral Science and Technology, Private communication.
3. Jackson, D., Corhart Refractories Company, private communication.
4. Trostel, L.J., Norton Company, private communication.
5. Johns Manville Refractory Product Information, Section 150, Part 10.

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TABLE 1

MATERIALS DATA BASE INFORMATION FOR CORHART X-317

Generic Designation: Fusion Cast Magnesia 35% Alumina ASTM Designation: None

Method of Fabrication: Fusion Cast from Arc Furnace into Steel or Graphite Molds Annealed and Diamond Sawn

Manufacturers Name and Address: Corhart Refractories Co., 1600 West Lee St., Louisville, KY 40210, (502)778-3311

Application: Direct-Fired MHD Air Heater Matrix and Liner

MHD/HTAH Experience: 1100 Hours MTF Heat 201, 202

Composition: 64% Magnesia, 34% Alumina, 1% Silica, 1% Other

Mixing/Curing Instructions (castables):

Data Source and Validity: Measurements, Manufacturer's Data, and FluidDyne Estimates

Creep Data is Valid only for 500 psi, 2600°F.

Density: 2963 kg/m³ (185 lbm/ft³) Porosity: 15.0 Volume %

Data Valid from 294 K (70 F) to 2033 K (3200 F)

Property	Temperature, K (F)							
	294 (70)	811 (1000)	1033 (1400)	1256 (1800)	1478 (2200)	1700 (2600)	1922 (3000)	2033 (3200)
Modulus of Elasticity, GPa (psi)	172 (25 x 10 ⁶)	172 (25 x 10 ⁶)	172 (25 x 10 ⁶)	172 (25 x 10 ⁶)	166 (24 x 10 ⁶)	159 (23 x 10 ⁶)	145 (21 x 10 ⁶)	124 (18.0 x 10 ⁶)
Poisson's Ratio	.29	.29	.30	.32	.35	.38	.40	.42
Thermal Conductivity ¹ W/m·K (Btu/hr-ft·F)	10.44 (6.03)	7.49 (4.33)	6.20 (3.58)	5.19 (3.00)	4.59 (2.65)	4.07 (2.35)	3.63 (2.10)	3.41 (1.97)
Specific Heat ¹ J/kg·K (Btu/lbm·F)	921.0 (.220)	1214.1 (.290)	1256.0 (.300)	1297.8 (.310)	1360.6 (.325)	1381.5 (.330)	1402.5 (.335)	1423.4 (.340)
Thermal Stress Limit MPa (psi)	31.0 (4500)	31.0 (4500)	31.0 (4500)	31.0 (4500)	31.0 (4500)	30.4 (4400)	29.7 (4300)	27.6 (4000)
Thermal Expansion Coeff. K ⁻¹ (F ⁻¹)	9.54 x 10 ⁻⁶ (5.3 x 10 ⁻⁶)	9.54 x 10 ⁻⁶ (5.3 x 10 ⁻⁶)	9.54 x 10 ⁻⁶ (5.3 x 10 ⁻⁶)	9.54 x 10 ⁻⁶ (5.3 x 10 ⁻⁶)	9.90 x 10 ⁻⁶ (5.5 x 10 ⁻⁶)	10.26x10 ⁻⁶ (5.7x10 ⁻⁶)	10.80x10 ⁻⁶ (6.0x10 ⁻⁶)	11.34x10 ⁻⁶ (6.3x10 ⁻⁶)
Modulus of Rupture ³ MPa (psi)	31.0 (4500)	31.0 (4500)	31.0 (4500)	31.0 (4500)	31.0 (4500)	30.4 (4400)	29.7 (4300)	27.6 (4000)
Compressive Strength ² MPa (psi)	138 (20,000)	138 (20,000)	138 (20,000)	124.2 (18,000)	103.5 (15,000)	82.8 (12,000)	55.2 (8,000)	41.4 (6,000)
Critical Stress Intensity Factor ³ MPa·m ^{1/2} (psi·in ^{1/2})	.00462 (4.2)	.00462 (4.2)	.00462 (4.2)	.00462 (4.2)	.00462 (4.2)	.00451 (4.1)	.00440 (4.0)	.00418 (3.8)
Creep Rate Under Load, %/hr ²								
@ 0.2 MPa (25 psi)	1.0x10 ⁻¹⁴	1.0x10 ⁻¹³	1.0x10 ⁻¹²	1.0x10 ⁻¹¹	1.0x10 ⁻¹⁰	1.0x10 ⁻⁹	1.0x10 ⁻⁸	1.0x10 ⁻⁷
@ 0.7 MPa (100 psi)	1.0x10 ⁻¹³	1.0x10 ⁻¹²	1.0x10 ⁻¹¹	1.0x10 ⁻¹⁰	1.0x10 ⁻⁹	1.0x10 ⁻⁸	1.0x10 ⁻⁷	1.0x10 ⁻⁶
@ 3.4 MPa (500 psi)	1.0x10 ⁻¹²	1.0x10 ⁻¹¹	1.0x10 ⁻¹⁰	1.0x10 ⁻⁹	1.0x10 ⁻⁸	1.0x10 ⁻⁷	1.0x10 ⁻⁶	1.0x10 ⁻⁵
@ 6.9 MPa (1000 psi)	1.0x10 ⁻¹¹	1.0x10 ⁻¹⁰	1.0x10 ⁻⁹	1.0x10 ⁻⁸	1.0x10 ⁻⁷	1.0x10 ⁻⁶	1.0x10 ⁻⁵	1.0x10 ⁻⁴

