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MHD GENERATOR COMPONENT DEVELOPMENT

Quarterly Report for July–September 1983

November 1983

Work Performed Under Contract No. AC22-80ET15614

Avco Everett Research Laboratory, Inc.
Everett, Massachusetts

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United States Department of Energy

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MHD GENERATOR COMPONENT DEVELOPMENT

Quarterly Report for July 1983 - September 1983

November 1983

prepared for

U.S. DEPARTMENT OF ENERGY
Pittsburgh Energy Technology Center
Contract No. DE-AC22-80-ET15614

prepared by

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1.0 PROGRAM OBJECTIVES AND SCOPE OF WORK

The overall objectives of this program are two-fold:

1. To contribute, by appropriate systematic experimental and analytical investigations, to the engineering data base necessary for the design and construction of MHD generators at CDIF-scale (50 MW_{th}) and baseload scale (2000 MW_{th}).
2. To design and fabricate specific hardware items to be tested at the CDIF site in Butte, Montana.

A contract change order incorporated in Modification Mod. A042 effective September 27, 1983, has been executed.

The revised program consists of a series of related tasks, described as follows:

Task 1 - MHD Channel Design and Performance

Perform experimental investigations related to MHD channel design and performance by testing existing channel hardware and by fabricating and testing new channel hardware. This task includes comparison of coal-fired versus (Mk VI type) AIC, oil-fired channels, with the coal combustor provided, through DOE/MHD, by TRW, Inc.

Task 2 - MHD Channel Construction and Lifetime

Perform experimental investigations related to MHD channel performance and lifetime, with the principal aim of systematically obtaining data on the prototype electrodes for coal-fired, subsonic, long-duration CDIF Generators.

Task 3 - MHD Channel Loading and Control

Perform testing on channel loading and control utilizing the supersonic Reference Channel No. 4 and other appropriate channel and/or test modules, at magnetic fields to 4 T.

Task 4 - Facility Operation

Provide for facility operation and maintenance of the Mk VI and Mk VII test bays.

Task 5 - CDIF Related Hardware

Design and fabricate the following items of hardware:

5.3. CDIF Generator 1A2

5.4 Diagonal current control and load consolidation circuits 1A1 and 1A2 generators.

Task 6 - High Interaction Tests of a Supersonic Channel

Utilizing the Mk VI test facility and draft fan, experimentally investigate the supersonic operation of an MHD channel at 4 T magnetic field and characterize its performance in the configuration and electrical regimes presently proposed for early commercial MHD power plants.

2.0 SUMMARY OF PROGRESS TO DATE

Program schedules are shown in Fig. 2.1. Summaries of individual program tasks follow:

Task 1 - MHD Channel Design and Performance

Initial tests of a supersonic channel in a high magnetic field were performed. Initial tests of a laser doppler velocimeter built by Mississippi State University were performed.

Task 2 - MHD Channel Construction and Lifetime

Gas cooling of ceramic sidewall elements was enhanced by use of inserts in the coolant passages. A promising technique for limiting damage resulting from interelectrode arcs may be use of interelectrode cavities below the gas-side surface.

Task 3 - MHD Channel Loading and Control

Initial testing of a new semiconductor device, the Gate Turn-off Switch, was started. This device could replace all the SCR's and commutation circuits now used.

Task 4 - Facility Operations

Test time for both Mk VI and Mk VII facilities totalled 33 1/2 hours, of which 27 hours were in the Mk VI facility. Only 6.5 power hours were run, due to the large amount of time spent on diagnostics.

U.S. DEPARTMENT OF ENERGY
MILESTONE SCHEDULE AND STATUS REPORT

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FORM APPROVED
OHS-NC 28-7-81

1. Contract Identification MHD Generator Component Development for CDIF Testing		2. Reporting Period 1 July 1983 through 30 Sept. 1983		3. Contract Number DE-AC22-80ET15614																								
4. Contractor (name, address) Avco Everett Research Laboratory, Inc. 2385 Revere Beach Parkway Everett, MA 02149		5. Contract Start Date 1 October 1979		6. Contract Completion Date 30 April 1983																								
7. Identification Number	8. Reporting Category (e.g., contract line item or work breakdown structure element)	9. Fiscal Years and Months												10. Percent Complete														
		FY83												FY84												a) Planned	b) Actual	
		O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A								
1.0	MHD Channel Des. & Perf.																										95	
2.0	MHD Channel Construction																										95	
3.0	MHD Channel Load & Control																										89	
4.0	Facility Operations																										91	
5.1/5.2	CDIF Gens. 1B2/1B3																										Discontinued	
5.3	CDIF Generator AIC																										Discontinued	
5.4	CDIF Generator 1A2 (Anode Wall)																										Complete	
5.4	CDIF Generator 1A2 (Bail.)																										Complete	
5.5	1A1/1A2 Controls																										0	
6.0(6.2)	High Interaction Tests																										0	
7.0	CDIF Field & Test Support																										97	
8.0	Program Management																										92	
9.0	Configuration Management																										99	
10.0	Q.A. Requirements																										Complete	
11. Remarks																												
12. Signature of Contractor's Project Manager and Date R Kinsle														13. Signature of Government Technical Representative and Date														

Fig. 2.1 Program Schedule

3.0 MHD CHANNEL DESIGN AND PERFORMANCE, TASK 1

3.1 SUMMARY

The principal technical efforts performed during this quarter were the completion of the reduction of the test data from the high Hall voltage tests, the initial test series using the high magnetic field, supersonic channel designed to operate at conditions producing a high Hall parameter, and the initial test of the laser doppler velocimeter (LDV) system from Mississippi State University (MSU) in the Avco Mark VI test facility.

Tests were conducted to assess the effect of high Hall voltage on the operation of the Reference Channel No. 3 and the Mark VI test facility. The Hall voltage was varied by varying seed concentration. The seed was varied from 0.001 percent to 1.75 percent by mass potassium concentration, and Hall voltages up to 5000 V were obtained. These tests were conducted with western ash.

The initial tests of the high magnetic field, supersonic channel were completed. During these tests the channel produced $\sim 310 \text{ kW}_e$ of output power at a Hall voltage of 2500 V. These tests are continuing and only the initial results are discussed in this report.

An LDV system from MSU was installed in the diffuser of the Reference Channel No. 3 flow train. Velocity profiles were obtained in the direction parallel to the magnetic field at an axial location $\sim 70 \text{ cm}$ downstream of the channel/diffuser interface. At low velocities agreement was obtained between the centerline velocity measured by the LDV and the total stagnation pressure probe.

