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INVESTIGATION OF A NON-EQUILIBRIUM MHD GENERATOR

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General Electric Company

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ANNUAL REPORT

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13. ABSTRACT

This report presents the results obtained during the past year in the study of the non-equilibrium MHD generator. The following major results were obtained:

See page b

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ANNUAL REPORT

INVESTIGATION OF A NON-EQUILIBRIUM MHD GENERATOR

Contract No. N00014-73-C- 0039
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August 1, 1972 to July 31, 1973

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FORWARD

The work presented in this report was performed at the General Electric Company, Space Division, Space Sciences Laboratory, King of Prussia, Pennsylvania, under Office of Naval Research Contract N00014-70-C-0321, Project Code 9800. Mr. J. A. Satkowski was the technical monitor.

The studies presented cover a 12-month period from August 1, 1972 to July 31, 1973.

Dr. Bert Zauderer was the principal investigator. Mr. E. Tate was responsible for the operation and diagnostic evaluation of experiments in the facility. Messrs. H. Sharp, W. Frey, and G. Fecik provided technical assistance in the operation of the facility. Mr. D. DeDominicis was responsible for the design of the new components for this facility. Dr. C. H. Marston contributed to the analyses and evaluation of the test results.

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I. SUMMARY OF KEY RESULTS OF THE PAST YEAR

1. The most significant result of the past year was the successful completion of the first series of tests in the new 6 to 1 area ratio MHD channel and 4 Tesla magnet. These experiments represent a major advance in the field of MHD power generation since no previous MHD generator has been operated at such high area ratios. Only with such high area ratios can the high enthalpy extractions needed for efficient MHD power generation be achieved.

2. To date, the magnet has been operated at a maximum field of 2.2 Tesla, where 12.6% enthalpy extraction (i.e. heat to electric conversion) has been measured in cesium seeded neon at 3470°K. This record enthalpy extraction represents the best performance obtained anywhere, and it exceeds the maximum 8.0% enthalpy extraction obtained in open cycle, combustion MHD generators having 50 times the volume of the present generator.

3. Of greater significance is the fact that the generator power output was uniformly distributed along the axial length of the MHD channel. It was thought that the rapid expansion of the flow in the presence of strong, adverse, electromagnetic pressure gradients would lead to boundary layer separation and power cutoff at the downstream end of the generator. Since this did not occur, it now appears that enthalpy extractions considerably higher than the previously established goals of 20% should be attainable in larger non-equilibrium MHD generators.

4. Difficulties with the 4 Tesla magnet windings necessitated extensive reworking of the magnet during the third quarter of this contract year. With the reworked magnet, it is anticipated that the 15-20% enthalpy extractions should be achieved. With 20% enthalpy extractions, 50% overall MHD power plant efficiencies are attainable.

II. PUBLICATIONS OF THE PAST 12 MONTHS

1. B. Zauderer and E. Tate, "Electrode and Gas Dynamic Effects in a Large Non-Equilibrium MHD Generator", AIAA Journal, Vol. 11, No. 2, Feb. 1973, pp. 144-155.
2. B. Zauderer and E. Tate, "High Enthalpy Extraction Experiments in a Large Non-Equilibrium MHD Generator", in Proceedings of the 13th Symposium on Engineering Aspects of MHD (Stanford University, Stanford, March 1973) GE-TIS#73SD214.
3. B. Zauderer, "Investigation of a Large Non-Equilibrium MHD Generator", Annual Report - Office of Naval Research - Contract N00014-70-C-0321, August 1972.
4. B. Zauderer, C. H. Marston, C. S. Cook and L. D. DeDominicis, "Blowdown Test Facility for a Fossil Fueled, Non-Equilibrium MHD Generator", in Proceedings of the 13th Symposium on Engineering Aspects of MHD (Stanford University, Stanford, March 1973). Also GE TIS#73SD213 (Supported in part by GE).
5. B. Zauderer, C. H. Marston and C. S. Cook, "Closed Cycle MHD for Central Station Power with Fossil or Nuclear Fuels", GE Co. TIS#73SD231, August 1973 (Supported in part by GE).

III. EFFORT OF THE PAST YEAR

During past year testing of a new MHD channel, designated ST-40, was initiated. In addition, studies of electrode effects and molecular contamination effects were initiated in a specially constructed high Mach number MHD channel. Finally, analyses of MHD power cycles were undertaken.

1. The ST-40 MHD Channel

Previous studies of the supersonic, non-equilibrium MHD generator were performed in the ST-20 (20 liter channel volume) MHD generators(1-3). The ST-20 channels had a 3 to 1 area ratio and a 75 cm. axial generator length. The first of these generators[3] (ST-20F) had flush mounted copper electrodes arranged axially in 37 rows. The maximum power output of the ST-20F generator was measured in Run #76 where 430 KW, representing 7.5% enthalpy extraction was obtained in Neon + 1% Xenon. At this power output, gas dynamic pressure disturbances were observed in the generator and no power was extracted from the downstream third of the generator. It was suspected that this power cut-off was caused by oblique shock wave-boundary layer interactions which increased the electrode voltage loss to a value greater than the induced voltage in the generator. To verify this hypothesis, another channel (ST-20W) was constructed with identical geometry as the ST-20F channel. The ST-20W channel had 37 pairs of wire electrodes located beyond the boundary layer displacement thickness. A maximum power output of 1200 KW, representing 11% enthalpy extraction, was measured in Run #362 with cesium seeded argon at 4000°K and 1.4 Tesla magnetic field strength. Static pressure measurements showed the presence of oblique shock waves of similar magnitude as had been observed at peak enthalpy extraction (Run #76) in the ST-20F flush mounted electrode channel. However, with the wire electrodes the power output remained at a high level up to the generator exit. It was thus clear that, by placing the electrodes outside the coldest part of the boundary layer, the effect of shock wave-boundary layer interactions on the electrode voltage losses was minimized. This effect can be seen in Figure 1 where the axial power output distribution is plotted for the maximum enthalpy extraction experiment in the ST-20W wire electrode channel. As noted, in the flush electrode channel, the enthalpy extraction was 7.5% and there was no power output in the downstream third of the channel. With wire electrodes, the enthalpy extraction in the cesium seeded neon experiment at 3080° was 10% and the power was reasonably uniformly distributed over much of the channel despite the presence of shock waves. As is discussed in detail in reference 1, the high enthalpy extraction experiments in the ST-20W wire electrode channel were performed at high temperatures to obtain higher velocities and higher cesium concentrations for improved electrode emission. Experiments at lower gas temperatures in the ST-20W channel yielded almost as high enthalpy extractions. Run #327 in Table I is a representative low temperature, 2150°K, experiment where the enthalpy extraction was 8.5%.

The above results suggested that to increase the enthalpy extraction, the following changes in the MHD generator should be made. Channel expansion ratio should be increased to suppress the on-set of shock waves, the generator should be lengthened to determine the influence of increasing boundary layer thickness on electode performance and the magnetic field should be considerably increased above the low values used in the previous experiments. To achieve these aims, a new MHD channel (ST-40) and magnet were constructed. (Figure 2) Since no previous experience existed on very high expansion, linear, MHD generators, it was decided to limit the area ratio of the new ST-40 (40 liter generator volume) channel to 6 to 1 (based on the nozzle throat) compared to 3 to 1 in the ST-20 channel. Due to constraints imposed by the shock tunnel facility, it was necessary to maintain the generator exit area at the same value as in the previous channel, namely 25.4 cm x 19.1 cm. Thus, the nozzle throat area of 80 cm^2 was one half that of the ST-20 channel, and the generator entrance area was 95 cm^2, where the Mach number is 1.5. Boundary layer calculations[4] indicated that the optimum channel length from the nozzle throat should be 140 cm to limit the boundary layer displacement thickness to less than 20% at the channel exit. The length of the supersonic portion of the nozzle was the same 20 cm as in the previous channels and the generator entrance Mach number of 1.5 was about the same as in the old channel. As in the previous channels, both the electrode and insulator walls were diverged. There were 74 electrode pairs. Due to the large electrode wall width near the generator exit, the last 24 electrode pairs were located in 12 rows with two separately loaded electrode pairs at each axial location along the electrode wall. The channel was designed for use with either flush mounted or protruding tungsten wire electrodes. At present, wire electrodes of construction similar to the ST-20 wire electrode channel are in use.