1. Superscripted Numbers Refer to References at End of Text.

Generic Designation: Spinel Castable

ASTM Designation: None

Method of Fabrication: Fused Spinel Grains are Mixed with Calcium Aluminate Cement

Manufacturers Name and Address: Norton Co., 1 New Bond Street, Worcester, MA 01606, (617) 853-1000 (Louis Trostel)

Application: Direct-Fired MHD Hot Liner, Do Not Use for Matrix Above 2400°F

MHD/HTAH Experience: MTF Heat 202 Hot Liner Six-Inch ZJ Valve

Composition: 73% Alumina, 24% Magnesia, 2.4% Calcia, 1% Silica

Mixing/Curing Instructions (castables): Nine Pints Water Per 100 lbs, Use Paddle Mixer, see Norton Bulletin S-AP-G1

Data Source and Validity: Measurements and FluidVne Estimates

Data is for Material Fired to 2500°F

Density: $2499/\text{m}^3$ (156 lbm/ft³) Porosity: 30.0 Volume %

Data Valid from 294K (70 F) to 2033 K (3200 F)

Property	Temperature, K (F)							
	294 (70)	811 (1000)	1033 (1400)	1256 (1800)	1478 (2200)	1700 (2600)	1922 (3000)	2033 (3200)
Modulus of Elasticity, GPa (psi)	104 (15 x 10 ⁶)	104 (15 x 10 ⁶)	104 (15 x 10 ⁶)	97 (14 x 10 ⁶)	90 (13 x 10 ⁶)	83 (12 x 10 ⁶)	76 (11 x 10 ⁶)	69 (10 x 10 ⁶)
Poisson's Ratio	.29	.29	.30	.32	.35	.38	.40	.42
Thermal Conductivity ¹ W/m·K (Btu/hr-ft-F)	5.76 (3.33)	3.55 (2.05)	3.06 (1.77)	2.68 (1.55)	2.34 (1.35)	2.08 (1.20)	1.73 (1.0)	1.60 (.925)
Specific Heat ¹ J/kg·K (Btu/lbm·F)	921.0 (.220)	1214.1 (.290)	1256.0 (.300)	1297.8 (.310)	1360.6 (.325)	1381.5 (.330)	1402.5 (.335)	1423.4 (.340)
Thermal Stress Limit MPa (psi)	13.5 (1950)	13.5 (1950)	13.5 (1950)	12.4 (1800)	10.4 (1500)	8.3 (1200)	6.9 (1000)	4.8 (700)
Thermal Expansion Coeff. K ⁻¹ (F ⁻¹)	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})
Modulus of Rupture MPa (psi)	13.5 (1950)	13.5 (1950)	13.5 (1950)	12.4 (1800)	10.4 (1500)	8.3 (1200)	6.9 (1000)	4.8 (700)
Compressive Strength ² MPa (psi)	41.4 (6000)	41.4 (6000)	27.6 (4000)	20.7 (3000)	17.9 (2600)	13.8 (2000)	10.4 (1500)	6.9 (1000)
Critical Stress Intensity Factor MPa·m ^{1/2} (psi·in ^{1/2})								
Creep Rate Under Load, %/hr								
@ 0.2 MPa (25 psi)								
@ 0.7 MPa (100 psi)								
@ 3.4 MPa (500 psi)								
@ 6.9 MPa (1000 psi)								

1. Superscripted Numbers Refer to References at End of Text.

TABLE 3

MATERIALS DATA BASE INFORMATION FOR JOHNS MANVILLE YUMA

Generic Designation: High Strength Insulating Firebrick

ASTM Designation: None

Method of Fabrication: Sintered with Fugitive Organic Filler

Manufacturers Name and Address: Johns Manville, Inc., Ken Caryl Ranch, Denver, CO 80217, (303) 979-1000

Application: Backup, Do Not Expose to MHD Gas

MHD/HTAH Experience: None

Composition: 39.3% Alumina, 56.3% Silica, 1.6% Ferric Oxide, 1.6% TiO_2 , .27% CAO, 31% MGO, .53% Alkali

Mixing/Curing Instructions (castables):

Data Source and Validity: Manufacturer's Data (not verified) and Fluidyne Estimates

Density: 977 kg/m^3 (61 lbm/ft^3)

Porosity: 60.