The Reference Channel No. 3 test data reduction and analysis is discussed in Section 3.2. The initial test results from the high magnetic field, supersonic channel tests are shown in Section 3.3. The results from the LDV measurements are presented in Section 3.4.

3.2 REFERENCE CHANNEL NO. 3, TASK 1.1

The last test sequence of the Reference Channel No. 3 subsonic generator test program was an investigation of the effects of potassium seed variations on the performance of the generator. Seed concentrations ranging from 0.001 to 1.75 percent by mass potassium of the total mass flow with no ash (bare walls) and eastern and western ash (slagged walls) were investigated. The purpose of these tests was to provide data at high Hall voltages for comparison to the Avco computer models as well as to investigate the effects of seed loss on a loaded MHD generator.

3.2.1 Description of the Experiment

The experiment was performed using the Reference Channel No. 3 subsonic generator which was loaded as shown in Fig. 3.1. The operating conditions for the test are shown in Table 3.1. Mass flow rate, N/O ratio, and equivalence ratio were held relatively constant.

Tests were conducted using both liquid and powder seed. With liquid seed, the seed concentrations were altered by varying the amount of potassium carbonate in the water solution and introducing the solution at two relatively constant flow rates. Using this procedure, the seed concentrations in the plasma were varied from 0.001 to 1.75 percent by mass potassium. With powder seed, seed concentrations were changed by varying the amount of dry seed injected into the burner. Dry seed could be controlled only to levels of about 0.3 to 2.0 percent by mass potassium because of the limitations of the seed injection system.

During the test, mass flow, N/O, stoichiometry and seed injection rates were held constant and then data was taken at magnetic fields of 0, 2, and 4T. The experiment was performed first with no ash injection, which results in clean channel walls. Seed injection was gradually increased with both wet and dry seed. Without any ash injection the N/O ratio was 0.4.

After the experiments were completed without any ash, the test sequence was repeated with eastern ash injection and then with western ash injection. The operating condition with ash injection and slagged walls was at $N/O = 0.8$. The lower N/O ratio used with the no ash tests partially compensated for the higher heat fluxes, and thus, colder plasma of these no ash, bare wall tests. The N/O variation between the ash injection case ($N/O = 0.8$) and the no ash case ($N/O = 0.4$) resulted in similar generator electrical conductivities.

3.2 Experimental Results

The results of these tests are shown in Figs. 3.2 through 3.8 in which the conductivities, Hall voltage, and power are compared at peak magnetic fields of 0, 2, and 4T for the conditions of bare and slagged walls. The comparison between bare and slagged walls is not directly comparable because of the large differences in combustor efficiency and channel heat losses. The comparison between the two slag conditions is significant, however, because the heat losses in the combustor and channel are comparable. The curves have been approximated through the data to show the general trends in the data.

Though the conductivities shown in Fig. 3.2 were similar when operating with clean walls or walls covered with eastern and western ash, differences were apparent in the generated power output and Hall voltages. These differences are most notable at 2T and low seed concentrations. As the seed concentrations are increased, the Hall voltage (Figs. 3.3, 3.4 and 3.5) increases to a maximum and then decreases. The maximum voltage point moves from a seed concentration of 0.04 percent by mass K with bare walls, to 0.3 percent K with

Fig. 3.1 Faraday Load Profile

TABLE 3.1
TEST CONDITIONS INVESTIGATED

Total Mass Flow Rate (kg/s)	2.0	2.0	2.0
N/O	0.4	0.8	0.8
Equivalence Ratio	1.06	1.06	1.06
Magnetic Field (T)	0,2,4	0,2,4	0,2,4
Ash	--	Eastern	Western
Seed (percent by mass K) wet	0 - 1.75	0 - 0.97	0 - 1.74
dry	0.14 - 2.03	0.54 - 1.99	0.59 - 1.99

Fig. 3.2 Average Electrical Conductivity for Various Potassium Seed Concentrations

Fig. 3.3 Hall Voltage for Various Potassium Seed Concentrations (No Ash)

Fig. 3.4 Hall Voltage for Various Potassium Seed Concentrations (Eastern Ash)

Fig. 3.5 Hall Voltage for Various Potassium Seed Concentrations (Western Ash)

Fig. 3.6 Output Power for Various Potassium Seed Concentrations (No Ash)

Fig. 3.7 Output Power for Various Potassium Seed Concentrations (Eastern Ash)

Fig. 3.8 Output Power for Various Potassium Seed Concentrations (Western Ash)

eastern ash on the walls, and to 0.6 percent K with western ash on the walls. The same trend occurs in the 4T data although the peak for the bare wall condition was not identified because it occurs at very small seed concentrations.

In Figs. 3.6, 3.7, and 3.8, the effect of the wall condition on the output power is noted by the decreasing power levels at given seed concentrations as the tests progressed from bare walls, to eastern ash and then to western ash. In both the power and Hall voltage data, the effects of the wall condition are hard to distinguish at normal seed concentration of about 1 percent by mass K.

The reason for this effect is probably slag conductivity. As the slag or wall conductivity increases the generator must produce more power in order to maintain given Hall voltages. Figures 3.9 and 3.10 demonstrate the effect of varying the slag conductivity as calculated by the AERL design and predictive code MHD4 using an infinite segmentation model. The same qualitative effects are evident in the analysis as in the data.

Based on the comparison between the analysis and the data at 4T, slag conductivity should be between 10 and 100 mho/m. A choice of 10 mho/m for the slag conductivity would be made based on the results from the power curve, and ~ 100 mho/m would be required to match the Hall voltage. This disagreement was one of the problems which has prompted the development of a segmented Faraday electrical model. Though still under development this model provides much better agreement. Comparisons between the 2T analysis and data are inadequate for estimating the slag conductivity.

After the testing, analysis of dry seed conditions was performed with the finite segmentation electrical model at 4T using a slag conductivity of 15 mho/m. In Figs. 3.11 and 3.12, the results of this analysis effort are compared to the data obtained for the eastern and western ash tests with dry seed. The comparison between the experimental data and the calculated results using the finite segmentation model shows excellent agreement.

