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Session Name: Open Cycle I
SEAM: 18 (1979)

SEAM EDX URL: https://edx.netl.doe.gov/dataset/seam-18
EDX Paper ID: 784
Study of the U-25B MHD Generator System in Strong Electric and Magnetic Fields

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INTRODUCTION

The development of MHD power generation technology requires the use of moderately-large test components and facilities, which can produce conditions of high electrical and magnetic stresses for the evaluation of MHD generator systems. The Soviet Union and the United States have worked together to create this test capability in the U-25B facility at the Institute of High Temperatures in Moscow. The results of the first two tests in the U-25B, with a Soviet facility, including gas-fired combustor and a diagonal-conducting wall generator, and a U.S.-supplied superconducting magnet were described during the 17th Symposium (Ref. 1). Over the past year, two additional runs have been completed on the U-25B facility, Test 3 in June of 1978, and Test 4 in December of 1978. This paper summarizes the results of both the June and December tests and provides a progress report on the joint test activities in the U-25B.

TEST FACILITY

A schematic of the U-25B test facility is shown in Fig. 1. The preheated oxidizer with an oxygen content up to 40% is supplied by the U-25 preheaters. Provisions have also been made to add additional oxygen downstream of the preheaters to achieve oxygen levels up to 60%. Detailed descriptions of the combustor, MHD generator and magnet have been provided in Refs. 3, 4, and 5, respectively. Further details of the characteristics and operation of the U-25B test facility were given at the 17th Symposium (Ref. 1) and are contained in two joint reports (Refs. 2 and 6), which have been published in both languages.

During the course of Tests 3 and 4, the U-25B facility was operated at mass flows between 2 and 4 kg/s, with oxygen enrichment of 40, 50, and 60% by volume, and at magnetic fields intensities between 2 and 5 T. Most tests were conducted with potassium seed at 0.5 to 1% by weight. Some test points in Test 4 were obtained with cesium seeding, at up to about 2% by weight. Both potassium and cesium seed are introduced as aqueous solutions.

Up to this time, the U-25B flow train has been operated for approximately 50 h, and the superconducting magnet for approximately 35 h, a large portion of which was at 5 T. The maximum power achieved to date was slightly under 600 kW. The highest level of axial voltage across the generator was approximately 4200 V, resulting in a Hall field of 2100 V/m. The operation of the facility and all of the test components has been satisfactory over the first four tests.

A number of diagnostic measurements described in a later section are made of plasma conditions entering the generator. In addition, conventional electrical and gas-dynamic data are obtained; details of these measurements are given in Refs. 2 and 6. The U-25B generator is loaded by three inverters with the loading arrangement shown in Fig. 2. Power takeoff sections were slightly different for Tests 3 and 4 which is also illustrated in Fig. 2.

TEST RESULTS

Channel Fluid Flow Condition

As described in Ref. 2, wall friction significantly influences the electrical performance of an MHD generator. During testing of the U-25B generator, experimental data are routinely obtained to allow a determination of the overall wall friction coefficient. The channel friction characteristics have been obtained at mass flows between 2 and 4 kg/s and at flow temperatures of 70°C and 900°C. Methods used to calculate friction coefficients from the pressure distribution data are described in Ref. 2.
Figure 3 summarizes the experimental values of the friction coefficient, $C_f$, at temperatures of 70°C and 900°C as a function of Reynolds number for Tests 3 and 4. The wall friction coefficients in tubes are also shown in the figure for values of relative roughness from 0.005 to 0.1. It is observed that the average friction coefficient for Test 4 was approximately 0.02 and that, in general, friction coefficients obtained during the fourth test were somewhat higher than those in the previous tests. This is probably due to an increase in the effective wall roughness in Test 4 due to loss of some ceramic material on the electrodes. Based on the calculations for turbulent flow in tubes and on an average hydraulic diameter for the channel, the effective wall roughness is estimated to be about $k_e = 0.005$ m.

Analysis of the wall static pressure distribution indicates that at a temperature of 70°C, the channel flow was subsonic over the range of mass flows studied. However, when the temperature was increased to 900°C, supersonic flow existed in the upstream section of the channel for mass flows of about 4 kg/s and greater. Figure 4 shows the experimental static pressure distribution along the channel without the magnetic field for $m = 2.5$ kg/s and $T = 1141$ K. Numbers adjacent to the symbols designate the orifice location. A two-dimensional analytical mode (Ref. 6) was used to predict the pressure distribution for this case. From the previous discussion of the skin friction coefficient, the effective wall roughness has been assumed to be $k_e = 0.005$ m. Because of the relatively large discrepancies between the measured pressures on opposing walls of the channel ($P_1$ and $P_2$, see Fig. 4) near the exit of the constant-area section at the entrance to the channel, two computations were performed. The solid curve shown in Fig. 4 gives the predicted pressure distribution if the calculation starts with the measured value, $P_4$. The dashed curve corresponds to the computed pressure distribution where the exit pressure is kept to same as the measured values, $P_4$. Figure 4 indicated that there is a good agreement between the analytical results and the experimental data, thus giving confidence in the measured friction coefficients.