Volume %

Data Valid from 294 K (70 F) to 1644 K (2500 F)

Property	Temperature, K (F)							
	294 (70)	533 (500)	811 (1000)	1089 (1500)	1367 (2000)	1478 (2200)	1589 (2400)	1644 (2500)
Modulus of Elasticity, GPa (psi)	34.5 (5.0×10^6)	34.5 (5.0×10^6)	34.5 (5.0×10^6)	27.6 (4.0×10^6)	20.7 (3.0×10^6)	13.8 (2.0×10^6)	6.9 (1.0×10^6)	3.5 (5.0×10^5)
Poisson's Ratio	.20	.20	.20	.20	.20	.20	.20	.20
Thermal Conductivity ⁵ W/m·K (Btu/hr-ft-F)	-	.405 (.2342)	.424 (.2450)	.453 (.2617)	.488 (.2817)	.519 (.300)	.536 (.310)	.554 (.320)
Specific Heat J/kg·K (Btu/lbm·F)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)
Thermal Stress Limit MPa (psi)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	1.73 (250)	1.38 (200)	1.04 (150)	.69 (100)
Thermal Expansion Coeff. K^{-1} (F^{-1})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})
Modulus of Rupture ⁵ MPa (psi)	2.07 (300)	2.07 (300)	2.07 (300)	2.07 (300)	1.73 (250)	1.38 (200)	1.04 (150)	.69 (100)
Compressive Strength ⁵ MPa (psi)	3.80 (550)	3.80 (550)	3.80 (550)	3.80 (550)	3.11 (450)	2.42 (350)	2.07 (300)	1.38 (200)
Critical Stress Intensity Factor $\text{MPa}\cdot\text{m}^{1/2}$ ($\text{psi}\cdot\text{in}^{1/2}$)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)
Creep Rate Under Load, %/hr								
@ 0.2 MPa (25psi)								
@ 0.7 MPa (100psi)								
@ 3.4 MPa (500psi)								
@ 6.9 MPa (1000psi)								

1. Superscripted Numbers Refer to References at End of Text.

TABLE 4

MATERIALS DATA BASE INFORMATION FOR JOHNS MANVILLE C-22Z

Generic Designation: High Strength Insulating Brick

ASTM Designation: None

Method of Fabrication: Sintered with Fugitive Organic Binder

Manufacturers Name and Address: Johns Manville, Inc., Ken Caryl Ranch, Denver, CO 80217, (303) 979-1000

Application: Back-up Only, Do Not Expose to Combustion Gas

MHD/HTAH Experience: None

Composition: 34.1% Al_2O_3 , 59.4% SiO_2 , .8% Fe_2O_3 , 1.2% TiO_2 , 3.4% CAO, .2% MGO, 1.0% Alkali

Mixing/Curing Instructions (castables):

Data Source and Validity: Manufacturer's Data (not verified) and FluidDyne Estimates

Density: 753 kg/m^3 (47 lbm/ft^3)

Porosity: 65 Volume %

Data Valid from 294 K (70 F) to 1367 K (2000 F)

Property	Temperature, K (F)							
	294 (70)	533 (500)	811 (1000)	922 (1200)	1033 (1400)	1144 (1600)	1256 (1800)	1367 (2000)
Modulus of Elasticity, GPa (psi)	34.5 (5.0×10^6)	34.5 (5.0×10^6)	34.5 (5.0×10^6)	27.6 (4.0×10^6)	20.7 (3.0×10^6)	13.8 (2.0×10^6)	6.9 (1.0×10^6)	3.5 (5.0×10^5)
Poisson's Ratio	.20	.20	.20	.20	.20	.20	.20	.20
Thermal Conductivity ⁵ W/m-k (Btu/hr-ft-F)	2.51 (1.45)	2.80 (1.62)	3.55 (2.05)	-	-	-	-	-
Specific Heat J/kg-K (Btu/lbm-F)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)
Thermal Stress Limit MPa (psi)	1.45 (210)	1.45 (210)	1.45 (210)	1.38 (200)	1.24 (180)	1.04 (150.3)	.76 (110.0)	.41 (60.0)
Thermal Expansion Coeff. ⁵ K^{-1} (F^{-1})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})
Modulus of Rupture ⁵ MPa (psi)	1.45 (210)	1.45 (210)	1.45 (210)	1.38 (200)	1.24 (180)	1.04 (150)	.76 (110)	.41 (60)
Compressive Strength ⁵ MPa (psi)	2.28 (330)	2.28 (330)	2.28 (330)	2.21 (320)	2.07 (300)	1.86 (270)	1.59 (230)	1.24 (180)
Critical Stress Intensity Factor $MPa \cdot m^{1/2}$ ($psi \cdot in^{1/2}$)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)	.00011 (.1)
Creep Rate Under Load, %/hr								
@ 0.2 MPa (25 psi)								
@ 0.7 MPa (100 psi)								
@ 3.4 MPa (500 psi)								
@ 6.9 MPa (1000 psi)								