2. The 4 Tesla Magnet for the ST-40 MHD Channel

A 1 megajoule capacitor driven magnet was designed. It had a field which tapered from 3.8 Tesla near the generator entrance to about 2 Tesla at the exit. To reduce the coil resistance and thereby increase the temporal uniformity of the field during the 5 ms. test time, the magnet vendor used stranded Litz wire to construct the coil. Due to poor construction by the vendor (MCA, Inc.) one of the leads of the magnet arced internally to the support structure and it was severely damaged in June 1972. The vendor repaired the coil and it was returned in September 1972. At that time, it was felt by our technical staff that further improvements in the magnet lead construction were necessary. These modifications took an additional two months to complete. From November 1972 to January 1973, the MHD experiments to be reported below were performed with magnetic fields held to 60% or less of the rated 4 Tesla peak field. In January 1973, the magnet short circuited again at the place where it had been repaired, namely, at the lead junction (see Figures 3 and 4). However, due to an elaborate electrical testing system which had been installed, the incipient failure was detected before an explosive failure could occur. It was decided to construct two new coils using solid conductor cable instead of stranded Litz wire used by MCA. Everson Electric in Reading, Pa. has wound both coils at a total cost which is only 25% greater than the cost of repairing the old leads by MCA; and they were delivered in June 1973.

Figure 5 is a photograph of the new coils shown standing on end. The metal support structure for the other end can be seen on the floor in the background. In this coil, the leads were placed at the side of the magnet to prevent arcing to the end support and to remove the leads from the peak field region. Figure 6 which shows a top view of the high field end of the magnet, should be compared with the old coil construction in Figure 2. Figure 3 shows the magnet assembled around the ST-40 MHD channel. It should be noted that the electromagnetic noise generated by this magnet necessitated the relocation of the entire instrumentation complex used in the shock tube facility.

3. MHD Generator Theoretical Analyses

The one dimensional theory of the non-equilibrium MHD generator which had been in use for the past 5 years(1-3) was modified during this contract period. Analyses showed that numerical instabilities can develop in the computation of the electron temperature in the generator. Also, instabilities at the supersonic nozzle throat affected the local Mach number of the flow in the generator. The electron temperature instability accounts for the part of the discrepancy between computed and measured electron temperatures obtained in some early experiments and we intend to pursue this investigation at some future date.

Other changes in the numerical analyses were designed to increase the flexibility of the analyses.. For example, in the old program, the current density in the generator had to be specified. In the new program, either current density, the load factor, or the load resistance can be specified. These changes enable one to better optimize MHD generator geometries. A major result of this change in the analyses has been our decision not to design a subsonic MHD generator. The reason for this is as follows: The Lorentz force in the generator decelerates the flow and thereby converts the kinetic energy of the gas to electrical energy. In supersonic MHD generators, the area expansion of the generator must be large to prevent excessive flow deceleration and boundary layer separation. The objective of this years' MHD program was to prove that large area expansion ratios (e.g. 6 to 1) are feasible in supersonic MHD generators. On the other hand, in subsonic generators, the generator must operate near Mach 1 where choking occurs. Area expansion of the channel reduces the Mach number and prevents choking. However, our calculations showed that area expansions in excess of 2.5 in a 1.5 meter long subsonic channel would lead to excessive flow deceleration. This reduces the power density which is proportional to the square of the velocity. Furthermore, to achieve high isentropic generator efficiencies the load factor (i.e. the ratio of the load voltage to the induced voltage) should be greater than 0.8. Extensive calculations showed that the satisfaction of all these requirements requires careful adjustment of the load resistors in the generator to prevent choking. Since in a shock tube experiment the load resistors are pre-set before the test, it would be very difficult to achieve the required control. We thus believe that subsonic generator experiments should be performed in a steady state device such as a blowdown experiment.

The analyses also indicated that enthalpy extractions in excess of 30% could be achieved in a properly designed supersonic MHD generator. The attainment of very high enthalpy extractions would greatly increase the usefulness of MHD generators.

Finally, one additional change in the analyses was to include an option where a friction factor could be introduced into the gas momentum equation in place of a separate inviscid core flow-boundary layer solution. With the friction factor, the effect of protruding electrodes on the gas dynamic characteristics of the generator could be analyzed.

4. Gas Dynamic Performance, ST-40W Channel

The small entrance area combined with the use of protruding wire electrodes in the ST-40 channel considerably increased the gas dynamic frictional effects in the present channel. In the ST-20 wire electrode channel, the electrodes had a negligible effect on the flow and a one-dimensional core flow solution with a separate boundary layer solution accurately described the flow at zero magnetic field[1-3]. In the ST-40 channel, the separate core flow-boundary layer solution under-estimated the wall friction effects. This can be seen in Figure 8 where the axial pressure and Mach number variation are plotted for zero magnetic field. It was found that by selecting a friction factor of 0.008 and solving the one-dimensional flow equations without a separate boundary layer solution, a good fit to the measured Mach number and static pressure data at zero field was obtained (see Figure 8). However, a slight change had little effect. It should be recognized that the legitimacy of a constant artificial friction factor is not clear since the effect of the wire electrodes decreases rapidly in the downstream direction.

5. MHD Generator Performance, ST-40 W Channel

Due to the necessity of operating the magnet at lower field strength, the initial MHD power experiments were performed at high stagnation temperatures to obtain high gas velocities and induced voltages. It should be noted that due to the large area expansion, the static gas temperature is less than 60% of T_o at the generator entrance and 25% of T_o at open circuit at the generator entrance. Also, the long nozzle greatly reduces the stagnation electron density. Thus, in all the experiments to be reported, the electron temperature and density in the generator was considerably higher than the local gas temperature. Due to the previously noted difficulties with the magnet, the MHD experiments reported in this paper were performed at between 30% and 60% of the rated peak field strength of 3.8 Tesla. Two sets of experiments were performed. In one set, the test gas was argon + 1.5% cesium at stagnation temperatures of 3600 to 3900°K and pressures of 4.78 to 5 atmospheres. In the second set, the test gas was neon + 1.5% cesium at temperatures of 3100 - 3500°K and pressures of 4.24 to 5.48 atmospheres. It has been previously observed[2] that a minimum induced ignition voltage is required to achieve electrode conduction. In the argon experiments, this minimum ignition voltage was obtained at 30% of the peak field strength (about 1.1 Tesla near the generator entrance). For this case, the induced voltage increased from 170 volts at the upstream electrodes to 220 volts at the downstream electrodes. Figure 9 shows the total MHD power output for the argon and neon experiments as a function of the magnetic field strength. In all the experiments, the external load per electrode pair was 0.585 ohms. One notes that once the current ignition voltage is exceeded, the power in both sets of experiments increases very roughly as the square of the magnet field. The maximum power measured in the argon experiments was 520 KW, which equalled 9% of the thermal input power. In the neon experiments the peak power was 1200 KW (Run #429) which represented 12.6% enthalpy extraction. (See Figure 9). Figure 1 shows the axial power distribution for one of the high enthalpy extraction experiments in neon. One notes that for this experiment (Run #424) the power is fairly uniformly distributed along the generator. This result is extremely important since at the downstream end of the generator, the computed boundary layer displacement thickness of 2 cm is greater than the 0.5 cm protrusion of the electrode wires from the wall. Due to high amplitude, very low frequency interference from the magnet, coupled with low static pressures in the channel, it was not possible to obtain a base-line for the static pressure measurements in Run #429. Nevertheless, examination of the static pressure data in the generator did not show any great pressure variation which would indicate the presence of shock waves in the generator. As noted in Section 1, at high enthalpy extraction in the ST-20 channels, oblique shock waves were detected. A one-dimensional analyses of the maximum enthalpy extraction experiment (Run #429 in Table 1) was performed using wall friction factors of .007 and .008. The latter predicted choking at the generator exit but the former yielded essentially a smooth pressure decrease to the channel exit, which is consistent with experimental observations of no choking effect. Local Mach number reached a peak of 1.9 in the central region of the generator. This should be compared to the open circuit Mach number which continuously increased to over 3 at the generator exit as shown in Figure 8. As noted in Section 5, the validity of a constant artificial friction factor is questionable, thus the proper method of gas dynamic analysis of the wire electrode channel under heavy electrical load requires further study. Nevertheless, one can conclude that the record 12.6% enthalpy extraction achieved in this test sequency will be exceeded when the magnetic field strength is increased.

6. Electrode Conduction Studies

While the magnet for the ST-40 channel was being rebuilt, a test series on electrode effects was conducted on another MHD channel. This channel also had removable electrode plates (Fig. 10 and 11) which allowed easy modification to the electrode structure. The aim of these experiments was to compare the performance of flush mounted and protruding electrodes.