3.2.3 Conclusions

Tests of the Reference Channel No. 3 were performed to determine the effect of varying the seed concentration and slag composition on the performance of the generator. The results of these tests are presented and can be compared to the predictions made by the AERL MHD4 computer model. Calculations were made assuming both infinite and finite segmentation. Results with the infinite segmentation model are mixed while the results obtained from the finite segmentation model compare well with the 4 Tesla data.

Since development of the finite segmentation model is continuing, future work will include more comparisons of this model with data.

Fig. 3.9 Calculated Power for Various Potassium Seed Concentrations as a Function of Slag Conductivity

Fig. 3.10 Calculated Hall Voltage for Various Potassium Seed Concentrations as a Function of Slag Conductivity

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Fig. 3.11 Electrical Power for Various Potassium Seed Concentrations

Fig. 3.12 Hall Voltage for Various Potassium Seed Concentrations

3.3 DRAFT FAN EXPERIMENTS, TASK 1.4

The test series using the supersonic, high magnetic field channel with the draft fan was initiated. These tests use the modified Ref. No. 3 channel and are being conducted at electrical conditions similar to the supersonic Advanced Power Train (APT) channel designs.¹ To obtain these electrical conditions, a draft fan is used to reduce the pressure distribution in the hot gas flow train. Figure 3.13 shows a schematic of the generator test configuration including the draft fan. Reference No. 2 provides a complete description of the draft fan.

The design of the channel for these experiments has been reported in previous quarterly reports.^{3,4} Figure 3.14 shows the dimensional relationships of the MHD channel and magnetic field profile. The channel is loaded in the Faraday mode with a load resistance profile designed to produce conditions with a high transverse electric field (E_y) and a high Hall parameter (β), as well as simulate the supersonic APT channel design axial electric field (E_x) and transverse current density (J_y).

The tests were conducted with slagged walls using eastern ash. The experimental operating conditions are listed in Table 3.2. These conditions were selected to provide the APT electrical conditions.

Some preliminary data from the initial tests of the channel has been reduced. This data is for the nominal operating conditions and is compared with the performance predictions. Except for the Hall voltage, the results agreed with the predictions.

The operating conditions differ slightly from the conditions of the pre-test predictions. These differences result from small deviations in the flow from assigned conditions. Consequently, the N/O ratio, the stoichiometry, the potassium seed rate, and the total mass flow differ slightly from the pre-test predictions. For example, in the conductivity measurements the theoretical curve is below the experimental curve for most of the axial length. This is consistent with the lower N/O and higher seed rate used in the experiment. Variations of this type are considered normal experimental errors.

In addition to the discrepancies described above, the electrode model used for the pre-test calculations assumed finite segmentation and the number of cathodes shorted to be one. While this assumption is not exactly correct, it provides a reasonable slag shorting model for Eastern ash. Post-test performance analysis will be used to assess the effect of the actual cathode wall short distribution.

The electrical conductivity of the gas was measured before and after each power run. Figure 3.15 shows the predicted electrical conductivity of the gas and the measured conductivity for the nominal design condition. Figure 3.16 shows a similar comparison for the static pressure.

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1. CLOSURE PLATE	7. PUMP ISOLATION VALVE
2. CLOSURE PLATE	8. CYCLONE DRAIN VALVE
3. CLOSURE PLATE	9. QUENCH WATER PUMP FLOAT SWITCH
4. PRESSURE RELIEF VALVE	10. BLOWER INLET SILENCER FLOAT SWITCH
5. VACUUM CONTROL VALVE	11. MAXIMUM WATER LEVEL FLOAT SWITCH
6. VACUUM RELIEF VALVE	P3 BLOWER PRESSURE DIFFERENCE

Fig. 3.13 Mark VI/Mark VII Draft Fan Schematic

Fig. 3.14 High Magnetic Field Channel Dimensions with Magnetic Field Profiles

TABLE 3.2

CHANNEL OPERATING CONDITIONS
SUPERSONIC, HIGH MAGNETIC FIELD TESTS

Mass Flow	1.5 kg/s
N/O	0.8
Seed Fraction	1.0 percent K (wt)
Oxygen Stoichiometry	0.9
Inlet Conductivity	10 mho/m
Inlet Mach No.	1.35
Faraday Loads	Variable Profile
Ash Carryover	10-20 percent

CHANNEL ELECTRICAL CONDITIONS

		<u>Test</u>	<u>APT</u>
Transverse Electric Field	kV/m	3.5	4.0
Axial Electric Field	kV/m	1.8	1.9
Transverse Current Density	A/cm ²	0.83	0.84
Hall Parameter	-	4.0	3.9

Fig. 3.15 Comparison of Calculated and Measured Electrical Conductivity

Fig. 3.16 Comparison of Calculated and Measured Static Pressure ($B = 0$)

Power tests at this operating condition were also performed. In Fig. 3.17, the static pressure distribution for the generator operating at 4 T is shown. The axial voltage profile is shown in Fig. 3.18. The power generated agrees well with the predicted power. The generated Hall voltage is substantially less than the predicted Hall voltage. A comparison of the transverse current density is shown in Fig. 3.19.

These experiments are continuing, and during the next quarter additional tests and data reduction will be completed. These will include tests at the high Hall parameter conditions and the APT channel design conditions. Seed variation tests will also be conducted.

3.4 ANALYTICAL MODELING, TASK 1.5

During this quarter the Mississippi State University (MSU) MHD Energy Center conducted a joint experiment with Avco using the MSU laser doppler velocimeter (LDV). The purpose of this experiment was to demonstrate the capability of the MSU monochromatic LDV for measuring plasma velocities in MHD flow trains in the presence of high magnetic fields, and ultimately to measure MHD velocity distributions to confirm analytical models.

3.4.1 Description of the Experiment

The experiment was performed with a portable LDV developed by MSU. Details of the LDV are contained in the MSU quarterly progress report.⁵ Optical access to the plasma was provided through the diffuser sidewall port of the Reference Channel No. 3 diffuser. This port was used previously for the stagnation pressure probe measurements. During the testing the stagnation pressure probe was mounted in its top wall port and traversed to compare centerline values of the velocity to those obtained with the LDV.

The test of the LDV system was performed during the preliminary tests of the supersonic, high magnetic field test program. The conditions at which the measurements were made are shown in Table 3.2. After the LDV was removed, this channel was operated again at the same conditions with the stagnation pressure probe positioned in the sidewall port. Stagnation pressure profiles were obtained for comparison to the measurements made by the LDV.