1. Superscripted Numbers Refer to References at End of Text.

TABLE 5

MATERIALS DATA BASE INFORMATION FOR JOHNS MANVILLE SUPEREX 2000

Generic Designation: 2000°F Block Insulation

ASTM Designation: None

Method of Fabrication: Sintered

Manufacturers Name and Address: Johns Manville, Inc. , Ken Caryl Ranch, Denver CO 80217, (303) 979-1000

Application: Backup Only

MHD/HTAH Experience: None

Composition: 74.8% SiO_2 , 4.3% Al_2O_3 , 6.0% CaO , 2.0% Fe_2O_3 , .3% TiO_2 , .8% MCO , 2.7% Alkali

Mixing/Curing Instructions (castables):

Data Source and Validity: Manufacturer's Data (not verified) and FluidDyne Estimates

Density: 384 kg/m^3 (24.0 lbm/ft^3)

Porosity: 85.0 Volume %

Data Valid from 294K (70 F) to 1367 K (2000 F)

Property	Temperature, K (F)							
	294 (70)	367 (200)	478 (400)	589 (600)	700 (800)	811 (1000)	1089 (1500)	1367 (2000)
Modulus of Elasticity, GPa (psi)	6.9 (1.0×10^6)	6.9 (1.0×10^6)	6.9 (1.0×10^6)	6.9 (1.0×10^6)	6.9 (1.0×10^6)	.69 (1.0×10^5)	.069 (1.0×10^4)	.0069 (1.0×10^3)
Poisson's Ratio	.20	.20	.20	.20	.20	.20	.20	.20
Thermal Conductivity ⁵ W/m.K (Btu/hr-ft-F)	.0678 (.0392)	.0722 (.0417)	.0779 (.0450)	.0851 (.0492)	.0922 (.0533)	.0995 (.0575)	.1168 (.0675)	.1341 (.0775)
Specific Heat J/kg-K (Btu/lbm-F)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)	1256.0 (.30)
Thermal Stress Limit MPa (psi)	.311 (45.0)	.311 (45.0)	.311 (45.0)	.311 (45.0)	.311 (45.0)	.276 (40)	.207 (30)	.069 (10)
Thermal Expansion Coeff. K^{-1} ($^{\circ}\text{F}^{-1}$)	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})	9.0×10^{-6} (5.0×10^{-6})
Modulus of Rupture ⁵ MPa (psi)	.311 (45.0)	.311 (45.0)	.311 (45.0)	.311 (45.0)	.311 (45.0)	.276 (40)	.207 (30)	.069 (10)
Compressive Strength ⁵ MPa (psi)	.897 (130)	.897 (130)	.897 (130)	.897 (130)	.897 (130)	.828 (120)	.690 (100)	.345 (50)
Critical Stress Intensity Factor $\text{MPa}\cdot\text{m}^{1/2}$ ($\text{psi}\cdot\text{in}^{1/2}$)								
Creep Rate Under Load, %/hr								
@ 0.2 MPa (25 psi)								
@ 0.7 MPa (100 psi)								
@ 3.4 MPa (500 psi)								
@ 6.9 MPa (1000 psi)								