The two primary criteria affecting generator performance are the bulk plasma conditions and electrode conduction. In a shock tunnel, the boundary layers as well as the electrodes are cold. Previous work(2) has shown that to maintain electrode conduction, the induced voltage in the generator must exceed both the electrode current ignition voltage, which is considerably higher than the current sustaining voltage. An MHD generator(3) having flush mounted, cold electrodes operated poorly because the electrode ignition voltages were of the same order as the induced voltages which ranged from 300 to 500 V. The ignition voltage is also a function of the initial electron density at the generator entrance. Thus, at low electron densities, large ignition voltages are necessary. To reduce the ignition problem the new MHD generator channel was operated at induced voltages in excess of 1000V. The electrodes were segmented in both the axial and magnetic field direction (Fig. 10 and 11) to obtain a uniform discharge in the channel. Each electrode pair had its own electrically isolated load resistor.

The first series of experiments were performed in argon + 1% cesium at 3700°K and 4 atm. stagnation conditions, in order to obtain a high electron density in the generator. The magnetic field strength was 20,000 gauss. The results clearly indicated that electrode conduction was the limiting factor in generator output. Figure 12 shows two oscilloscope traces of the generator current from electrodes in the fifth and seventh row of electrodes (there were 19 electrode rows (see Fig. 10 and 11)). After an initial current spike as the shock front passes through the generator, the current is very intermittent during the 6 millisecond test time. The current peaks are up to 20 amperes in magnitude. This pattern of high current pulses clearly indicates that the electrodes are limiting the current and not the bulk plasma properties.

A series of runs with the flush electrodes was performed using higher fields and neon to obtain higher induced voltages. The results were the same as the argon experiments. To verify that the electrodes were limiting the current, a pair of electrostatic probes in the insulator wall of the channel were converted to electrodes by protruding them 1 1/2 inches into the flow. This protruding wire electrode configuration has been used successfully in the ST-40 generator channel. These electrode wires are aligned parallel to the magnetic field and the upstream edge of the electrode is at gas stagnation conditions. Figure 13 shows two oscilloscope traces of electrode currents for one of the argon experiments. The top current trace was obtained by the two protruding pin electrodes mounted in the insulator wall. The bottom trace was obtained with an electrode pair mounted in the electrode wall. These electrodes are also of a protruding design and they will be described shortly. In the top trace, there is a current spike indicating the passage of the shock front. The current then goes to zero for reasons which are related to the flow starting processes in this particular channel. After 1 1/2 milliseconds (1 1/2 cm. in the figure) current ignition occurs and it is maintained at an average level of 15 amp. for the rest of the test time.

As a result of this observation, it was decided to use a protruding pin electrode configuration with the pins aligned in the $\bar{U} \times \bar{B}$ direction instead of the $\vec{B}$ direction used in the protruding wire electrode configuration. The electrode plates were removed and photographed (see Figures 10 and 11). The cathode wall electrodes showed the existence of a small arc spot at downstream edge of each of the 1/8 in. diameter tungsten electrodes. The location of this spot is in agreement with the direction of the current vector at the cathode and its presence proves that the electrodes were conducting in the arc mode. The anode wall shows a more interesting pattern (Fig. 11). One notes charing of the insulator material upstream of each anode. This indicates that the current is approaching the anode from the upstream direction, in agreement with MHD theory. This tendency of the current flowing along the anode wall has been obtained in both open cycle and closed cycle MHD generators and it is a major cause of internal shorting of the current in many MHD generators. In the present generator, it can be seen (Fig. 11) that by using a large axial electrode spacing the anode current effect is localized to the vicinity of the anode. This eliminates anode shorting. To reduce the electrode ignition voltages, a tungsten pin was placed in each electrode. The pins were long enough to protrude past the boundary layer. Figures 10 and 11 were photographed with the pin assembly half completed.

The bottom oscilloscope trace in Figure 13 is the current measured with the protruding pin electrodes. The argon and cesium gas conditions are the same as in all previous experiments. The electrode current is continuous as is the case with the protruding wires, except that in the former the magnitude of the current is about 4 amps compared to 15 amps in the latter. The lower current level with the pins is caused by the ignition of less arc spots at the tip of the pin compared to the multiple arc spots at the wire electrodes. Thus, one can conclude that in the shock tube generator, the best conduction is obtained from electrodes which are aligned parallel to the magnetic field and which are placed in the free stream, outside the boundary layer.

IV. REFERENCES

1. B. Zauderer and E. Tate, "Electrode Effects and Gas Dynamic Characteristics of a Non-Equilibrium MHD Generator", Proceedings 12th EAM Symposium, (Argonne National Laboratory, Argonne, Illinois, March 1972) p. I. 6.
2. B. Zauderer and E. Tate, "Experiments in a Large Non-Equilibrium MHD Generator with Cesium Seeded, Noble Gases", in 5th International MHD Power Generation Conference (ZAED, Karlsruhe, 1971), Vol. II, pp. 431-446.
3. B. Zauderer and E. Tate, "Performance of a Large Scale Non-Equilibrium MHD Generator with Rare Gases", AIAA Journal, Vol. 9, No. 6, June 1971.
4. B. Zauderer, "Optimization of a Linear Non-Equilibrium MHD Generator", General Electric Co., TIS No. 70SD261, June 1970.

Table 1. Highest Measured Enthalpy Extraction in Various MHD Channels Used in the GE/ONR Shock-Tube Facility

RUN	DATE	CHANNEL	PEAK MAGNETIC FIELD (TESLA)	GENERATOR VOLUME (LITRES)	TEMP, °K	GAS	MHD POWER OUT, KW	POWER OUT / HEAT IN
76	1968	ST-20F	1.4	19.7	3,950	NEON + 1% Xe	430	7.5%
327	1970	ST-20W	1.4	19.7	2,150	NEON + 1.2% Cs	440	8.5%
362	1971	ST-20W	1.4	19.7	4,000	ARGON + 1.75% Cs	1,100	11.0%
429	1973	ST-40W	2.2	39.4	3,470	NEON + 1.54% Cs	1,200	12.6%

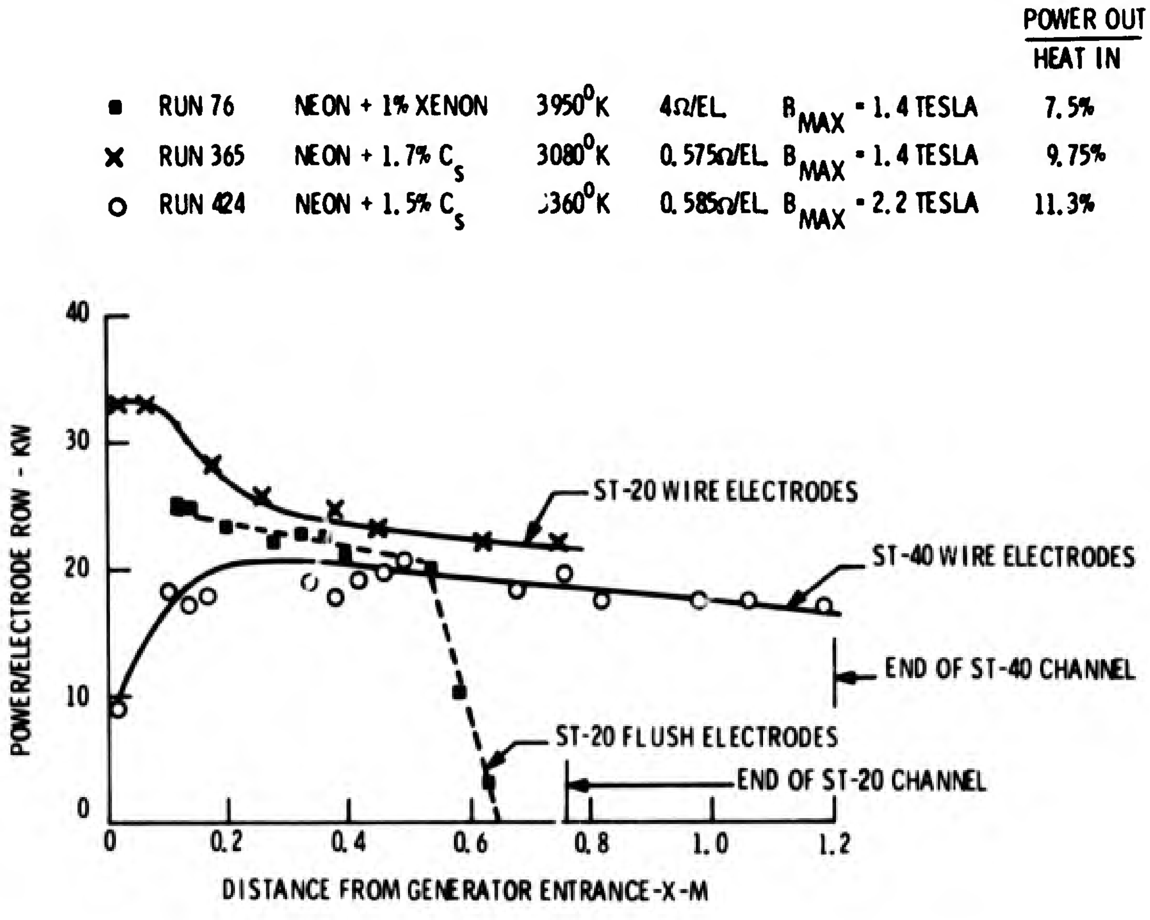

Figure 1. Power/Electrode Row, Distribution for Large Power Extraction Ratio Experiments in Three Different MHD Channels.