3.4.2 Experimental Results

The setup and use of the MSU LDV was accomplished without any difficulties. The comparisons of the velocity profiles measured by the LDV and the stagnation pressure probe are shown in Figs. 3.20 and 3.21. Measurements of the velocity profiles determined with the stagnation pressure probe rely on use of the isentropic expression relating stagnation pressure and static pressures to Mach number. Velocities are calculated assuming a constant sound speed given by analysis of the operating conditions with the Avco computer code MHD9. The uncertainty in the sound speed gives high and low values of the plasma velocity.

Fig. 3.17 Comparison of Calculated and Measured Static Pressure (B = 4T)

Fig. 3.18 Comparison of Calculated and Measured Hall Voltage

Fig. 3.19 Comparison of Calculated and Measured Transverse Current Density (Jy)

Fig. 3.20 Velocities Obtained from MSU LDV (Supplied by MSU)

Fig. 3.21 Velocities Calculated from Stagnation Pressure Probe Data

In comparing the data, good agreement was obtained at the lower velocities created when the magnetic field strength was at its peak. The comparison between the lower magnetic field data is not as good. The reason for this discrepancy has not as yet been identified. Discussions are in progress with MSU. The results of this comparison are summarized in Table 3.3.

3.4.3 Conclusions and Future Work

The transport and setup of the MSU LDV system was accomplished very quickly and efficiently. Velocity measurements of particles in the MHD plasma were made with the MSU LDV. The particles in the plasma appeared to be ash particles because their density decreased significantly when the ash was removed. Separate measurements of the plasma velocity were made with a stagnation pressure probe. Comparisons between the resulting data indicate good agreement at the lower velocities associated with high field strengths and less satisfactory agreement at the higher velocities which occur at low field strengths. Additional interaction between Avco and MSU will continue and further experiments may be conducted in the future.

TABLE 3.3
COMPARISON OF RESULTS TAKEN FROM STAGNATION
PRESSURE PROBE AND LDV

Peak Magnetic Field (T)	Centerline Velocity Measured by	
	Probe (m/s)	LDV (m/s)
0	1110 - 1230	800
2	990 - 1110	700
3		625
4	490 - 550	650

SECTION 3.0

REFERENCES

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2. "MHD Generator Component Development," Avco Everett Research Laboratory, Inc., Quarterly Report, Contract No. EF-77-C-01-2519, June 1980.
3. "MHD Generator Component Development," Avco Everett Research Laboratory, Inc., Quarterly Report, Contract No. DE-AC22-80-ET15614, May 1983.
4. "MHD Generator Component Development," Avco Everett Research Laboratory, Inc., Quarterly Report, Contract No. DE-AC22-80-ET15614, August 1983.
5. "Diagnostic Development and Support of MHD Test Facilities," Mississippi State University, Quarterly Report, Contract No. DE-AC02-80-ET15601, October 1983.

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4.0 MHD CHANNEL CONSTRUCTION AND LIFETIME, TASK 2

4.1 SUMMARY

Tests of ceramic elements were continued in the Mk VII channel. Various designs and cooling techniques were tested. Hot-pressed silicon nitride appears promising, but fracture free operation has not been achieved. Electrical erosion of silicon carbide electrode is substantial. Exploratory experiments to test the influence of gas injection on electrode/channel performance as well as replacement of potassium seed by cesium ore have been performed.

Supporting experiments are in progress and will be reported later. They include:

- Development of techniques for joining ceramics to cooled supports.
- Study of intercathode arcing in the presence of slag layer.

4.2 CHARACTERIZATION OF THE MK VII TESTS

General characteristics of the last four Mk VII tests are given in Table 4.1. In the last column of the table the experiments and measurements conducted during these tests are listed.

4.2.1 Thermal Conditions

In this series of experiments, heat flux to 12 individual copper and ceramic elements in the electrode walls and the side walls were measured and recorded (in addition to the total heat flux to channel walls). To reduce measurement errors mentioned in previous tests⁽¹⁾ water flow through individual electrodes was reduced to 0.75 gpm. Beginning from Test VII, nitrogen cooling was replaced by air cooling, the air being supplied by a separate line from the exit of the main compressor, at 70-80 psig pressure. Air temperature at the entrance of the cooling passages in the ceramic elements was about 70°C or 80°C higher than in the case of nitrogen cooling. The difference corresponds to ~ 20 percent reduction of cooling efficiency at the same gas flow rate.

Maximum air temperature at the exit of the cooling passages was 250°C. Depending on the design of the ceramic element and its contact with copper, 60 to 80 percent of the heat was transferred to the gas. No enhancing devices for heat exchange improvement were used in these tests.

TABLE 4.1
Mk VII TEST RUNS

<u>Data</u>	<u>Test No.</u>	<u>Test Duration, min</u>		<u>Design</u>		<u>Observations and Measurements</u>
		<u>Burner Time</u>	<u>Magnet Time</u>	<u>Extension</u>	<u>Main Channel</u>	
4-29-83	VII	268	45	Fig.*4.1a,b	Fig. *4.3 - Cathode Wall	1,2,3,4,5,7
6-24-83	VIII	284	48	Fig. 4.2 + Fig. 4.4	Fig. 4.5 - Anode Wall	1,2,3,4,7,8,
7-13-83	VIIIa	130	30		Fig. *4.1c + Fig. 4.5 - Left Sidewall	1,2,3,4
8-26-83	IX	240	50		Fig. 4.6 - Right Siewall	1,2,3,4,5,6,8,9

* From Report FE-15614-16

1. Observation of erosion and fracture
2. Heat fluxes, surface and gas temperature
3. MHD current and voltage distribution
4. Interelectrode breakdown and current
5. Voltage applied from external power supply
6. Conductivity measurements
7. Gas and slag sampling
8. Gas injection
9. Cesium ore feeding

The values of heat flux to individual elements and time histories for a few selected pieces are shown in Table 4.2 and Fig. 4.1. Changes in heat flux during the tests, under constant thermal input, are due to several factors: slagging, generation of electrical current, current supplied from external source, gas injection, feeding cesium ore into the combustor. The increase of heat flux to electrodes by current transport was substantial, up to 40 percent at some anodes. Additional Joule heating of the boundary layer or the slag layer was transmitted to downstream elements only along the affected wall, and did not influence the other channel walls.