1. Superscripted Numbers Refer to References at End of Text.

TABLE 6
SUMMARY OF MATERIALS SELECTION FOR FULL-SCALE STUDIES

Area	Gas Temp.	Diameter	Heat Flux		Cost*		Layers Inside Shell
	K (F)	m (ft)	W/m ²	(Btu/hr-ft ²)	\$/m ²	(\$/ft ²)	
1. Gas Inlet Duct	1963 (3075)	2.18 (7.2)	1051	333	2614	243	4
2. Gas Outlet Duct	1333 (1940)	1.83 (6.0)	1011	321	1171	109	2
3. Air Inlet Duct	920 (1200)	0.79 (2.6)	402	127	85	8	1
4. Air Outlet Duct	1787 (2760)	1.07 (3.5)	904	287	1994	185	4
5. Pressurization Duct	920 (1200)	0.36 (1.2)	381	121	85	8	1
6. Depressurization Duct	1333 (1940)	0.41 (1.3)	1018	323	1165	108	2
7. Vessel Center	1875 (2915)	4.27 (14.0)	1009	320	2673	248	4
8. Upper Plenum (Master)	1875 (2915)	4.27 (14.0)	1009	320	2673	248	4
9. Upper Plenum (Max. Nozzle)	1875 (2915)	2.18 (7.2)	992	315	2295	213	4
10. Upper Plenum (Min. Nozzle)	1875 (2915)	1.07 (3.9)	905	287	2295	213	4
11. Lower Plenum (Master)	1333 (1940)	2.74 (9.0)	834	264	2271	211	3
12. Lower Plenum (Max. Nozzle)	1333 (1940)	1.83 (6.0)	1011	321	1171	109	2
13. Lower Plenum (Min. Nozzle)	920 (1200)	0.79 (2.6)	453	144	1171	109	2
14. Gas Inlet Manifold Small End	1963 (3075)	3.10 (10.2)	1053	334	3003	279	4
15. Gas Outlet Manifold Small End	1333 (1940)	2.59 (8.5)	1010	320	1548	144	2
16. Air Inlet Manifold Small End	920 (1200)	1.12 (3.7)	490	155	85	8	1
17. Air Outlet Mani- fold, Small End	1787 (2760)	1.52 (5.0)	968	307	2299	214	4
18. Gas Inlet Manifold Large End	1963 (3075)	6.20 (20.3)	1120	355	3011	280	4

* 1980 Dollars/Shell Surface Area

TABLE 6 (Continued)
SUMMARY OF MATERIALS SELECTION FOR FULL-SCALE STUDIES

Area	Gas Temp.	Diameter	Heat Flux		Cost*		Layers Inside Shell
			W/m^2	(Btu/hr-ft ²)	$\$/m^2$	(\$/ft ²)	
19. Gas Outlet Manifold Large End	1333 (1940)	5.18 (17.0)	933	296	1543	143	2
20. Air Inlet Manifold Large End	920 (1200)	1.57 (5.1)	464	147	85	8	1
21. Air Outlet Mani- fold, Large End	1787 (2760)	2.13 (7.0)	1032	327	2299	214	4

* 1980 Dollars/Shell Surface Area

TABLE 7
GAS INLET DUCT - REFRACTORY LAYUP CONCEPT

Description: 2.18 m (86 inch) Inside Diameter Vertical Duct
Carrying MHD Exhaust Gas from Manifold to Heater

Interface Temperature		Material	Diameter		Thermal Conductivity	
K	(F)		m	(in)	W/m-K	(Btu-in/hr-ft ² -F)
1963	(3075)	_____	2.18	(86)		
		Dense Spinel Brick			1.76	(12.2)
1860	(2888)	_____	2.41	(95)		
		Insulating Spinel Brick			1.35	(9.4)
1554	(2338)	_____	3.02	(119)		
		High Strength Insulation Brick			0.50	(3.5)
1286	(1855)	_____	3.25	(128)		
		Block Insulation			0.14	(1.0)
577	(578)	_____	3.43	(135)		
		Shell			0.14	(1.0)
		_____	3.48	(137)		
		External Coating			0.07	(0.5)
		_____	3.51	(138)		

$$Q = 1051 \text{ W/m}^2 \text{ (333 Btu/ft}^2 \text{ hr)}$$

$$\text{Cost} = \$2614/\text{m}^2 \text{ } (\$243/\text{ft}^2) + \text{Labor}$$

TABLE 8

COMPARISON OF CALCIUM ALUMINATE BONDED SPINEL CASTABLE
 (NORTON LS-812), PHOSPHATE BONDED SPINEL CASTABLE
 (TAYLOR X-13337) AND FUSION CAST SPINEL (CORHART X-317)

<u>Oxide</u>	<u>Method</u>	<u>Norton</u>	<u>Taylor</u>	<u>Corhart</u>
Al_2O_3	Wet	73.9%	65.2%	18.5%
CaO	Wet	3.0	0.9	0.4
Fe_2O_3	Wet	0.1	0.2	0.2
MgO	Wet	22.3	32.0	79.3
P_2O_5	Wet	N.D.	N.D.*	N.D.
SiO_2	Wet	0.40	0.52	0.1
MgAl_2O_4 Spinel	XRD	65%	65%	30%
Corundum	XRD	30%	15	-
MgO Periclase	XRD	5%	-	55
Amorphous	XRD	-	-	15