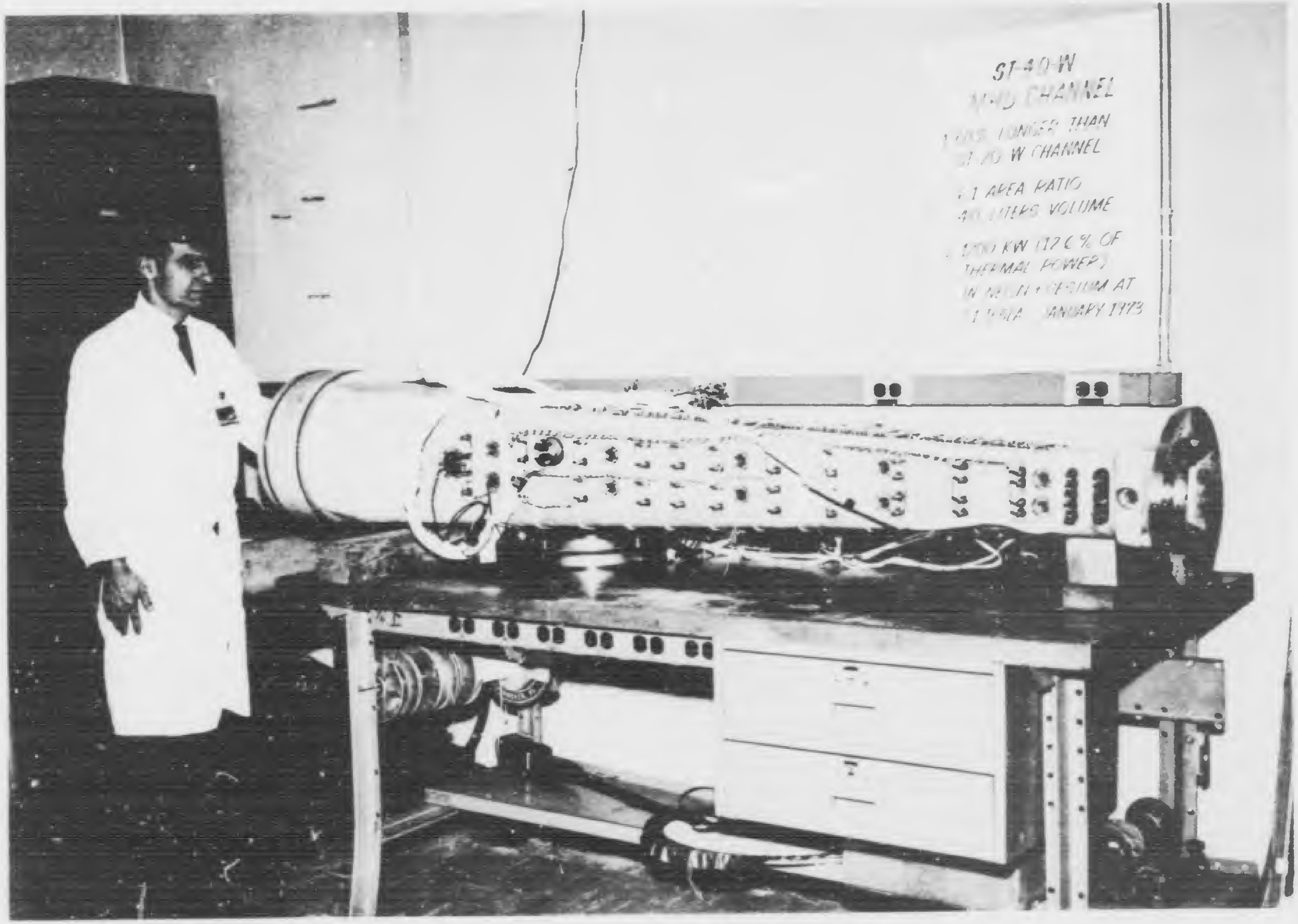

Figure 2. The ST-40W - MHD Channel

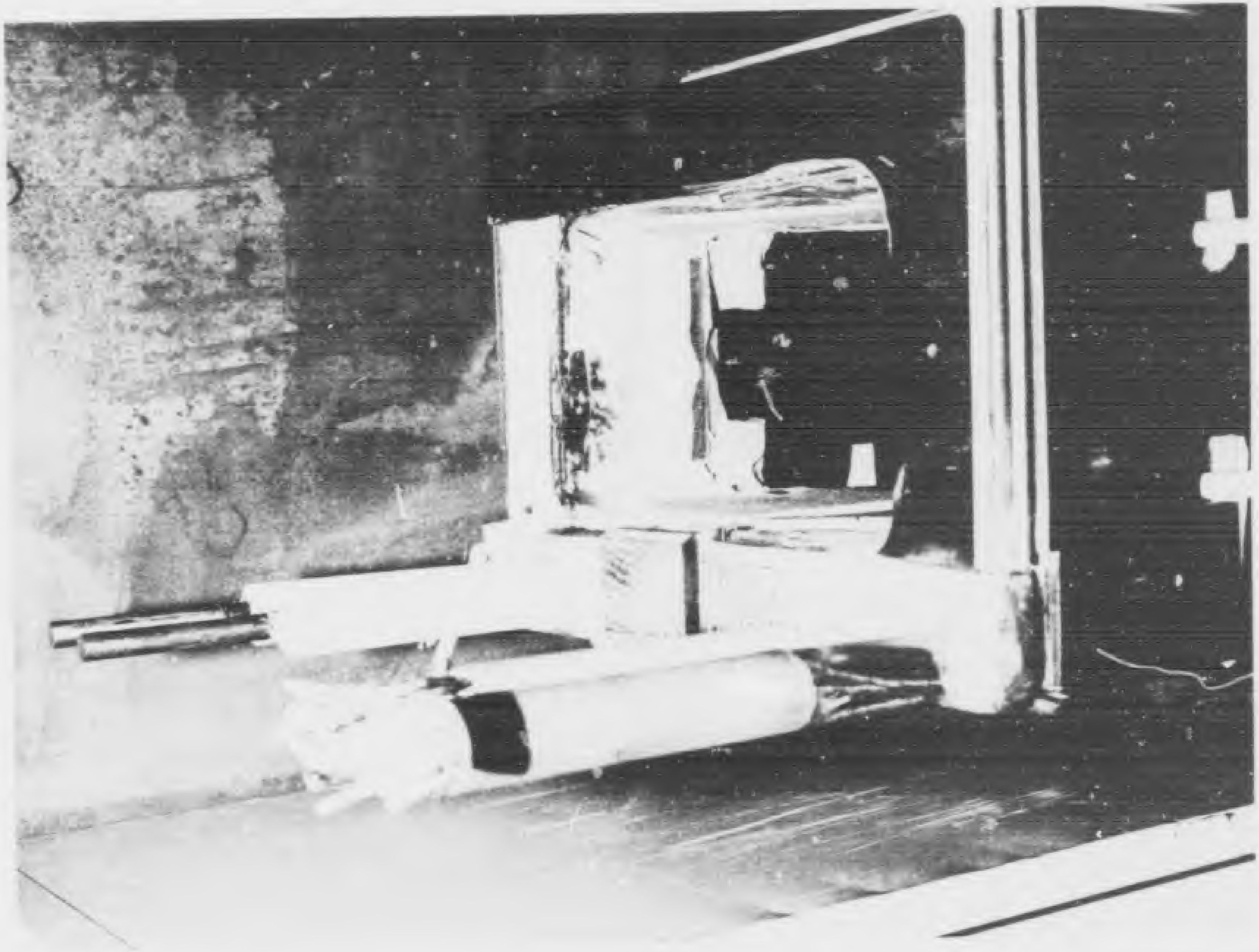

Figure 3. High Field End of the 4 Tesla Magnet. The Two Conductors at the Far End Were Repaired Last Year and the Second Failure Occurred at the Repaired Joint. The Failure Area is Visible to the Right of Leads.