The pressure distribution data also illustrate that with the combustor in operation, subsonic flow is achieved in the channel when the mass flow was reduced to about 1.9 kg/s (including an additional 0.2 kg/s of cold air entering the combustion chamber around the optical ports and through the seed nozzles). At all other test conditions, a region of supersonic flow existed in the upstream portion of the channel and through a shockwave system, subsonic flow occurred in the downstream portion. With increase in mass flow, the location of the shock system moved further downstream in the channel, as discussed in a later section.

In the upstream portion of the channel where the flow is supersonic, the wall pressure distribution for Tests 3 and 4 were in satisfactory agreement. In Test 4, the air gap (see Fig. 1) located between the diffuser exit and the combustion product cooling system was decreased from 50 mm to 30 mm. This resulted in a lower exhaust pressure than that of Test 3. Consequently, the pressure distribution in the downstream, or subsonic, portion of the channel for Test 4 was shifted to somewhat lower pressures compared with that of Test 3. Because of the variations in pressure measurements along the length of the channel, both for Tests 3 and 4, gasdynamic parameters for the channel for other calculations were obtained from averaged values of the experimental static pressure distribution along the channel. A typical distribution of the gasdynamic parameters for tests with cesium and potassium seed is summarized in Table 1.

Methods used to calculate the temperature variation and velocity variation through the channel are discussed in detail in Ref. 2.

Channel Electrical Performance

Typical current distributions over the current-collecting electrodes measured during Test 3 are shown in Fig. 5. The loading scheme schematic given in Fig. 2 illustrates the region of current take-off for this test. Extension of the current collection region into the electrical active portion of the channel for Test 3 resulted in a somewhat smoother current distribution than that obtained during Test 2 and described in Ref. 6. Figures 5a and 5b illustrate that the current gradient along the take-off section became steeper when the oxygen enrichment was increased from 40% to 50% by volume. This effect is due to the increase in power by a factor of about three. In the downstream section, currents were uniformly distributed, and increasing the oxygen enrichment merely increased the current level. Figures 5c and 5d compare the current distribution at near the maximum power point with that obtained at near short-circuit condition for a mass flow of 4 kg/s and with a magnetic field of 5 T. These current distributions were similar in shape, but the current level is shifted to higher values as short-circuit conditions are approached. For Test 4, the current take-off configuration was slightly modified as illustrated in Fig. 2. To reduce the possibility of flow separation in the supersonic diverging portion of the channel during Test 4, the upstream current take-off region was shifted forward by 0.08 m, from the location used in Test 3 (that is, by three frames) and into a region of lower magnetic field.

Typical current distributions over the take-off regions between frames 5 and 15, and 132 and 143 for Test 4 are shown in Fig. 6. Comparing Figs. 5 and 6, it is observed that this shift of the current take-off section away from the active part of the channel resulted in a more non-uniform current distribution over the current collection section. The current gradients are especially pronounced at the lower levels of oxygen enrichment, corresponding to reduced levels of plasma conductivity.

Comparison of Figs. 6a and 6b illustrates that a mass flow of 3 kg/s and an oxygen enrichment of 50% by volume, the shape of the current distribution over the take-off sections are similar between operation at near maximum power and at near short-circuit during Test 4. Only the current level increases as the short circuit operation condition is approached. The trend is identical to that observed in Test 3.

Comparison of Figures 5b and 6a, for example, which correspond to operation at near maximum power at roughly the same test conditions clearly shows that the upstream current distribution for the fourth test was much steeper in the upstream current collection section. Comparison of Figs.
5d and 6b, which correspond to a short-circuit condition for approximately the same power level show a similar trend, particularly on the last two downstream current-coll ecting electrodes.

The effect on current distribution of the use of cesium seed in Test 4 is shown by Fig. 6c. When cesium seed was employed, the axial current gradient over both the upstream and downstream current collection sections became less steep, as compared to tests at the same conditions with potassium seed. In this case, the maximum frame current at near optimum loading did not exceed 20 A. Increasing the oxygen enrichment from 50 to 60% while using cesium seed, Fig. 6d, resulted in a steeper current distribution in the upstream take-off section due to the increase of power level.

For Test 3 the distribution of current over the downstream section, in general, was similar to that of the upstream section, except the current gradients over downstream section were somewhat reduced. The distribution of current over the downstream section for Test 4 was different from that upstream. One exception is those test points where the conductivity was increased by raising the oxygen enrichment to 60%. In these cases the shape of the current distribution downstream was similar to that upstream.

Figures 5 and 6 also depict the variation of current in the intermediate voltage balancing leads to frames 57 and 93 (see Fig. 2). It may be noted that for most operating conditions, currents in frame 57 did not exceed 5 A, while those in frame 93 exceeded 10 A on a number of occasions with a maximum current of 40 A under one near short-circuit condition. During Test 4, the greatest current extracted from frame 93 was in the neighborhood of 20 A.