N.D. Below Detection Limits of 0.3% and *0.01%

TABLE 9
ANALYSIS OF MATRIX CORE DEPOSITS FROM HEAT 202

Oxide	Method	Melting Point	Distance from Top of Matrix (m)			
		K	0.4	1.4	4.1	
Al ₂ O ₃	Wet	2323	52.2	38.4	17.7	
CaO	Wet	2853	1.7	3.1	3.6	
Fe ₂ O ₃	Wet	1838	0.9	1.9	1.4	
MgO	Wet	3075	36.6	45.6	47.1	
SiO ₂	Wet	~2000	7.7	10.7	30.0	
K ₂ O	Flame	-	0.02	0.3	0.03	
MgAl ₂ O ₄	Spinel	XRD	2378	65	55	40
MgO	Periclase	XRD	3075	20	35	40
Mg ₂ SiO ₄	Forsterite	XRD	2163	15	-	5
CaMgSiO ₄	Montecellite	XRD	1923	-	10	-

TABLE 10

ANALYSIS OF REFRACTORIES AND DEPOSITS FROM TEST VALVE AFTER TESTS 1 AND 2

Oxide	Method	Sliding Gate (T)								
		Valve Body				Follower		Gate		Follower Ring Throat (Inner Surface)
		Lower Throat Lining (T) (Inner Surface)	Lower Throat Lining (T) (Interior)	Gate Cavity Deposits	Upper Throat Lining (N) (Inner Surface)	Upper Surface	Lower Surface	Upper Surface	Lower Surface	
Al_2O_3	Wet	30.9	49.2	39.3	43.1	58.5	30.7	61.9	64.1	38.4
CaO	Wet	5.5	4.2	2.0	4.2	0.8	6.0	0.8	0.8	2.7
Fe_2O_3	Wet	4.6	5.4	3.3	3.4	0.3	4.1	2.7	0.3	4.6
MgO	Wet	26.5	11.0	20.9	25.0	37.6*	29.8	32.3*	33.2	33.8
P_2O_5	Wet	0.3	0.4	0.15	0.4	N.D.	0.4	N.D.	N.D.	0.3
SiO_2	Wet	23.4	21.9	7.8	15.6	0.7	23.8	0.6	0.6	11.6
K_2O	Flame	8.9	7.3	15.0	8.0	2.1	5.3	1.7	1.0	5.3
MgAl_2O_4	Spinel	XRD	15	35	15	40	70	30	80	30
MgO	Periclase	XRD	15	10	30	30	5	10	20	7
KAlSi_3O_8	Kalsilite	XRD	20	-	-	15	-	10	-	10
Mg_2SiO_4	Forsterite	XRD	-	15	-	-	-	-	-	-
$\text{CaMgSi}_2\text{O}_6$	Montecellite	XRD	30	15	-	-	-	-	-	20
K_2SO_4	Arcanite	XRD	-	-	15	-	-	-	-	-

*, By Difference

T, Taylor Spinel

N, Norton Spinel

TABLE 11
HTAH DESCRIPTION - FY 80 CASE

Item	MHD Gas	Air	Units
Flow In	836 (1844)	683 (1506)	kg/sec (lbm/sec)
Flow Out	849 (1872)	670 (1478)	kg/sec (lbm/sec)
T _{in}	1978 (3100)	919 (1200)	K (F)
T _{out}	1326 (1927)	1788 (2748)	K (F)
P	869 (126)	108 (15.6)	kPa (psi)
ΔP	4.5 (0.65)	17.2 (2.5)	kPa (psid)
Vessels	20	8	Heaters
Flow Duration	2000	800	Seconds
Heat Duty	706 (6.7 x 10 ⁵)	-	MW (Btu/sec)
Bed Diameter	4.3 (14)	-	m (ft)
Bed Height	6.7 (22)	-	m (ft)
Thermal Stress	25.5 (3700)	-	MPa (psi)
Hole Size/Web	25/14 (1.0/0.55)		mm (inches)
P/DP Units	2	-	Vessels
Inlet Valve Diameter	2.2 (86)	0.8 (31)	m (inches)
Outlet Valve Diameter	1.8 (72)	1.1 (42)	m (inches)
Heat Loss	6	-	Percent