4.2.2 Behavior of Ceramic Elements - Erosion and Fracture

Principal information which describes behavior of the ceramic elements during the four tests is presented in Table 4.3. The following conclusions can be drawn with respect to particular materials:

1. Hot pressed silicon nitride (HPSN) plates in the extension top wall and in the anode wall (element 43a), which have combined contact and gas cooling, were exposed to moderate heat flux ($q_{av} = 70-80 \text{ W/cm}^2$, $q_{max} = 140-180 \text{ W/cm}^2$) and remain in good condition. After 30 hours of service, no appreciable erosion occurred. However, development of superficial white discoloration was observed, presumably due to surface oxidation (Fig. 4.2). The oxide layer is more pronounced on the surfaces of elements adjacent to the gap where the strongest leakage of cooling air occurred. Axial breakdowns induced by externally applied voltage between copper electrodes leave traces on the surface of silicon nitride separators (Fig. 4.3). It is possible though that the higher temperature of these elements, compared to that of the narrower spacers is responsible for stronger oxidation.

Cracks developed in the HPSN element of the extension bottom wall and reaction sintered silicon nitride in the anode wall. They were cooled by internal gas flow (Fig. 4.3, 4.4). The same phenomenon was observed in earlier tests of internally cooled elements and silicon nitride plates with sides exposed to the flow and cooled from the bottom. It seems that the temperature field and thermal stress distribution in side-cooled plates is more favorable. The observations are not conclusive - two other internally cooled HPSN elements (No. 40 and 42 in anode walls) did not fracture despite higher thermal fluxes, up to 180 W/cm^2 . Additional mechanical stresses arise when thermal deformation of elements is restricted. These stresses depend on position and anchoring of the specific element. From tests of only a few ceramic elements it is difficult to determine which of these factors is most critical in fracturing. It should be mentioned that the electrode walls of the Mk VII channel that were used for these experiments were built using worn copper elements. In some cases this results in poor ceramic/copper alignment and partial exposure of the edges and side surfaces of some ceramic elements to the hot flow.

2. Silicon carbide "Crystar" (made by Norton Co.) electrodes installed in the main channel and in the extension bottom wall experienced substantial erosion after (3-6) power generating hours. This corresponds to charge transfer of 1.10^5 - 5.10^5 coulombs. Thermal tests of these electrode continued for 30-50 hours.

TABLE 4.2
HEAT FLUX TO INDIVIDUAL WALL ELEMENTS

<u>Element. No.*</u>	<u>Heat Flux, W/cm² Time Averaged</u>	<u>Maximum</u>
10- bottom	120	170
10 side, ceramic	100	150
31+ top	130	220
31- bottom	90	140
34+ top	140	220
34- bottom	75	110
39+ top	60	190
39- bottom	95	130
51+ top	80	150
51+ bottom	50	100
51 side, ceramic	70	100

*The number indicates the axial distance from channel inlet (= No. x 0.7 in.)

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Fig. 4.1 Heat Fluxes to Some Mk VII Channel Elements during Run IX.

TABLE 4.3
BEHAVIOR OF CERAMICS IN MK VII TESTS

PART OF THE CHANNEL	TEST			
	VII	VIII	VIIIA	IX
Extension, top wall	No visible damage of Si-N. Substantial gas leakage between ceramic elements	No changes except whitish surface	No changes	No changes
Extension, bottom and sidewalls	Transverse fracture in bottom Si-C; No damage in SiN, small leak. Gas leak through old crack and pores in side SiC	Transverse fracture in SiN. Channel left assembled for the next test, detailed investigation impossible. No mechanical damages. Some gas leaks.	No changes	Some surface erosion of SiC. Increased leaks through cracks in SiC and SiN
Channel, top wall (anode)	Electrical erosion (~ 0.2 mm deep) of SiC anodes. Si-N in good condition; micro-cracks on the surface		No changes except small crack in gas-cooled Si-N	No changes except small erosion of SiN
Channel, bottom wall (cathode)	Moderate electrical erosion of SiC cathodes. No fractures		No changes	Deeper erosion of SiC cathodes at trailing edges
Channel, left sidewall	Small erosion of SiC (crystalon) elements. No fractures		No changes	Non-uniform erosion of SiC elements
Channel, right sidewall	-	No water leaks in SiN (Wesgo). Water-cooled elements	Fractures and water leaks in 7 Si-N (Wesgo) elements	Fractures and water leaks in 10 Si-N (Wesgo) elements

Fig. 4.2 Extension Section after Test VIIIa. HPSN electrode separators in a top wall; crystolon element in a side wall.

Fig. 4.3 Anode Wall of the Main Channel after Test VIII - 40,42, 46 Air Cooled HPSN, 46 (Bot)-Water Cooled HPSN, 43a - Contact Cooled HPSN, 38-Gas Cooled SiC-Si Anode.

Fig. 4.4 Extension Section after Test VIII. HPSN (cracked) and Si-C cathodes in a bottom wall.

As in previous tests, anode erosion was more severe than cathode erosion, which can be partly attributed to the higher temperature of the anode wall. The measured maximum heat fluxes to the anodes and cathodes were 200 W/cm² and 150 W/cm² respectively. In addition to electrical erosion which concentrates in the areas of high current density the U-shaped cross section electrodes tend to have transverse fractures (Fig. 4.4). Notwithstanding formation of these cracks, electrodes in the main channel still retain working capacity and were left in their positions for more further tests under power-generating conditions.

3. Silicon carbide "Crystalon" (coarse grained Si bound material) elements have, as has been shown earlier, lower erosion resistance. They had been installed to test feasibility of the "checker-board" side wall design in which ceramic gas-cooled elements separate water-cooled copper bars (Fig. 4.5a,b). After 11 hours of cumulative testing, a 4-row wall section shows substantial erosion (local defects up to 2 mm deep), but is still useable.