**Determination of Plasma Conductivity and Channel Resistance**

The conductivity of the combustion gas is determined by diagnostic measurements close to outlet of the nozzle as described in another section. In addition, during Test 4, a conductivity measurement through the channel was made in a mass flow of 2.8 kg/s with an oxygen enrichment of 51%. The potassium seed addition was approximately 1.4% by weight. This measurement was carried out by applying an external power source over the upstream and downstream current take-off frames. The potential distribution of all channel frames were measured at several current levels producing volt-ampere characteristics shown in Fig. 7. As seen in Fig. 7, the V-I characteristic is essentially linear over the range of applied voltage. The plasma conductivity can then be estimated by application of the load current equation for the diagonal conducting wall channel given below (Ref. 7).

\[
I_L = \frac{E}{R} = \frac{E}{R_0} (1 + a^2) \left( 1 + \frac{E}{E_0} \right) \left( 1 + \frac{B}{L_0} \right) \left( 1 + \frac{L}{L_0} \right)
\]

where

\[ a = \frac{E}{E_0} - 1; \]

\[ E = \frac{E}{E_0}; \]

\[ \sigma_a = \frac{1}{R_0} \left( 1 + a^2 \right) \left( 1 + \frac{E}{E_0} \right) \left( 1 + \frac{B}{L_0} \right) \left( 1 + \frac{L}{L_0} \right) \]

For conditions of an applied external source with no magnetic field, and assuming that \( a = 0, \sigma = 0 \) and \( a = 1 \), Equation (1) can be simplified to the following relationship for conductivity,

\[
\sigma = \frac{I_L}{2E_x A}
\]

where \( E_x \) is the Hall field and \( A \) is the cross-sectional area of the channel. The values of \( E_x \) were obtained from the measured axial potential distribution \( V_x \).

For two values of applied voltage, 577 V, and 1028 V, the experimentally determined electrical conductivities are summarized in Table II at various axial locations in the channel. In addition, Table II gives a calculated value of conductivity, based upon the measured combustion-gas plasma temperature taking into account the thermal losses of the combustor, nozzle, and MHD generator.

The axial distribution of the experimental conductivities which decrease to a minimum at \( x = 2.2 \text{ m} \) and then increase is totally consistent with the supersonic/subsonic flow mode in the channel. Conductivity at first decreases in the supersonic region with decreasing temperature and then rises, to much higher values across the shock system where the temperature increases.

This comparison indicates that the experimentally determined conductivities range from about 2 to 4 mhos/m and are between 30 and 50% of the levels expected from analytical considerations.

The external power source may also be used to make a measurement of the equivalent electrical resistance of the channel above ground in the X-direction. This is achieved by applying an external voltage, when the seed injection is discontinued. Such a measurement with an external voltage of 880 V resulted in a current flow of 6.7 A and corresponds to an insulation resistance leakage to ground of the order of 120 ohms.

The axial equivalent insulation of the channel may be characterized by a relative leakage resistance given by

\[
\sigma = \frac{R}{R_0}
\]

where \( R \) is the plasma volume resistance and \( R_0 \) is the leakage resistance described above. The channel relative resistance can be expressed by the following relationship

\[
\sigma = 0.027/E_0
\]

Equation 3 will be used for carrying out local analysis of the electrical performance of the generator given in a later section.

**Axial Voltage Distribution**

The Hall voltage distribution obtained during Test 3 with a mass flow of 4 kg/s at 5 T is shown in Fig. 8a. During this test the Hall voltage distribution was relatively uniform at moderate
voltage levels. However, at voltages greater than 4000 V, shown in Fig. 8a, large interframe voltage fluctuations occurred. This figure also corresponds to the maximum Hall field produced during these tests of approximately 1000 V/m. A similar Hall voltage distribution for Test 4 is shown by Fig. 8b, obtained at a mass flow of 1.5 kg/s and a magnetic field of 5 T. Figure 8a illustrates that the Hall voltage distribution for Test 3 was approximately symmetrical about the ground potential, illustrating that the resistance to ground of the combustor and the diffuser were approximately the same. In contrast during Test 4, Fig. 8b shows the potential of the upstream frames were slightly below ground potential. This occurred because the resistance of the combustor to ground during this test was about one-tenth of the resistance of the diffuser to ground. The voltage distributions at all points in Test 4 were considerably more uniform. Lower resistance to ground of the combustor did not provide any limitation to the experiment. The downstream insulation was able to support the total voltage generated by the channel. The location of the shock system may also be observed in the Hall voltage plots by a decrease of the slope of the distribution (see Fig. 8b) at X = 2m.

**Load Line Characteristics**

Typical load lines obtained during Test 3 for each of the inverters, as well as a composite load line for the entire channel, are given in Fig. 9. The inverter load lines illustrate that when shock waves are located in the upstream portion of the channel, the first section of the channel contains the lowest conductivity compared to the last two sections, that is, the load line is steeper, indicating a higher impedance in that section. As noted above, this trend is observed in the axial measurements of C. Figure 10 summarizes load lines obtained during Test 4 at a mass flow of 3 kg/s and an oxygen enrichment of 60% and cesium seed. In this case, the load lines from each inverter tend to be parallel, indicating similar values of the plasma impedance in each section of the channel.