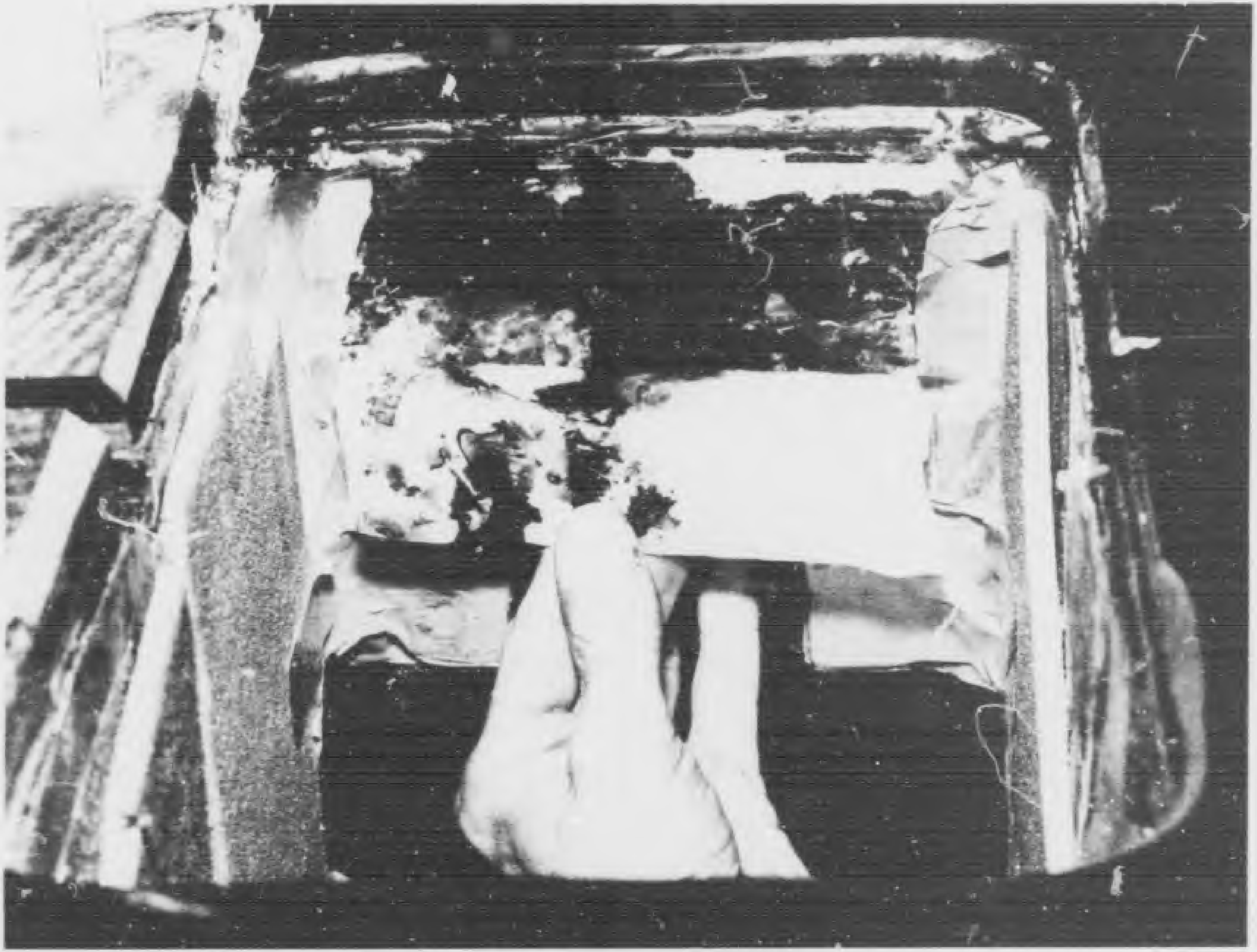

Figure 4. Close-up of the Burnt Region Where the Magnet Failed.

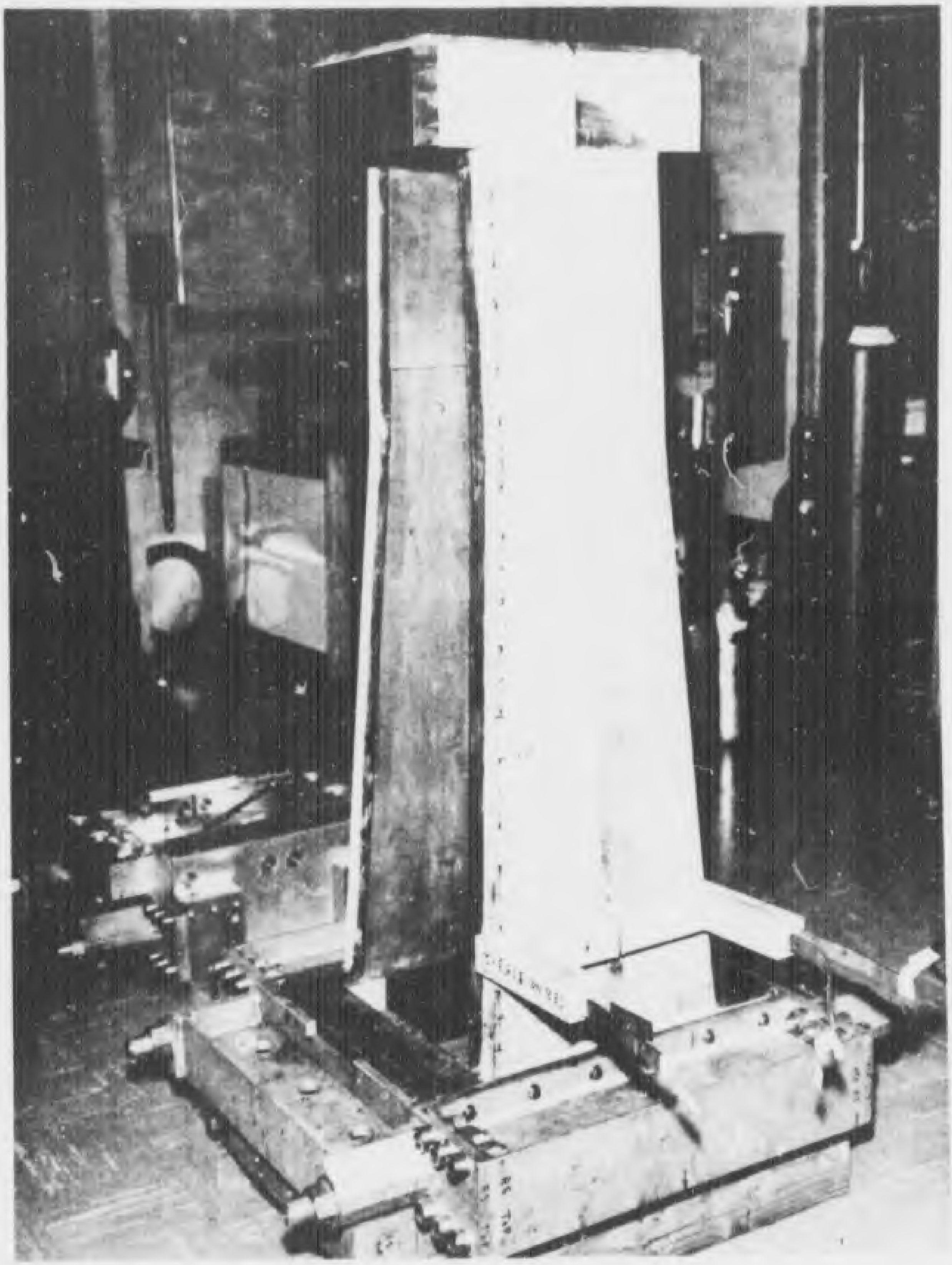

Figure 5. The New 4 Tesla Coils Shown Standing Upright in the Downstream End Support Structure. The Upstream Support is on the Floor in the Background.