4. Many of the water-cooled reaction bonded silicon nitride (RBSN) elements installed in a right sidewall parted during their initial test, many of them fractured, and serious water leaks developed. These elements were positioned between successive copper peg rows (Fig. 4.6). A cross section of the row containing a ceramic element is shown in Fig. 4.7. Two kinds of ceramic element were used, differing by the distance between the heated surface and the cooling passage. In addition, two different silicon nitride powders were used by Wesgo Co. to manufacture these elements. Therefore the elements were quoted as having somewhat different composition, hardness and thermal shock resistance. However, no substantial difference in behavior of the two different materials was observed. Development of fractures in approximately half of the elements shows that thermal stresses surpass tensile strength. For RBSN the thermal stress resistance factor $R = \sigma E / \alpha = 300-400K$ (where α is a coefficient of thermal expansion, E is the modulus of elasticity and σ is the tensile strength). This value approximates the temperature gradient which this material can sustain. The temperature difference between the heated and the water-cooled parts of the ceramic blocks is about 400°C; this shows that thermal stress resistance is marginal. Reduction of the cross section by longitudinal slag-retaining grooves, stress concentration at corners, introduction of microcracks by machining, possible additional stresses from anchoring and during transients caused by start-up and shutdown and slag irregularities are all possible reasons for thermal stresses to exceed tensile strength. A typical fracture pattern is shown in Fig. 4.8. Computation of the temperature field and stress distribution is planned. Replacement of water cooling by gas cooling is not expected to reduce thermal stresses for slagged surfaces when heat fluxes are essentially constant. Hence, temperature gradients are nearly the same irrespective of cooling medium. However during unslagged periods of operation, the stresses in gas-cooled elements should be lower. More importantly, the cooling gas leakage which would occur in the event of fractures of gas-cooled elements would not quench the plasma as would a water leak, and hence, performance deterioration would be much less.

Fig. 4.5a Section of the Sidewall Containing Alternate Gas-Cooled SiC (Crystolon and Water-Cooled Copper Elements before Tests.)

Fig. 4.5b Same Sidewall as in Fig. 4.5 after Test VIIIa. Slag layer formed by pollucite is seen at the right.

Fig. 4.6 Sidewall with Ceramic Water-Cooled Elements

Fig. 4.7 Cross Section of the Copper Peg-Ceramic Row in a Sidewall.

Fig. 4.8 Part of the Sidewall after Test IX. Typical fracture in RBSN ceramic elements No. 30, 32, 34, 37, 41. Erosion of upstream edges of elements No. 45, 47 is visible.

Fracture of silicon nitride elements in the last two tests does not mean that direct water cooling of this ceramic is impossible. Besides un-optimized geometry of the elements, anomalies in the Mk VII operation due to pollutite injection produces stronger than usual variations in heat fluxes and gas pressure. Additional tests of silicon nitride elements of improved geometry or orientation are needed.

4.3 GAS INJECTION EXPERIMENTS

4.3.1 Effects of gas injection in the Mk VII channel through the electrode walls have been studied for two reasons:

- It is felt that some leakage of the gas through walls containing gas-cooled ceramic elements is inevitable because it is difficult, if not impossible, to prevent ceramic fractures, development of porosity, and loss of sealing in the joints between wall elements. These types of defects can be considered permissible from the point of view of overall structural and electrical integrity.
- Gas injection could be used as a method to provide efficient cooling of the wall elements, as for instance, in gas turbine blade cooling. It could be combined with internal gas or water cooling of the wall elements. Film cooling of the side walls may increase their breakdown strength. Injection cooling of the electrode walls however will increase the electrical resistance of the boundary layer. It has been shown^(1,2) that wall heat fluxes could be reduced very substantially by gas injection through porous or perforated walls without reducing performance of the MHD system as a whole, if the amount of injected gas does not exceed 10-30 percent of the total flow (depending on other parameters). Transfer of the thermal energy to the injected gas instead of the cooling water also has the advantage that no special provisions are necessary to conduct energy to a downstream (steam) part of the power plant. However, despite its many advantages the film cooling concept is difficult to implement in other than clean fuel situations.

4.3.2 Experiments

Air, nitrogen, and methane oxygen mixture were injected in anode and cathode boundary layers through a perforated gap between electrodes No. 30 and 31 (Fig. 4.9). Influence of the injection on heat flux, current and voltage distribution, generated electrical power, plasma conductivity and interelectrode breakdown were studied for slagged as well as unslagged walls. Fig. 4.10 and Fig. 4.14 illustrate some results which could be summarized as follows:

- Heat flux to the immediate downstream electrodes (No. 31) are reduced 30-80 percent depending on the flow rate of gas injected. (These flow rates were about 25-60 percent of the gas which was used for internal convective gas cooling of electrodes.)

Fig. 4.9 Schematic of Gas Injection in Anode and Cathode Boundary Layers.

Fig. 4.10 Injection of Nitrogen and Oxygen-Methane Mixture in Unslagged Channel. Influence on heat flux and current to anodes No. 31 and 34.

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Fig. 4.11 Injection of Nitrogen in Anode and Cathode Boundary Layers of a Slagged Channel $G_{inj} = 8$ g/sec.

Fig. 4.12 Redistribution of Current and Voltages during Oxygen-Methane Injection in Unslagged Channel.

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Fig. 4.13a Changes in Cathode

Fig. 4.13b Voltages during Nitrogen Injection in Slagged Channel.
 $G_{inj} = 8 \text{ g/sec.}$

Fig. 4.14a,b Changes in Current (a), Power and Electrical Field (b), during Nitrogen Injection in Slagged Channel. $G_{inj} = 8$ g/sec.

- Decrease of heat flux to electrodes located further downstream is less pronounced, but it could be still felt 5-6 pitches (10 cm) apart.
- Continuous injection of gas through a slagged wall is possible. The reduction of heat flux is even somewhat stronger for a slagged wall; probably the slag layer thickness is increasing or a gas gap is formed between the slag and the electrode surface.
- Gas injection in the electrode wall boundary layer has no influence on the sidewall heat flux. Minor influence is felt on the opposite electrode wall through the core flow. At high injection rate and unslagged wall the opposite wall was observed to experience a 5-10 percent increase in heat flux. This could be explained by a "shift" of the main flow by the injection gas momentum.
- All 3 types of gases injected had the same observed effects, which means that combustion does not take place in the boundary layer. With injection velocity transonic, the residence time of the portion of the gas in a boundary layer on the perforated electrode and several downstream electrodes (i.e., region where changes in heat fluxes were measured) is about 10^{-4} sec. This is not enough to produce local thermal effect of combustion even when premixed CH_4/O_2 gas was injected. The heat of combustion must therefore be distributed over the downstream part of the channel. An increase in the injected mass of combustible gas through several electrodes of an order of magnitude is necessary to determine if local heating of the boundary layer and an increase of the electrical conductivity takes place.
- Electrical currents, generated power and E_x component of electrical field are reduced downstream of the injection point (Fig. 4.14). This reduction is lower percentage wise than the reduction of heat flux. This unfavorable effect will be less important for a large channel, but any increase in injected gas conductivity is important. Bulk plasma conductivity changes appear not to exceed 10-20 percent.
- Some voltage redistribution along the wall takes place. The most pronounced increase in potential difference is across the gap where gas is injected. Breakdown voltage between adjoining electrodes increases ~ 1.5 times (from 80-85 V to 120-130 V without a slag layer and magnetic field). According to the limited data obtained, a wall with gas injection would be able to sustain somewhat higher electrical fields than a conventionally cooled wall.