During Test 4, the power output of the generator was increased substantially as the oxygen enrichment increased to 60%. For example, increasing the oxygen enrichment from 50 to 60% while maintaining the same mass flow rate, magnetic field and seed rate resulted in an increase of power from 192 kW to 322 kW. Power output was also increased by 20 to 25% when cesium seed was used in place of potassium seed.

During Test 3, a maximum power level of 575 kW was produced at a mass flow of 4 kg/s at a magnetic field of 5 T, and with oxygen enrichment of 50% by volume. Potassium seed was utilized, approximately 0.5% by weight. During the course of Test 4, the highest power achieved was 406 kW, at a mass flow of 3.1 kg/s, at a magnetic field of 5 T, and oxygen enrichment of 62%, and with about 2% by weight cesium seed. During Test 4, the maximum power achieved with potassium seed was approximately 370 kW, but a higher mass flow rate of 3.5 kg/s was employed.

Power levels achieved at different operating conditions for Test 4 are summarized by the power-current characteristic curves in Fig. 11. Maximum power was obtained at a loading coefficient value V/V = 0.5 to 0.6, and at I/I = 0.5. Variation of power with current for potassium and cesium seed are compared in Fig. 11. In addition, the variation of power with current with an increase of oxygen enrichment from 50 to 60% and with potassium seed is also illustrated.

**Plasma Conductivity with Potassium and Cesium Seed**

Plasma conductivities achieved during Test 4 with potassium and cesium seed have been compared at essentially the same operating conditions, a mass flow of 3 kg/s and an oxygen enrichment of 45% by volume. At these test points, the potassium seed addition corresponded to 1.27% by weight and the cesium seed addition was 2.13% by weight. An analysis of the generator performance indicated that under these conditions, the gasdynamic characteristics of the plasma flow are essentially the same. As a result, it is possible to obtain a ratio of the plasma conductivities for cesium and potassium seed by ratioing the short-circuit currents given below,

\[
\frac{\sigma_{Cs}}{\sigma_{K}} = \frac{I_{Sc}}{I_{Sk}} \text{s.c.}
\]

where \(I_{Sk}\) and \(I_{Sc}\) are short-circuit currents obtained with potassium and cesium seed, respectively. Figure 12 summarizes load-line characteristics for each inverter and for the overall channel while operating with cesium and potassium seed. Extrapolating the load line characteristic results in the following values of short-circuit current, \(I_{Sc}\) potassium = 150 A, \(I_{Sc}\) cesium = 204 A. Thus,

\[
\frac{\sigma_{Cs}}{\sigma_{K}} \text{ s.c.} = 1.36
\]

The theoretical value of the conductivity ratio obtained on the basis of thermodynamic considerations at channel section of X = 0.15 m and at a plasma temperature of 2660 K and a static pressure of 1.165 atm is

\[
\frac{\sigma_{Cs}}{\sigma_{K}} = 1.43
\]

It is apparent that the theoretical value of the conductivity ratio is in approximate agreement with the experimentally determined value.

It is also of interest to compare the experimental conductivity ratio on the basis of equal addition by weight. Assuming that conductivity varies at the square root of the addition rate \(\sigma \propto \sqrt{X}\), then for a seed addition of cesium and potassium corresponding to 1.27% by weight, the conductivity ratio is

\[
\frac{\sigma_{Cs}}{\sigma_{K}} = 1.36 \sqrt{1.27/2.13} = 1.05
\]

**Plasma Diagnostic Measurements**

A schematic of the plasma diagnostic measurement locations for Test 4 is given in Fig. 13. (Similar measurements were made in Test 3, see Ref. 2.) Potassium atom concentration at the
combustor exit was measured by means of the potassium line intensity at the wavelengths of 6911 and 6936 angstroms. The measured value of the potassium number density was between 5 and 16 x 10^13 atoms/cm^3. This value is much lower than expected.

Using a line reversal doublet method, the potassium concentration concentrations in the diffuser were measured to vary between 0.2 and 1.0 x 10^13 atoms/cm^3. This measurement was made at a point located approximately 6 m downstream from the combustor. A comparison of the measurements suggests that the evaporation and ionization of potassium is not yet completed at the combustor exit. Potassium atom concentrations measured at the diffuser entrance are much closer to values that would be calculated on the basis of measured temperatures and seed injection rates.

The plasma temperature was measured at the entrance to the generator by using the sodium D-line reversal method. Industrial-grade potassium was used to make up the seed solution. It contained trace amounts of sodium. As a result, the sodium concentrations in the seed were quite low and light intensity fluctuations in the sodium lines result in temperature measurements which do not have high accuracy. As a consequence of experience gained during these tests, additional sodium will be added to the seed solution for future tests.