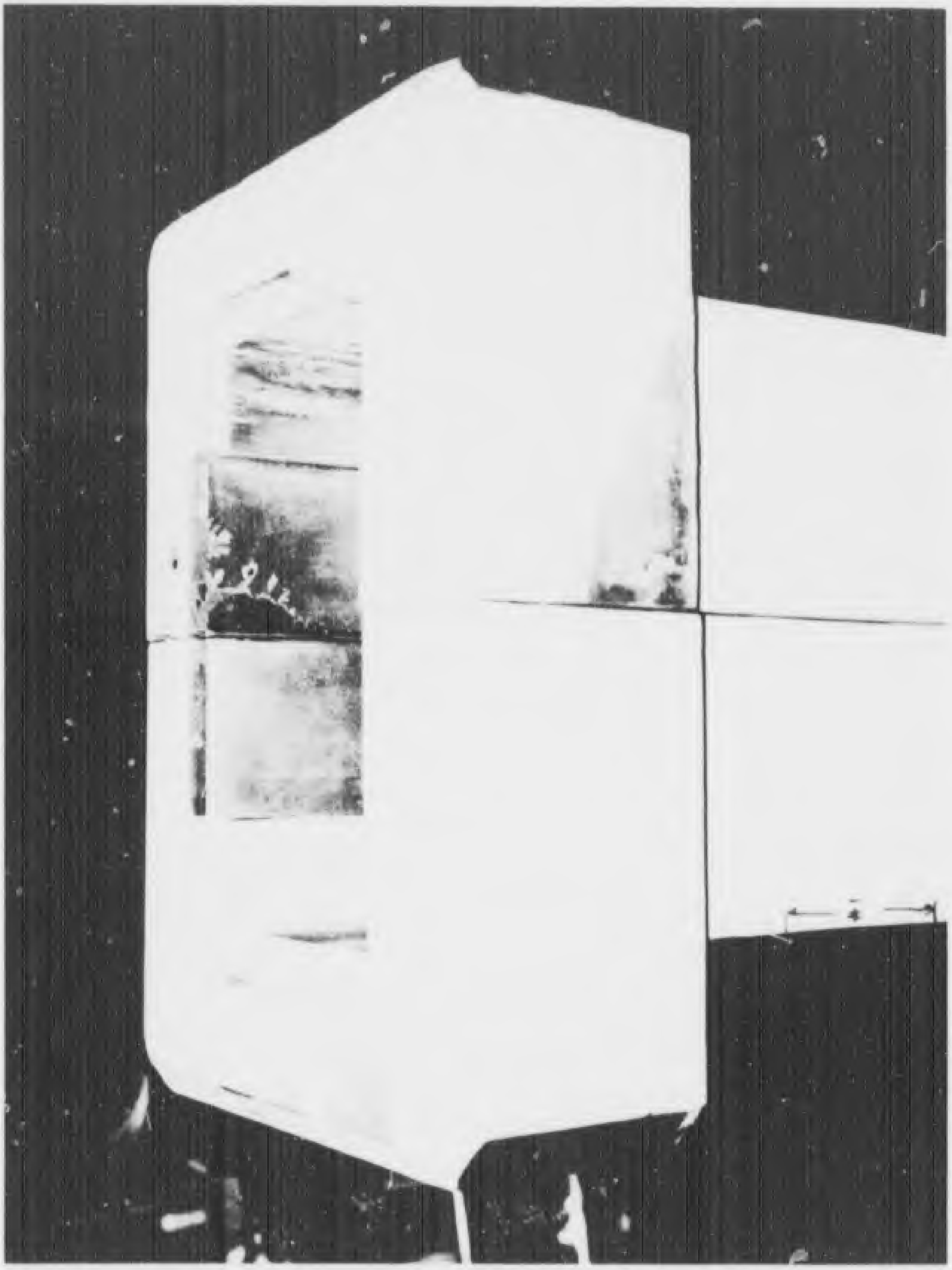

Figure 6. High Field End of the New 4 Tesla Coil (Compared with Figures 3 and 4).

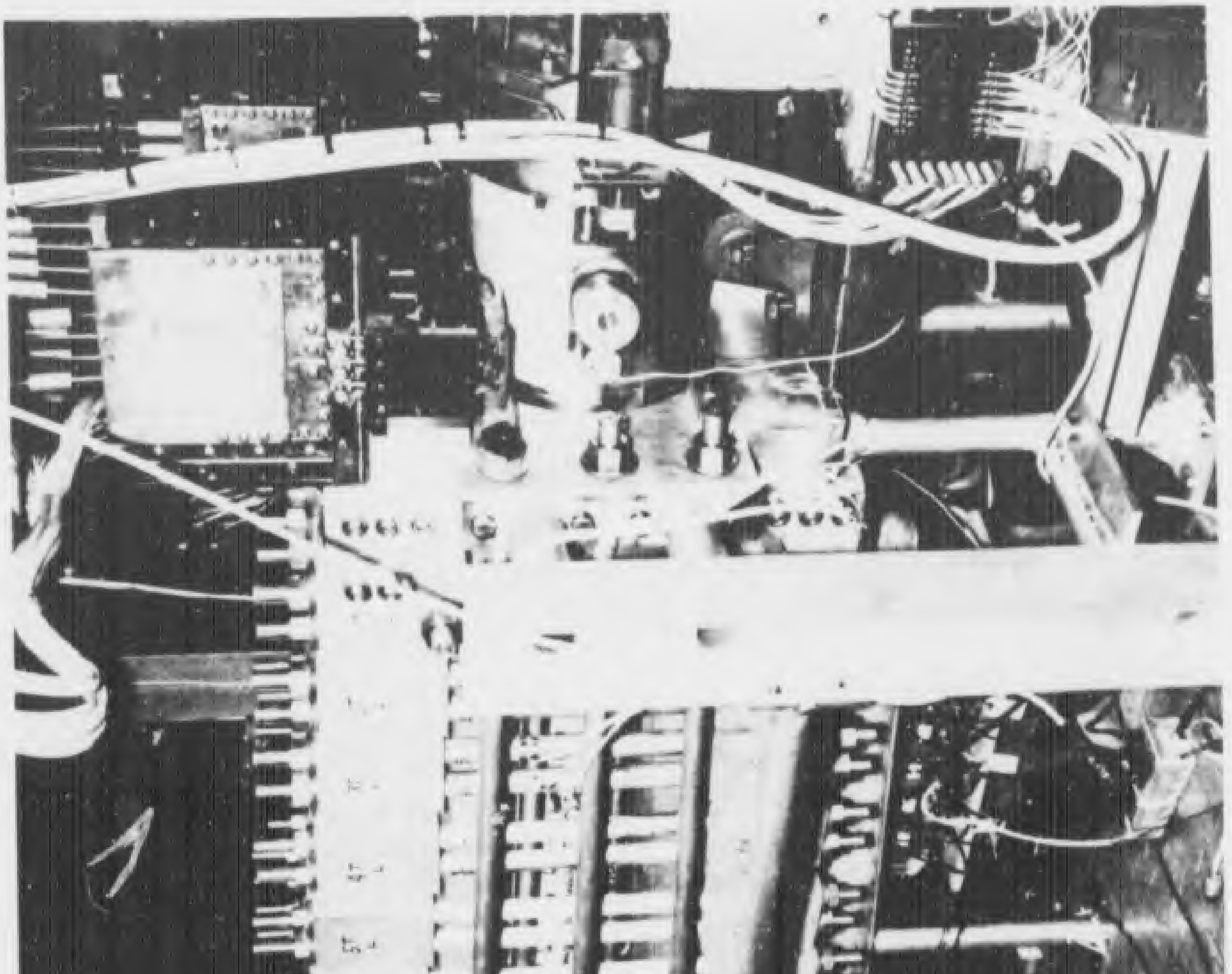

Figure 7. The ST-40W Channel and Magnet Assembled on the Shock Tunnel Facility. The Driven Tube is on the Right.