More systematic study would require injection of gases in several locations in the channel, preheat and seeding of the injected gas.

4.4 EFFECTS OF INTRODUCING A CESIUM ORE (POLLUCITE) IN MK VII CHANNEL

4.4.1 Prospects for Pollucite Use in MHD Generation

Using cesium instead of potassium as seed in an MHD channel is preferable because high gas conductivity could be achieved at the same temperature or, alternatively, the same conductivity obtained at a lower temperature. Unfortunately, the cost of cesium salts is intolerably high. Among cesium containing minerals pollucite has the lowest specific cost. However, its cost is still 5 times higher than potassium carbonate. Therefore, use of pollucite in MHD power generation would be possible only if: a) a 100 percent recovery system, or b) a useful by-product is developed. Glass-ceramics based on pollucite display unique refractoriness, having the highest melting point of any silicate above 1900°C, high thermal stability, corrosion and shock resistance and very low porosity. These properties may be used to advantage in channel design. The higher temperature of the slag surface would reduce heat losses, whereas reduction of concentration of iron and alkali-earths elements and increase of the slag layer thickness would probably reduce nonuniformities in voltage distribution. To obtain at least preliminary understanding of these problems, experiments with pollucite have been conducted on the arc heater - combustor rig and during two Mk VII tests.

4.4.2 Pollucite in Arc-Heater Rig Experiment

Pollucite powder was introduced in a hot flow 10 cm upstream of the slagging channel under conditions listed in Table 4.5. The residence time of the particulates in the flow was about 5 msec. Approximately 50 percent of the material was melted and formed a glassy or ceramic-like mass with a light-blue tint, and could be collected at the channel exit. The rest of the material was carried away as solid particles or as vapors. A plasma conductivity of about 10 mho/m was calculated from current and voltage distribution measurements along the channel.

For comparison, two other powders were introduced under the same conditions:

- A K_2CO_3 + western ash mixture provided the same conductivity at 12-14 g/min powder flow.
- Cs_2CO_3 powder provided 11-15 mho/m conductivity at lower (5-6 g/min) flow.

The results indicate that pollucite powder injected at the same rate as K_2CO_3 seed powder should provide approximately the same conductivity, as is to be expected.

4.4.3 Pollucite in MK VII Tests

During Mk VII tests VIIla and IX, pollucite powder was injected axially in the combustor at rates from 1 to 2 kg/min using one of the ash feeders. The following thermal and electrical phenomena were observed:

TABLE 4.4

COMPOSITION OF CESIUM ORE - POLLUCITE
(FROM BERNIC LAKE, MANITOBA, CANADA)

Cs_2O	27 percent
$\text{Rb}_2\text{O} + \text{K}_2\text{O}$	3
Fe_2O_3	0.1
Al_2O_3	17
SiO_2	49
Other oxides and elements	~ 3

TABLE 4.5
CHARACTERIZATION OF ARC HEATER RUN WITH POLLUCITE

Slagging Channel Dimensions	2.3 x 2.3 x 12 cm
Electrical Power	36 kW
Combustion Power	13 kW
Gas Flow (N ₂ + O ₂ + CH ₄)	150 g/min
Conductivity (measured)	8-12 ohm/m

- Initial transient increase of heat flux to the channel walls, due to increased radiative heat transfer or to increased gas temperature from reduced combustor heat loss resulting from increased slag layer thickness.
- Substantial redistribution of heat flux to the channel walls (Fig. 4.1). The heat flux to the side walls and to the bottom wall was reduced and the heat flux to the top wall increased. This could be explained by distortion of the gas flow due to formation of a thick slag deposit at the bottom of the combustor and nozzle or, more probably, by the downward flow of the low-viscosity slag under the influence of gravity. Indeed, observation of the slag flow* revealed high slag mobility. The slag flowed along the side wall with a high degree of fluidity approaching that of water, with a surface temperature of 1950 (+ 50) K. Fig. 4.5b and Fig. 4.15 illustrate appearance of the pollucite slag layer in the channel and nozzle respectively.
- Conductivity of the pollucite-seeded plasma was rather low and did not change substantially along the channel. Increase of the pollucite feed rate from 1.3 to 2 kg/min did not help. Conductivity of the potassium seeded plasma at about the same thermal input ($N/O = 0.97$) was nearly two times higher than that of the pollucite (Fig. 4.16). Typical current per electrode did not exceed 3A during pollucite seeding, voltages were low and pulsating, probably following irregularities in pollucite injection or evaporation. The generated power was under 1.5 KW, compared to 4 KW with potassium seeded plasma under the same thermal conditions.

Measured conductivity was compared to the results of calculations assuming thermal equilibrium. Figure 4.17 shows the conductivities resulting from the introduction of equal amounts of potassium carbonate and pollucite in a coal combustion gas. According to Cs plasma conductivity data from [3], approximately twice as much pollucite is needed to reach the conductivity of potassium carbonate seeded gas.

The measured conductivity of the potassium-seeded plasma agrees well with predictions. The Cs conductivity values at the same locations and the same thermal conditions are 25-50 percent lower than theoretical curve. At least three factors could be responsible for the discrepancy.

- Gas temperature is lower in the case of pollucite seed.
- Cesium is only partially evaporated from pollucite. High refractivity and thermal stability of pollucite makes this a reasonable explanation. Refractivity of pollucite was not taken into account in calculations. It was assumed that $Cs_2O - Al_2O_3 - SiO_2$ powder with elemental composition equivalent to pollucite is introduced.

*It has been made possible by installation of a viewing port protected from slagging by an auxilliary hot combustion gas flow.

Fig. 4.15 Pollucite Slag in Mk VII Channel after Test VIIIa. A view from the channel entrance.

Fig. 4.16 A Comparison of the Plasma Conductivity with Potassium and Cesium (Pollucite) Seed

Fig. 4.17 Conductivity of Potassium Carbonate-Seeded and Pollucite-Seeded Combustion Products.