During both tests, the electrical conductivity was measured directly with a conductivity probe made up of a transmitter and high-frequency generator installed in a streamlined probe that was transversed into the plasma. A teflon coating of the probe prevented arcing when conductivity measurements were made in the magnetic field. The conductivity measuring system was calibrated immediately before and after a measurement and an optical isolation system was used to transmit the signal from regions of high voltage to the instrumentation located at ground potential. These conductivity measurements were in reasonable agreement with those measured in the absence of a magnetic field (see Ref. 2).

Measured conductivity values at the location of the conductivity probe were two to three times lower than values calculated on the basis of the measured seed injection rate and plasma temperature. One reason for this discrepancy may be due to incomplete seed evaporation and ionization. Table III presents a comparison of experimental and theoretical conductivity values for several operating conditions.

As is observed from Table III, the value of K ranges between 0.32 and 0.55. The value of the conductivity calculated on the basis of temperature and pressure at the location of the probe was 1.4 to 1.5 times higher than the experimental value of K. As will be described later, this difference may be due to the presence of a small water leak at the seed nozzles installed in the combustor during Test 4. It is believed that this leak resulted in a temperature decrease of approximately 70 K and a corresponding decrease in plasma conductivity. While there is considerable scatter of the plasma temperature results obtained by optical means, it can be stated that on the average the plasma temperatures obtained using the optical measurements are lower than those measured in Test 3. This may also be attributed to the water leak mentioned above.

During the third and fourth tests, energy radiated from the combustor was measured. Details of the measuring system are given in Ref. 2. During Test 3, the increase of radiation flux measured due to seed addition was about 15 W/cm^2. Additional radiation flux measurements were made during Test 4 and found to vary between 0.6 and 3.0 W/cm^2, which are three to five times lower than those obtained in Test 3. This difference may be due to the change of the optical thickness at the point of measurement for the two tests. In Test 3, the radiation measurements were made in the combustor with an optical depth of 0.5 m, while in Test 4, the measurement location was moved to the nozzle, which had an optical depth of only 0.18 m. In addition, the lower temperatures obtained in Test 4 will contribute to lower heat fluxes.

ANALYSIS OF TEST RESULTS
Local Electrical Analysis

As described in Refs. 2 and 6, the load line characteristics may be used to analyze the electrical performance of the channel on a local basis. As shown previously in Figs. 9, 10, and 12, over the range covered in Tests 3 and 4, the load lines are essentially linear. The open-circuit voltage and short-circuit current characterize the linear load lines. In terms of the Hall field and current density may be expressed, the Hall parameter, and assuming infinite segmentation, $\Gamma_{dc}$ and $\Gamma_{sc}$ may be given by

$$\Gamma_{dc} = \frac{\langle u \rangle}{\mu} \left( \frac{1}{1 + \cot \gamma + 2} \right)$$

$$\Gamma_{sc} = \frac{\langle u \rangle}{\mu} \left( \frac{1}{\sigma \mu} \right)$$

which contain two variables, $\sigma$, electrical conductivity and $\alpha$, the nonuniformity factor. The limitation and the utility of these Equations 4 to 7 are described in detail in Ref. 2.
ship between E and I, obtained for two channel regions (between frames 67 and 85, and frames 103 to 121). Utilizing experimental values of $E_0$ and I, such as shown in Fig. 14, in conjunction with Equations 4 and 5, one obtains two equations with two unknowns, $\sigma$ and $\alpha$. Calculations then of $\sigma$ and $\alpha$ allows a verification of the conductivity obtained by other methods, as well as determination of some loss mechanisms in the MHD generator.

In general, the agreement between the local analysis and the experimental data in the downstream section of the channel for Test 3 was good, suggesting that the local properties were properly evaluated, and, more importantly, the calculation procedure for the nonuniformity factor was adequate. In contrast, the measured and predicted values of the open-circuit axial field in the upstream section differed by as much as a factor of five from the predicted values and were higher than those measured. Several phenomena could contribute to the discrepancy, for example, imperfect insulation, inhomogeneous distribution of conductivity, wall roughness, flow separation and other factors.

This method of local analysis was also carried out for Test 4 data in order to provide a better understanding as to why the electrical conductivity calculated on the basis of thermodynamic properties had values over twice those indicated by other experimental data. Local analysis of the Test 4 results included the effects of imperfect insulation. This was achieved by utilizing Equation 1, which defines the load current. Values of $E_o$ and $I_o$ can be readily obtained assuming that the load coefficient,

$$K = \frac{E_o}{I_o}$$

that $I_o = 0$ and $K = 0$, respectively. The effective relative resistance of the channel walls was then computed from Equation 2. Consequently, using experimental values of $E_0$ and I, we obtained two equations with two unknowns, $\sigma$ and $\alpha$.