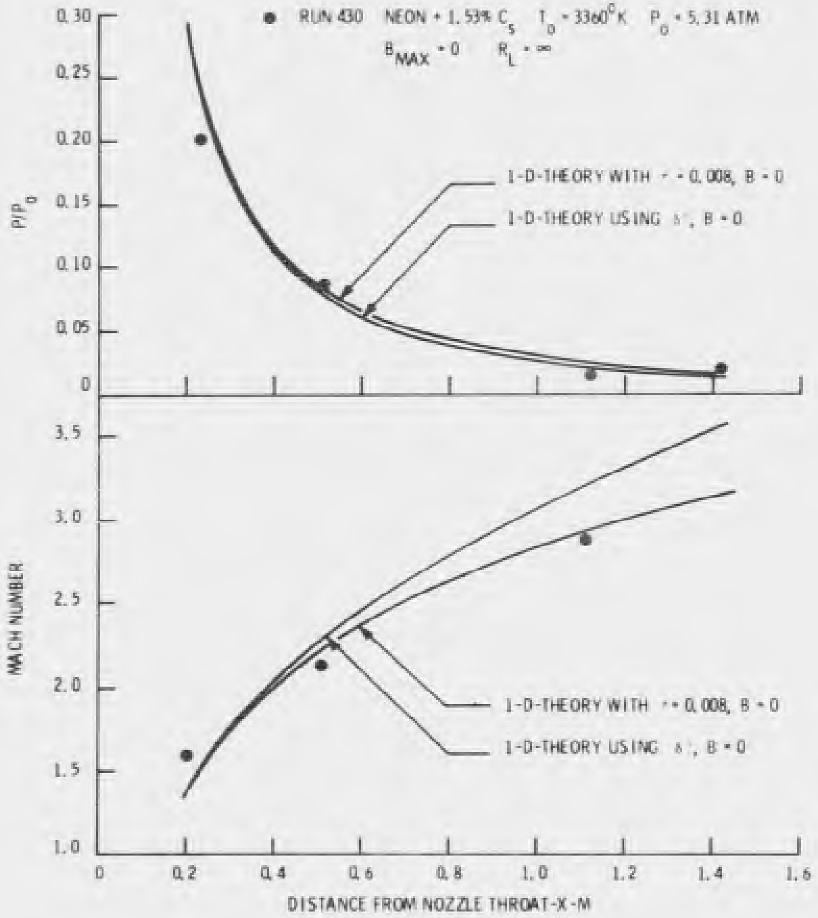

Figure 8. Static Pressure and Mach Number Distribution in the Channel and Theoretical Curve Using One-Dimensional Theory with (a) a Friction Factor f of .008 and (b) a Boundary Layer Displacement Thickness δ*.

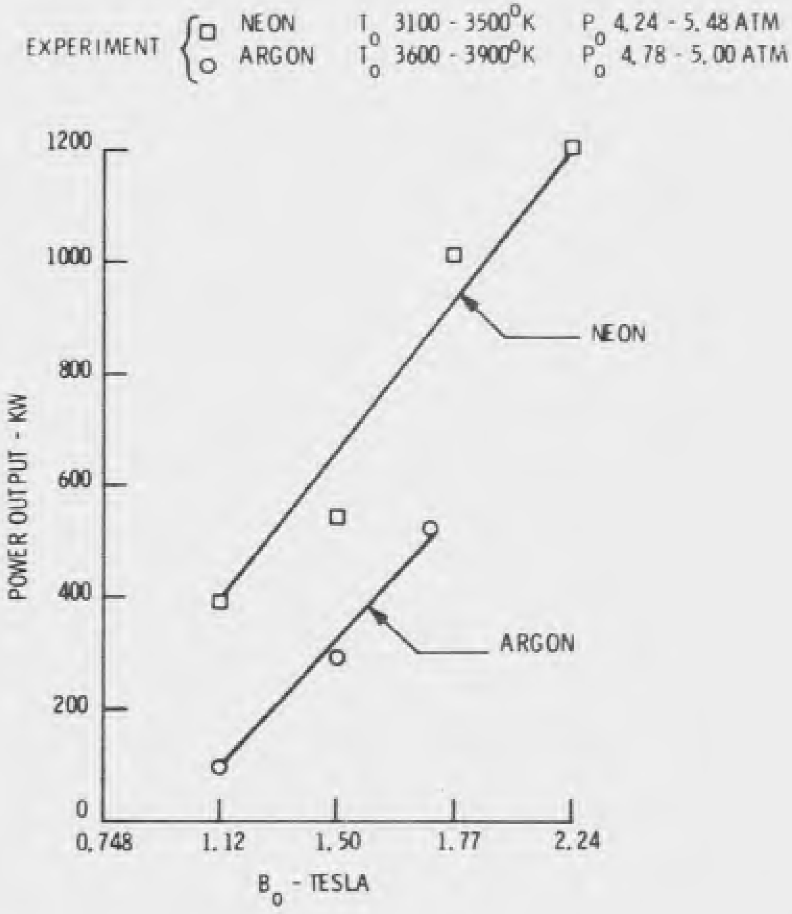

Figure 9. Power Output versus Magnetic Field for a Series of Neon and Argon Experiments in the ST-40W Channel.

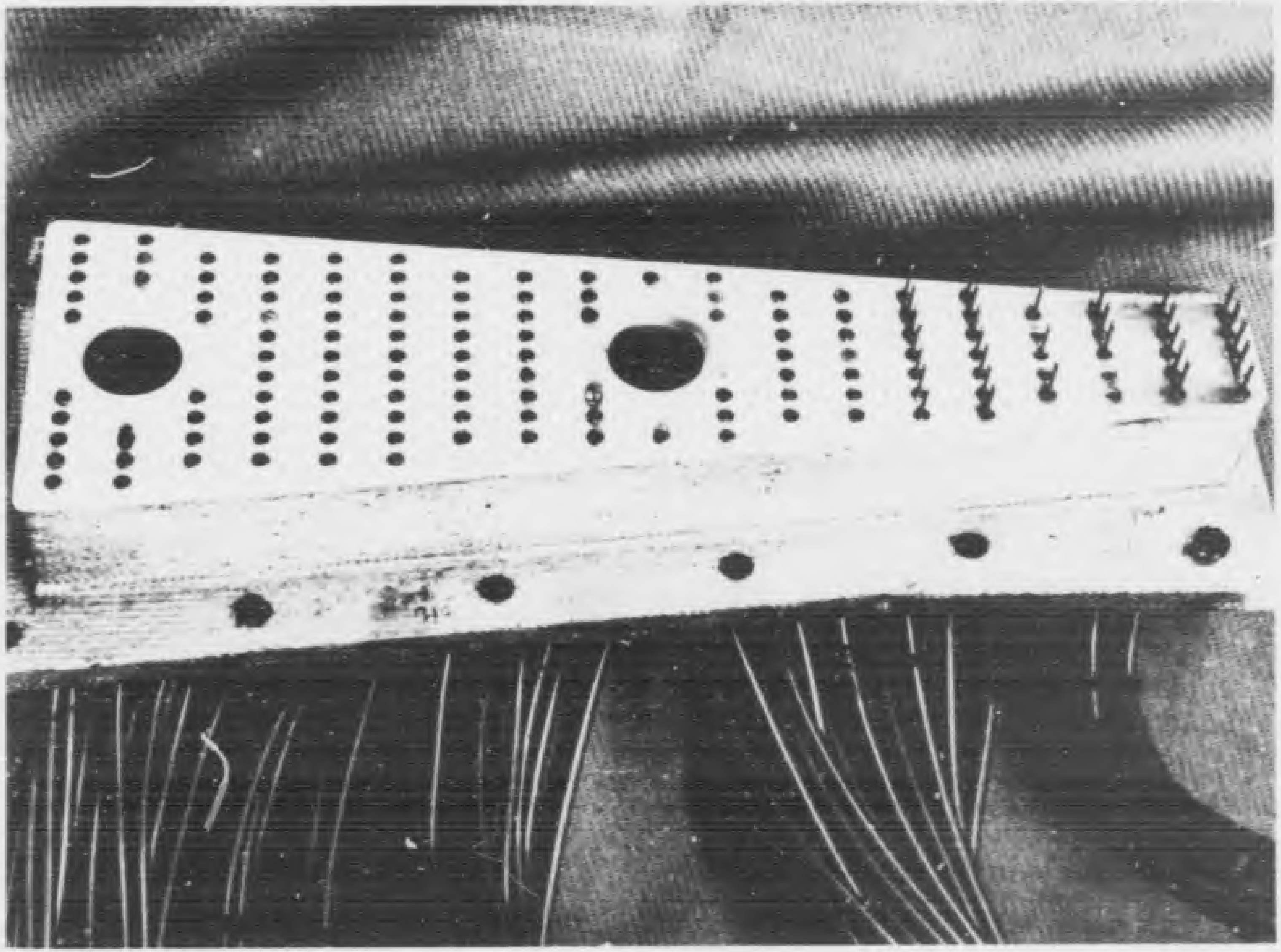

Figure 10. Photograph of the Cathode Wall Taken Halfway During the Installation of Protruding Pin Electrodes. The Narrow Section of the Plate is the Upstream Side of the Electrode Wall.