TABLE 12
CYCLE EVENTS FOR FY 80 CASE - INDIVIDUAL HEATER

Event	Running Time, Sec.	Delta Time, Seconds
"On Air"	0	800
Air Valve Full Open	7	7 /14
Air Valve Starts to Close	800	14
Air Valve Closed	814	-
Depressurization Valve Starts to Open	814	6
Depressurization Valve Full Open	820	61
Depressurization Valve Starts to Close	881	6
Depressurization Valve Full Closed	887	0
Gas Valve Starts to Open	887	13 /26
"On Gas"	900	2000
Gas Valve Full Open	913	13 /22
Gas Valve Starts to Close	2900	26
Gas Valve Full Closed	2926	0
Pressurization Valve Starts to Open	2926	6
Pressurization Valve Full Open	2932	55
Pressurization Valve Starts to Close	2987	6
Pressurization Valve Full Closed	2993	0
Air Valve Starts to Open	2993	7 /14
"On Air" - End of Cycle	3000	0

TABLE 13
DETAIL OF EVENTS FOR FY 80 - 15 HTR GROUP (1/2 FLOW)

Event	Number of Heaters On Air	Number of Heaters On Gas	Time, sec.	
Air Valve starts to open - HTR A	4.0	10.0	-7.0	Start of Air Valve Overlap
Air Valve 1/4 Open - HTR A	4.25	10.0	-3.5	
HTR A Air Valve 1/2 Open				End of Press/Valving Sequence - HTR A
HTR B Air Valve starts to Close	4.5	10.0	0.0	Start of Depress/Valving Sequence - HTR B
HTR A Air Valve 3/4 Open				
HTR B Air Valve 1/4 Closed	4.5	10.0	3.5	
HTR A Air Valve Full Open				
HTR B Air Valve 1/2 Closed	4.5	10.0	7.0	
HTR B Air Valve 3/4 Closed	4.25	10.0	10.5	
HTR B Air Valve Full Closed	4.0	10.0	14.0	End of Air Valve Overlap
HTR B Depress. Valve Opens	4.0	10.0	14.0	
HTR B Depress. Valve Full Open	4.0	10.0	20.0	Start of HTR B Depress.
HTR B Depress. Valve Closes	4.0	10.0	81.0	End of HTR B Depress.
HTR B Depress. Valve Closed	4.0	10.0	87.0	
HTR B Gas Valve Opens	4.0	10.0	87.0	Start of Gas Valve Overlap
HTR B Gas Valve 1/4 Open	4.0	10.25	93.5	
HTR C Gas Valve Closes				Start of Press/Valving Sequence - HTR C
HTR B Gas Valve 1/2 Open	4.0	10.50	100.0	End of Depress/Valving Sequence - HTR B
HTR C Gas Valve 1/4 Closed				
HTR B Gas Valve 3/4 Open	4.0	10.50	106.5	

TABLE 13 (Continued)
DETAIL OF EVENTS FOR FY 80 - 15 HTR GROUP (1/2 FLOW)

Event	Number of Heaters On Air	Number of Heaters On Gas	Time, sec.	
HTR C Gas Valve 1/2 Closed				
HTR B Gas Valve Full Open	4.0	10.4	113.0	
HTR C Gas Valve 3/4 Closed	4.0	10.25	119.5	
HTR C Gas Valve Full Closed	4.0	10.0	126.0	End of Gas Valve Overlap
HTR C Press. Valve Opens	4.0	10.0	126.0	
HTR C Press. Valve Full Open	4.0	10.0	132.0	Start of HTR C Press.
HTR C Press. Valve Closes	4.0	10.0	187.0	End of HTR C Press.
HTR C Press. Valve Closed	4.0	10.0	193.0	
HTR C Air Valve Opens	4.0	10.0	193.0	Start of Air Valve Overlap
HTR C Air Valve 1/4 Open	4.25	10.0	196.5	
HTR D Air Valve Closes				Start of Depress/Valving Sequence - HTR D
HTR C Air Valve 1/2 Open	4.5	10.0	200.0	End of Press/Valving Sequence - HTR C
HTR D Air Valve 1/4 Closed				
HTR C Air Valve 3/4 Open	4.5	10.0	203.5	
HTR D Air Valve 1/2 Closed				
HTR C Air Valve Closes	4.5	10.0	207.0	
HTR D Air Valve 3/4 Closed	4.25	10.0	210.5	
HTR D Air Valve Closed	4.0	10.0	214	End of Gas Valve Overlap

(Sequence repeats through 15 heaters.)