Figure 15 summarizes the result of this local analysis for six locations along the channel. The conductivity loss factor $K = 0.18t_{\text{exp}}/\text{other}$ at each channel axial location obtained by applying an external source across the channel without a magnetic field is also shown in the figure, together with the K values obtained on the basis of a theoretically calculated nonuniformity factor. Based on all of these results, it is observed that the average value of K resulting from the local analysis is approximately 0.35 and roughly constant over the length of the channel.

As shown in Table III, the value of K obtained on the basis of direct conductivity measurements was found to be about 0.40, thus these two independent methods for determining $K$ yield similar values and suggest that during the Test 4, this parameter was in the range between about 0.3 and 0.5. During Test 3, $K$ was subsequently higher, about 0.7, and its departure from the ideal value ($K = 1$) was believed to be due to incomplete seed ionization (see Ref. 2 for details). The same seed injection system was employed for Tests 3 and 4; consequently, the decrease of $K$ to about 0.4 for Test 4 must be due to additional factors. A post-test inspection of the combustion chamber after Test 4 revealed small water leaks in one of the seed injection sections. In addition, it was determined that more cold air was introduced into the combustor in Test 4 than in Test 3 around the optical ports and the seed injection nozzle. It is estimated that water leaks of about 0.07 kg/s occurred and that the air leakage for Test 4 was approximately 200 g/s. Approximate calculations indicate that the泄漏s would result in reducing the temperature of Test 4 by about 100 K. Taking all of these factors into account suggests that $K$ for Test 4 would be approximately half of that measured during Test 3, which is consistent with the results of the local analysis.

As mentioned above, the nonuniformity factor, $\alpha$, may also be obtained from local analysis of the MHD generator performance. Values of $\alpha$ obtained at six axial locations along the channel are summarized in Fig. 16 for three different test conditions. The large amount of scatter may be attributed to the accuracy of the experimental data and the sensitivity of this calculation procedure for the determination of $\alpha$. Overall, the values obtained are in reasonable agreement with $\alpha$ values cited in Ref. 2. As has been shown in Refs. 2, 6, and 7, at these values of $\alpha$ and at high values of the Hall parameter, the performance of an MHD generator is substantially reduced compared to the ideal performance. One of the most effective ways to reduce this negative influence of the conductivity nonuniformity on generator performance is to increase the electrode surface temperature. During Test 4, the average wall temperatures were believed to be about 1600 K.

Comparison of Theoretical and Experimental Performance

After Test 3, analytical calculations of the generator gasdynamic and electrical performance were made utilizing computer models at IVTAN and at ANL. Among the most important calculations are the predictions of the voltage-current characteristics and the prediction of power over a wide range of loadings. Diagnostic measurements made during the third test indicated that the electrical conductivities were less than those obtained by theoretical calculations. Other measurements indicated that incomplete seed ionization was responsible for the lower levels of conductivity. Calculations made at IVTAN and at ANL corresponding to Test 3 conditions consistently demonstrated a reasonable comparison between experiment and theory if a conductivity loss factor was used. Because of this, a coefficient was introduced into the IVTAN calculation model to correct for the conductivity loss appropriate to the experiment. Analytical calculations of the load line and power characteristics of the channel were performed for $K = 0.4$ and 0.5 for the U-258 channel geometry and for the magnetic field distribution of the superconducting magnet. Calculations were made for a mass flow rate of about 4 kg/s, and assuming that the pressure at the exit of the channel was 1.07 atm. The results of these calculations are summarized in Fig. 17a, and compared to experimental data obtained at the mass flow of 4 kg/s. The range of the experimental data is shown by the crosshatched regions. Comparison of the theoretical curves of the experimental results illustrate that the best agreement is achieved for values of $K$ between about 0.7 and 0.8. For a test point
corresponding to near maximum power at this test condition, the experimental value was measured to be 516 kW. Assuming $K = 0.7$, the calculated power was 530 kW. Somewhat similar calculations were made after Test 2 (see Ref. 6), and it was found also at that time that the agreement between experiment and theory was quite good if $K = 0.7$ was assumed.

To analyze data obtained during Test 4, similar gasdynamic and electrical performance calculations were made. The effects of water leakage around the seed nozzle and air leakage were taken into account. In the calculation of plasma properties entering the MHD generator, Table IV compared at two different test points the results of calculations for several important parameters with the experimental data. The experimental conditions and calculations were made for mass flow rates of 3.1 and 3.5 kg/s, respectively. Values of $K = 0.375$ and 0.350 were used for these calculations and resulted in good agreement between the calculated and experimental results for Hall voltage, shock location in the channel, as well as the pressure at the channel inlet and outlet. In the analytical calculation the load current was taken equal to the experimental value of 160 A and 140 A, respectively, for the two operating points. It is observed in Table IV that calculated values of the power at both of these test points result in higher values than were experimentally measured. The question of leakage current to ground was mentioned in the previous section. If leakage losses are taken into account, the electrical resistance of the leakage path is about 120 ohms, which will result in a lowering of the analytical values of power in Table IV to 370 and 300 kW, respectively, which bring them into somewhat better agreement with the experimental power levels.