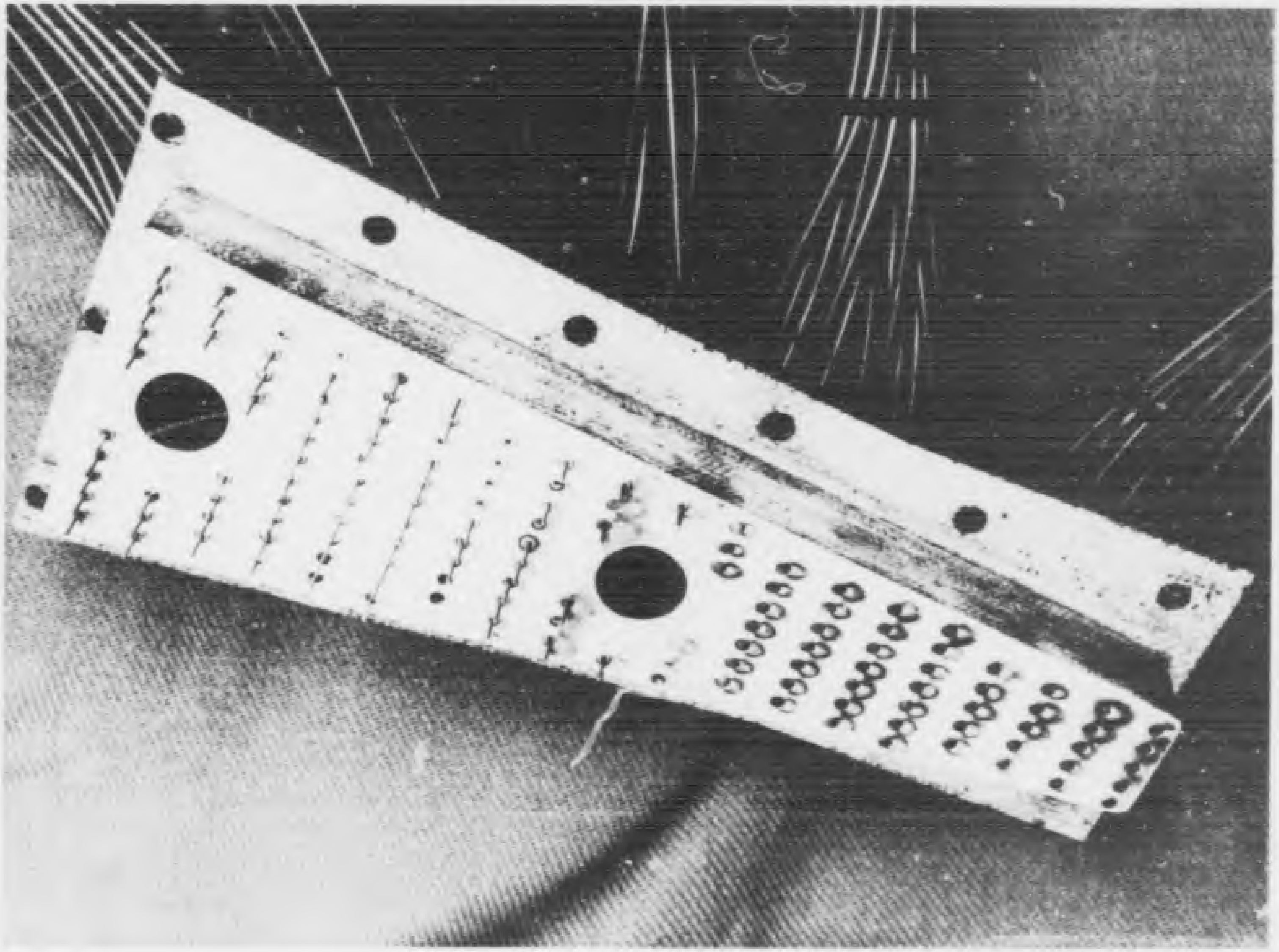

Figure 11. Photograph of the Anode Wall Taken During the Installation of the Pin Electrodes. Note the Burn Marks on the Insulators Upstream of the Flush Mounted Electrodes.

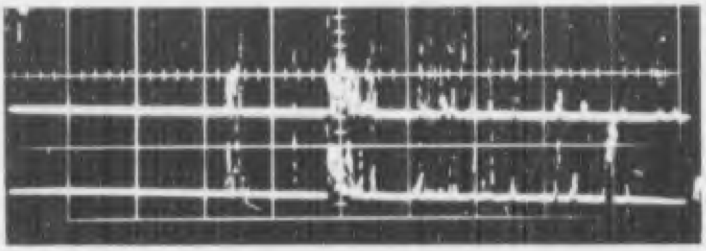

Figure 12. Oscilloscope Trace of the Electrode Current for a Flush Mounted Electrode Experiment. Time is from Left to Right at 1 Millisecond/cm. The Test Time is 6 Milliseconds. The First Current Spike Represents the Arrival of the Shock Front. The Current Setting is 20 A/cm.

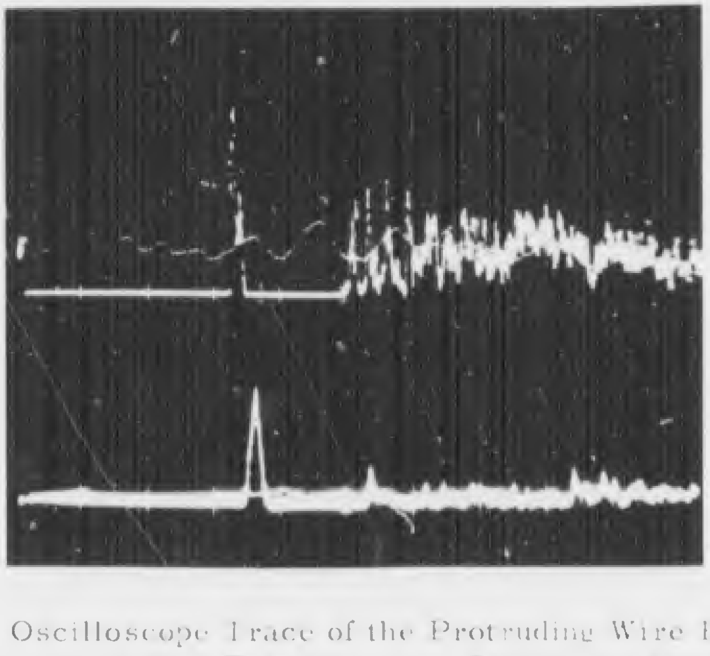

Figure 13. Oscilloscope Trace of the Protruding Wire Electrode Current (Top Trace) and the Protruding Pin Electrode Current. All Scope Settings are the Same as in Figure 10.

SUMMARY OF KEY RESULTS OF THE PAST YEAR

1. The most significant result of the past year was the successful completion of the first series of tests in the new 6 to 1 area ratio MHD channel and 4 Tesla magnet. These experiments represent a major advance in the field of MHD power generation since no previous MHD generator has been operated at such high area ratios. Only with such high area ratios can the high enthalpy extractions needed for efficient MHD power generation be achieved.

2. To date, the magnet has been operated at a maximum field of 2.2 Tesla, where 12.6% enthalpy extraction (i.e. heat to electric conversion) has been measured in cesium seeded neon at 3470°K. This record enthalpy extraction represents the best performance obtained anywhere, and it exceeds the maximum 8.0% enthalpy extraction obtained in open cycle, combustion MHD generators having 50 times the volume of the present generator.

3. Of greater significance is the fact that the generator power output was uniformly distributed along the axial length of the MHD channel. It was thought that the rapid expansion of the flow in the presence of strong, adverse, electromagnetic pressure gradients would lead to boundary layer separation and power cutoff at the downstream end of the generator. Since this did not occur, it now appears that enthalpy extractions considerably higher than the previously established goals of 20% should be attainable in larger non-equilibrium MHD generators.

4. Difficulties with the 4 Tesla magnet windings necessitated extensive reworking of the magnet during the third quarter of this contract year. With the reworked magnet, it is anticipated that the 15-20% enthalpy extractions should be achieved. With 20% enthalpy extractions, 50% overall MHD power plant efficiencies are attainable.