TABLE 14
SUMMARY OF TOTAL CYCLE FOR 30 HTR CONFIGURATION - FY 80 CASE

Time, Sec	Number of Heaters on Air	Number of Heaters on Gas
0.0	8.5	20.5
3.5	8.5	20.5
6.5	8.5	20.5
7.0	8.5	20.5
10.5	8.25	20.5
13.0		20.5
14.0	8.0	
19.5	8.0	20.25
20.0	8.0	
26	8.0	20.0
32	8.0	20.0
81	8.0	20.0
87	8.0	20.0
93.0	8.0	
93.5		20.25
96.5	8.25	
100.0	8.5	20.5

FIGURE 1. CREEP OF CORHART X-317 - MONTANA TECH MEASUREMENTS

-87-

Deformation
%

FIGURE 2. CREEP OF NORTON LS-812 - MONTANA TECH MEASUREMENTS

FIGURE 3. ACTIVATION ENERGY DETERMINATION FOR NORTON LS-812 - MONTANA TECH MEASUREMENTS

Ln
Steady
State
Creep
Rate
 Hr^{-1}

FIGURE 4. STRESS EXPONENT DETERMINATION FOR NORTON LS-812 - MONTANA TECH MEASUREMENTS

FIGURE 5. CYCLIC TEMPERATURE AND STRESS FOR THERMAL STRESS CYCLING EXPERIMENT

FIGURE 6. PRESSURE/TEMPERATURE RECORDING FROM VTF, TEST 3, SHOWING INCREASE IN LEAKAGE BETWEEN SUCCESSIVE CYCLES WHEN SEED/ASH INJECTION WAS STOPPED.

FIGURE 7. PRESSURE/TEMPERATURE RECORDING FROM VTF, TEST 3, SHOWING DECREASE IN LEAKAGE BETWEEN SUCCESSIVE CYCLES WHEN SEED/ASH INJECTION WAS RESTARTED.

FIGURE 8. DELIVERED AIR TEMPERATURE FOR VARIOUS RADIANT BOILER OUTLET GAS TEMPERATURES;

Hole Diameter = 31.8 mm (1.25 in)
 Web Thickness = 10.4 mm (0.409 in)

FIGURE 9. DELIVERED AIR TEMPERATURE FOR VARIOUS RADIANT BOILER OUTLET GAS TEMPERATURES;

Hole Diameter = 25.4 mm (1.0 in)
 Web Thickness = 13.8 mm (0.545 in)

FIGURE 10. DELIVERED AIR TEMPERATURE FOR VARIOUS RADIANT BOILER
OUTLET GAS TEMPERATURES;

Hole Diameter = 19.0 mm (0.75 in)
Web Thickness = 10.4 mm (0.409 in)

FIGURE 11. DED DIAMETER RELATIVE TO FY 80 CASE FOR VARIOUS HOLE DIAMETERS

FIGURE 12. BED HEIGHT RELATIVE TO FY 80 CASE FOR VARIOUS HOLE DIAMETERS

FIGURE 13. THERMAL STRESS RELATIVE TO FY 80 CASE FOR VARIOUS HOLE DIAMETERS

FIGURE 14. CYCLE TIME RELATIVE TO FY 80 CASE FOR VARIOUS HOLE DIAMETERS

FIGURE 15. COST RELATIVE TO FY 80 CASE FOR VARIOUS HOLE DIAMETERS

FIGURE 16 INDIVIDUAL HEATER PERFORMANCE FOR FY 80 CASE BASED ON IDEAL HEATER CYCLE (STRHEX CODE)

FIGURE 17 IDENTIFICATION OF HEATERS AND SEQUENCE FOR FY80
CASE PERFORMANCE CALCULATIONS

-79-

FIGURE 18. GAS AND AIR FLOW RATES FOR AN INDIVIDUAL HEATER WITH IDEAL FLOW DISTRIBUTION (INCLUDING PRESSURIZATION/DEPRESSURIZATION MASS EXCHANGE) -FY80 CASE

-65-

FLUID
TEMPERATURE

-99-

FLUID
TEMPERATURE
F

FIGURE 20. OUTLET GAS TEMPERATURE FOR
FY 80 SYSTEM - STEADY STATE.

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FIGURE 23. OUTLET AIR AND GAS TEMPERATURES FOR HEATER 14, FY80 CASE - SCAMP RESULTS

FIGURE 24, AIR AND GAS FLOW RATES THROUGH HEATER 14, FY80 CASE - SCAMP RESULTS

FIGURE 25. AIR SIDE PRESSURE LOSS THROUGH FY80 HTAH - SCAMP RESULTS

FIGURE 26. GAS SIDE PRESSURE LOSS THROUGH FY80 HTAH - SCAMP RESULTS

FIGURE 27. LAYOUT OF FY80 HTAH (1/2 SYSTEM)