- Both test Nos. VIIIa and IX were terminated due to damage of side-wall elements. In test VIIIa a pressure build-up in the combustor and channel resulted in gas leak between channel walls. After disassembling, the combustor was found partially filled with pollucite slag (Fig. 4.18). In test IX several silicon nitride elements in the right side wall fractured. It is difficult to ascertain if heat flux redistribution and slag run-down from ceramic elements were responsible for the fractures or if some of the fractures occurred independently of the pollucite.

Fig. 4.18 Combustor Inside View after Test VIIIa. Maximum pollucite injection rate. 2.5 Kg/min at $N/O \approx 0.9$.

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5.0 MHD CHANNEL LOADING AND CONTROL, TASK 3

As previously reported⁽¹⁾ the initial testing of a relatively new semiconductor device called a Gate Turn-off Switch (GTO) has begun. The GTO's could potentially replace all the SCR's in the present current control and consolidation circuitry, principally because of the likelihood of greater reliability of commutation.

5.1 BASIC CURRENT CONTROL/CONSOLIDATION CIRCUIT WITH GTO's

The basic building block of either the current control or consolidation network is shown in Fig. 5.1.

A GTO is a semiconductor switch very similar to an SCR in its turn-on and conduction mode. Both are 3 terminal devices with anode, cathode and gate. Either device can conduct only in the forward direction (similar to a diode). To turn on either the SCR or the GTO, positive voltage is applied on the gate terminal. Both the SCR or the GTO will begin to conduct if a positive voltage exists across the device (forward biased). To turn off the SCR a reverse bias must be applied. This is accomplished by a commutating circuit whose principal component is a relatively large commutating capacitor (Fig. 5.1a). To turn off a GTO a negative voltage is applied on the GTO gate. Therein lie the principal GTO advantages.

The advantages and disadvantages of the GTO compared to the SCR are listed below. The advantages are:

- a) elimination of relatively large commutating capacitor (capable of doubling the normal dc current during commutation time);
- b) elimination of capacitor associated losses;
- c) greater switching speed, allowing higher operating frequency and hence smaller magnetics,
- d) greater reliability of commutation, which will be explained later.

The disadvantages are:

- a) higher cost;
- b) the GTO "on state" voltage is nearly twice that of the SCR, which means that the GTO has greater losses and hence more severe cooling requirements. The overall circuit loss with GTO's versus SCR's is comparable.

Fig. 5.1 a) Basic Current Control/Consolidation Circuit with SCR's,
b) Basic Current Control/Consolidation Circuit with GTO's

As stated above, circuits using GTO's are expected to be more reliable than those with SCR's. This is because the commutation of an SCR circuit depends on the current through it (LC circuit), while commutation of a GTO is independent of the current through it. In circuits using SCR's, fast transients occurring in the MHD channel can cause loss of commutation from which the circuit cannot recover due to the SCR latching "on". This is followed by transformer saturation, thus resulting in complete loss of control. The only way then to restart the circuit is to shut down the MHD magnet, causing the electrode current to go to zero, to allow the recovery of the transformer. MHD operation can then resume. Interruption of MHD operation is of course highly undesirable. The GTO, however, cannot latch "on" and hence is immune to loss of commutation short of actual damage to components.

The GTO chosen for the initial testing is AMPEREX No. BTV 59-1000 R. Its maximum average current is 15 A and maximum controllable current is 50 A. The maximum "off state" voltage, i.e., the voltage the device is capable of blocking is 600 V. It cannot block reverse voltage and must be protected against it. This is accomplished by a parallel diode incorporated into a snubber circuit shown in Fig. 5.2. The gate circuitry was designed and manufactured by Mesta Electronics, Inc.

A set of 4 circuits as shown in Fig. 5.2 was built. The transformers and the main current diodes with their snubbers were used in previous tests of SCR's in place of the GTO's.

5.2 TESTING OF CONSOLIDATION CIRCUIT WITH GTO's

A circuit that consolidates 4 cathode electrodes of a simulated MHD channel is shown in Fig. 5.3. A similar "bench top channel" was tested earlier with SCR's in place of the present GTO's. As stated above, the transformers shown in the circuit were designed for use with the SCR's at 200 Hz switching frequency. This imposed a limitation on the operating frequency, and thus did not permit use of the fast switching capability of the GTO's.

The circuit was tested up to 250 Hz with the indicated resistor setting, and 50 V (nominal) in power supplies PS 1, 2, 3 and 4. The Hall voltage power supplies, PS 5, 6 and 7, were varied up to 30 V each. After minor component adjustments in the snubbing circuits the system worked reliably with excellent current control. Typical data is shown in Fig. 5.4, where under simulated Hall voltage of 100 V the difference between the minimum and maximum electrode current was ~ 1 A.

At present the system is being changed to incorporate the "anode" side consolidation as well. Because of an insufficient number of GTO based circuits the anode side consolidation will use the previously tested SCR based circuit. Also, new transformers for 1000 Hz operation are being designed. These are expected to be less expensive and less bulky than those used previously.

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Fig. 5.2 Basic Building Block of Current Control and Consolidation Circuit using GTO's

K9124

Fig. 5.3 Master/Slave 4 Electrode Bench Top Consolidation

Fig. 5.4 Maximum Electrode Current Difference Plotted vs Simulated Hall Voltage

5.0 REFERENCES

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6.0 FACILITY OPERATIONS, TASK 4

The Mk VI and Mk VII test facilities were run for 33-1/2 hours. Eighty percent of this operation was done in the Mk VI facility where both the Reference Channel Nos. 4 and 5 were run. Power was generated for just over 6-1/2 hours as considerable time was spent doing diagnostic measurements to measure gas conductivity and gas velocity, and with the testing of new current control circuitry.

Instrumentation in the Mk VI test facility was modified so that currents from segmented electrodes in both the anode and cathode walls could be measured. Transducers and meters were required so the current from each segment along with the total current for each electrode could be measured. Software for the data acquisition system was rewritten so that this additional data could be displayed both in real time and in playback.

Erosion to the conical section of the cyclone in the exhaust system to the draft fan has become so severe that a new section has been ordered. Fabrication from 316 SS will prevent future erosion by the acids formed during the quenching process.

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7.0 TECHNICAL REPORT DISTRIBUTION LIST

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