Theoretical calculation of the load lines and power production characteristics of the generator for conditions corresponding to Test 4 are summarized in Fig. 17b. Again, the experimental data is shown by the cross-hatched regions, and calculations have been made for $K$ varying from 0.3 to 0.7. It is observed that good agreement between theory and experiment occurs for a value of $K = 0.35$. This value of $K$ is consistent with estimates made previously by independent methods.

It should also be mentioned that the power variation along the length of the channel obtained in Test 4 is similar in nature to that which would be predicted. During Test 4 and in contrast to the previous test, power generated in the first two sections of the channel conducted to inverters 17 and 19 were relatively high, and the power level produced in the rear portion of the channel connected across inverter 21 was lower. This characteristic would be expected theoretically and is due to the lower velocities which result in the rear portion of the channel. It would be expected that power in the rear portion of the channel would be increased as the mass flow is increased and velocities in that region are higher.

Figure 1 compares theoretical and experimental static pressure distributions along the channel for Test 4. Good agreement between theory and experiment was observed when $K = 0.35$. During Test 3, this comparison between experiment and theory was good when $K = 0.7$. Thus, calculations of the gasdynamic characteristics of the channel lead to defining the same value of $K$ as do calculations of electrical characteristics.

**SUMMARY**

The third and fourth tests of the U-25B facility have demonstrated that the MHD flow train has operated for over 50 h with little difficulty. Review of the data reveals no significant problems associated with vibration, stress, or fluctuation of the electrical and gasdynamic parameters of the system components. In Test 3, the MHD generator produced a maximum power of 575 kW, a maximum Hall voltage of 4240 V, and a maximum Hall field of 2100 V/m. Inverter loading characteristics indicated that the upstream portion of the channel operated at low conductivity compared to the two downstream sections. During Test 4, at a lower mass flow rate but with cesium seed and oxygen enrichment to 60%, a power level of about 400 kW was generated. Because of inadvertent water and air leakage into the combustion chamber, however, combustion temperatures were lower in Test 4 than anticipated. These factors had a detrimental effect on the generator performance.

Analysis of the data obtained from Tests 3 and Test 4 illustrates that in order to increase the power of the U-25B channel, a number of steps should be taken to increase the effective plasma conductivity and channel mass flow. For example, as shown in Table V, increasing the mass flow rate to 5 kg/s and achieving a $K$ of 0.7 to 0.8, a channel inlet temperature about 2950 K may produce an electrical power output up to 1.3 MW. Steps are being taken to increase the preheat temperature in the facility, as well as to eliminate all water and air leakage into the combustor and decrease other thermal losses in the combustor nozzle and generator.

**REFERENCES**


Table I. Summary of the Gasdynamic Parameter Through the MHD Generator at Various Operating Conditions

<table>
<thead>
<tr>
<th>Measurement Number</th>
<th>Test Parameters</th>
<th>P&lt;sub&gt;exp&lt;/sub&gt; kg/s</th>
<th>P&lt;sub&gt;calc&lt;/sub&gt; kg/cm²</th>
<th>P&lt;sub&gt;0&lt;/sub&gt; kg/cm²</th>
<th>T&lt;sub&gt;1&lt;/sub&gt; K</th>
<th>T&lt;sub&gt;0&lt;/sub&gt; K</th>
<th>V m/s</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>3016 G&lt;sub&gt;cp&lt;/sub&gt; = 3.15 kg/s</td>
<td>0.15 C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>1.648</td>
<td>1.50</td>
<td>2.166</td>
<td>2771</td>
<td>2859</td>
<td>833</td>
<td>0.829</td>
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<tr>
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<td>0.15 C&lt;sub&gt;11&lt;/sub&gt;</td>
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<td>1.121</td>
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<td>1064</td>
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<tr>
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<td>0.15 C&lt;sub&gt;12&lt;/sub&gt;</td>
<td>1.21</td>
<td>1.21</td>
<td>1.763</td>
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<td>2780</td>
<td>1072</td>
<td>1.107</td>
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<tr>
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<td>0.74</td>
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<td>2574</td>
<td>2619</td>
<td>564</td>
<td>0.591</td>
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<tr>
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<td>0.854</td>
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<td></td>
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<td>3119 G&lt;sub&gt;cp&lt;/sub&gt; = 3.53 kg/s</td>
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<td>0.15 C&lt;sub&gt;12&lt;/sub&gt;</td>
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<td>1151</td>
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<tr>
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<td>0.74</td>
<td>1.315</td>
<td>2612</td>
<td>2739</td>
<td>999</td>
<td>1.039</td>
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<tr>
<td></td>
<td>0.15 C&lt;sub&gt;16&lt;/sub&gt;</td>
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<td>1.199</td>
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<td>740</td>
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<td>2669</td>
<td>637</td>
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<td>2535</td>
<td>2564</td>
<td>437</td>
<td>0.463</td>
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A.5.8
Table II. Comparison of Measured and Calculated Conductivity

<table>
<thead>
<tr>
<th>M</th>
<th>T,K</th>
<th>P,atm</th>
<th>$\sigma_{calc}$ mho/m</th>
<th>$\sigma_{exp}$ mho/m</th>
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<tr>
<td>1.20</td>
<td>2489</td>
<td>0.60</td>
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<td>2.21</td>
<td>2510</td>
<td>0.59</td>
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<td>2.72</td>
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<td>0.70</td>
<td>8.60</td>
<td>2.15</td>
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<td>3.22</td>
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<td>0.76</td>
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<td>3.72</td>
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<td>0.82</td>
<td>7.18</td>
<td>3.62</td>
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Table III. Comparison of Calculated and Measured Conductivities at the Generator Entrance

<table>
<thead>
<tr>
<th>Point No.</th>
<th>$\sigma_{exp}$ mho/m</th>
<th>$\sigma_{theo}$ mho/m</th>
<th>$K_d = \sigma_{exp}/\sigma_{theo}$</th>
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<tbody>
<tr>
<td>1483</td>
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<td>1497</td>
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<td>1849</td>
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Table IV. Comparison of Theoretical and Experimental MHD Channel Parameters, Test No. 4, December 7, 1978

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Measurement No.</th>
<th>G (kg/s)</th>
<th>N (kW)</th>
<th>$V_x$ (kV)</th>
<th>$X_{sh}$</th>
<th>$P_0$ (atm)</th>
<th>$P_2$ (atm)</th>
<th>$K_d$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>3119</td>
<td>3.5</td>
<td>346</td>
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<td>2</td>
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<td>1.9</td>
<td>2.5</td>
<td>2.4</td>
<td>0.920</td>
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Mode: G - Mass flow rate
N - Power
$V_x$ - Hall potential
$P_2$ - Static pressure at the channel outlet
$P_0$ - Total pressure at the channel inlet
$X_{sh}$ - Coordinate of the shock
$K_d$ - Conductivity reduction coefficient

Table V. Analytical Predictions for U-25B for a Mass Flow Rate of 5 kg/s

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mass flow rate, kg/s</td>
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<tr>
<td>Magnetic field, T</td>
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<tr>
<td>Oxygen enrichment, % by volume</td>
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<tr>
<td>Preheated air temperature, °C</td>
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</tr>
<tr>
<td>Temperature of additional oxygen, °C</td>
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</tr>
<tr>
<td>Stagnation outlet pressure, atm</td>
<td>1.0</td>
</tr>
<tr>
<td>Load current, A</td>
<td>225.0</td>
</tr>
<tr>
<td>Temperature at the channel inlet, K:</td>
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</tr>
<tr>
<td>Stagnation</td>
<td>2940</td>
</tr>
<tr>
<td>Static</td>
<td>2860</td>
</tr>
<tr>
<td>Channel inlet pressure, atm</td>
<td>3.6</td>
</tr>
<tr>
<td>Stagnation</td>
<td></td>
</tr>
<tr>
<td>Static</td>
<td>2.6</td>
</tr>
<tr>
<td>Maximum Hall field, kV/m</td>
<td>3.3</td>
</tr>
<tr>
<td>Channel voltage, kV</td>
<td>5.8</td>
</tr>
<tr>
<td>Electrical power, MW</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Fig. 1 U-25B Facility Schematic Diagram

Fig. 2 Electrical Loading Schematic for Tests 3 and 4

Fig. 3 Friction Coefficient for the Constant Area Section
Fig. 4 Channel Pressure Distribution for B = 0 (Test 4)

Fig. 5 Typical Current Distributions over the Current Collecting Electrodes (Test 3)

Fig. 6 Typical Current Distributions over the Current Collecting Electrodes (Test 4)

Fig. 7 Voltage vs Current with Applied External Source
G = 4 kg/s
M = 182 l/hr
B = 5 T
ψ = 50%

Fig. 8a Axial Voltage Distribution (Test 3)

Fig. 8b Axial Voltage Distribution (Test 4)

G = 3.0
ψ = 50%

○ INVERTER NO. 17
□ INVERTER NO. 19
△ INVERTER NO. 21
• TOTAL-ALL INVERTERS

B = 5 T
K SEED = 180 l/h

Fig. 9 Voltage-Current Load Line Characteristics (Test 3)

Fig. 10 Voltage-Current Load Line Characteristics (Test 4)
Fig. 11 Power vs Load Current (Test 4)

Fig. 12 Voltage-Current Characteristics for Potassium and Cesium Seed (Test 4)

Fig. 13 Schematic of Diagnostic Measurement Locations

Fig. 14 Typical Hall Field vs Current Characteristic used in Local Analysis
Fig. 15 Variation of Conductivity Factor Along the Channel

Fig. 16 Variation of Conductivity Nonuniformity Coefficient (a) Along the Channel

Fig. 17a MHD Generator Electrical Characteristics (Test 3)

Fig. 17b MHD Generator Electrical Characteristics (Test 4)
Fig. 18 Pressure Distribution--Calculated and Experimental